THE PARAGENETICAL MINERALOGY OF THE LEADHILLS AND WANLOCKHEAD LEAD AND ZINC DEPOSITS.

A Thesis
presented for the Degree of
Doctor of Philosophy

by

A. K. Temple.

The University of Leeds.

February 1954.

ABSTRACT.

The principal structural pattern of the Leadhills-Wanlockhead district, imposed by the Caledonian Orogeny, is characterised by complex folding, striking N.E.-S.W., crossed by a series of intersecting joints, whose average strike is N.N.W., and whose relative age of formation was adduced from the relationships of the Caledonian minor intrusives. Reorientation of the Caledonian stress towards a "Hercynian" direction would effect sinistral movement along the joint pattern, resulting in the production of open spaces on the more north westerly trending members of the joint system. Later deformation is evidenced by slight displacement of the veins, and by W.N.W. trending monchiquite and tholeiite dykes.

Investigation of the mineralisation revealed the presence of sixty minerals. Fifteen of these had not been previously recorded from the district, including one new mineral, akin to chromium bearing lanarkite, one new variety, chromian leadhillite, one mineral previously recorded only as an artificial product, lead hydroxyapatite, and two minerals, phoenicochroite and rammelsbergite, not previously confirmed from Britain.

Two periods of mineralisation were distinguished, the first consisting of quartz veins with which are associated small amounts of gold, pyrite, and muscovite, tentatively assigned to the Caledonian Orogeny, and the second comprising the lead-zinc mineralisation. The paragenetical relationships of the primary minerals of the latter mineralisation indicate two generations of sulphides, of which the second is accounted for by reprecipitation

of elements derived from the replacement of the first generation sulphides by late stage quartz. A study of the distribution of elements through the paragenesis suggests that some elements were derived from other than a magmatic source, and that contamination has probably played a considerable role in the control of the character of the gangue minerals.

Evidence of a deep-seated origin of the mineralising solutions is given by mineral zones and the geochemical character of the deposit. Emplacement of the minerals took place at a temperature of the order of 143°-281° C., and a depth of the order of 2000'-4000' below the surface.

The Leadhills-Wanlockhead area is related to other lead-zinc districts in Britain, and on the basis of geochemical assemblage and the relation to igneous activity, it is concluded that the deposits were probably derived from the top of the tholeiitic layer and the base of the granitic layer, and were genetically connected to the Hercynian Orogeny.

TABLE OF CONTENTS.

ACKNOWLEDGMENTS

The writer wishes to thank the Lowland Lead Mining Company for permission to undertake the investigation. A particular debt of gratitude is owed to Mr. G. W. Borthwick who unravelled the intricacies presented by the underground workings.

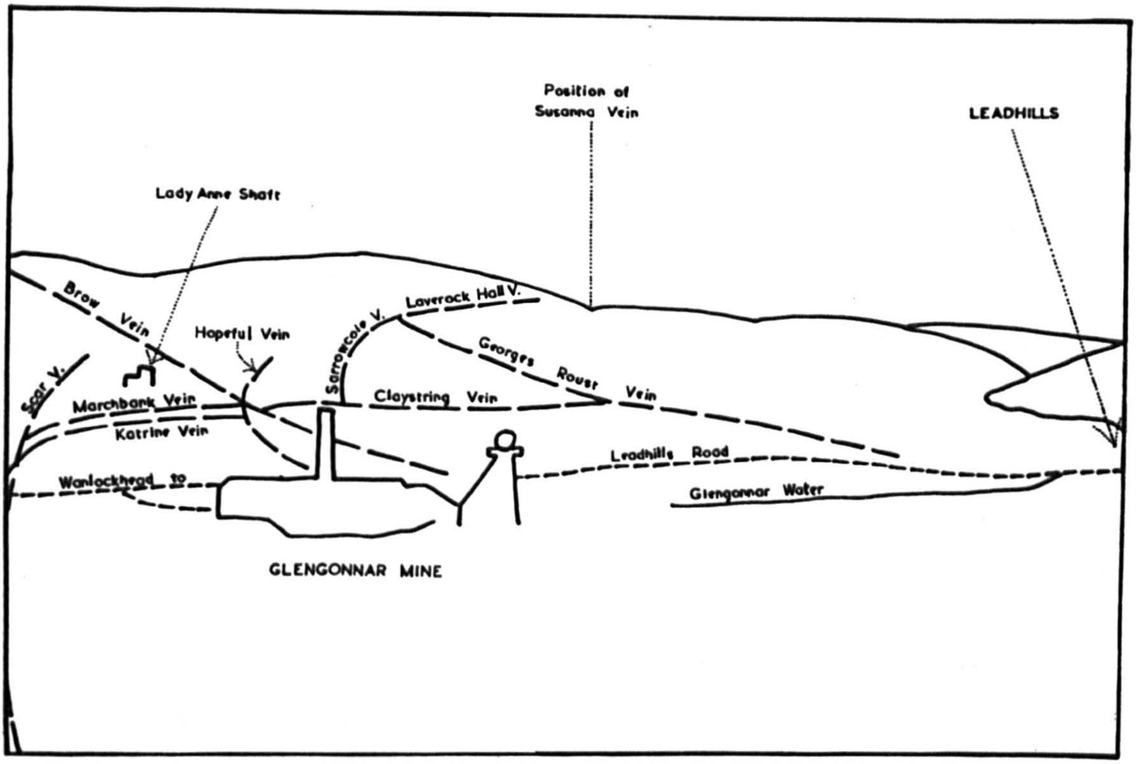
Appreciation is recorded of the facilities offered by Dr. C. D. Waterston and his staff, of the Royal Scottish Museum, Dr. A. M. Cockburn of the Grant Institute, Edinburgh, Dr. Currie of the Hunterian Museum, Glasgow, and the Curator of the Natural History Museum, Dumfries.

Grateful acknowledgment is made to Professor W. Q. Kennedy, who displayed an active interest throughout the work, and to Mr. O. von Knorring, without whose guidance many of the aspects of the problem would have remained very obscure. Sincere thanks are offered to other members of the Department, in particular to Mr. T. N. Clifford, for discussion, Dr. G. Nutter, for tuition in spectrochemical analysis, Mr. T. F. Johnston for thin sections and assistance in photomicrography, and Mr. W. L. Wilson for polished sections and X-ray powder photographs.

Plate I, (opposite).

A view of Glengonnar Mine looking in a north-westerly direction from near the Lanarkshire-Dumfriesshire County Boundary.

The photograph was taken prior to 1929 when mining operations were in pregress. At the present day only a few derelict buildings remain.


Position of Susanna Vein
LEADHILLS
Lady Anne Shaft
Brow Vein
Hopeful Vein
Sarrowcole V.
Laverock Hall V.
Georges Roust Vein
Scar V.
Marchbank Vein
Claystring Vein
Katrine Vein
Leadhills Road
Wanlockhead Rd
Glengonnar Water
GLENGONNAR MINE

INTRODUCTION.

Leadhills and Wanlockhead are situated in the Southern Uplands of Scotland, on the northern lower slopes of the Lowther Hills, which stretch between the Nith Valley and the head of the Clyde Valley. The two villages are separated by the Dumfriesshire-Lanarkshire county boundary which follows the watershed of the Lowther Hills.

As is suggested by the name "Leadhills", the area is rich in lead, one competent authority (a mining expert), going so far as to say that the value of the lead raised would suffice to completely pave the surface of the district with gold guineas, set on edge (Mitchell, 1919).

It is not proposed to discuss in detail the mining history of the district, as this has been ably summarised by several authors (Brown, 1918, 1925; Mitchell, 1919; Wilson, 1921; Watson, 1937). However, it may be pointed out that the original incentive for the investigation of the area was gold, which is associated with stone age implements in the south of Scotland, the focal point of the distribution being Leadhills (oral communication, Curator of the Dumfries Natural History Museum). The more significant history commenced in the latter part of the sixteenth century with the discovery of alluvial gold by Bevis Bulmer and Cornelius Hardskins, in Leadhills and Wanlockhead respectively. The intense search for a gold lode revealed several lead veins, which were worked by Thomas Foullis and Sir John Stampfield. Other veins were later discovered, and the

The mining operations were almost continuous from the end of the sixteenth century to the closing down which took place in 1929 in Leadhills, and 1931 at Wanlockhead. Recently (1950), investigations were instigated by the Siamese Tin Syndicate, and at the end of 1952 the Rio Tinto Mining Company stepped in, and the Lowland Lead Mining Company was formed. The work in the past year has consisted mainly of clearing out several old adit levels, and in commencing the opening of the Glencrieff Mine, Wanlockhead.

I. THE GEOLOGY OF THE LEADHILLS-WANLOCKHEAD DISTRICT.

THE STRATIGRAPHY.

The district is situated in the Southern Uplands of Scotland within an area of Ordovician rocks which have been intensely folded along north-east to south-west axes. The general succession comprises volcanic rocks, successively overlain by radiolarian cherts, black shales, and greywackes of the Lowther Group. The volcanic rocks have been assigned to the Arenig, and the black shales and Lowther Group to the Caradocian and the Ashgillian respectively (Pringle, 1948, p.18). However, discrepancies between the ideas of the age of the cherts occur, due to absence of fossils. Pringle (1948, p.14) regarded the cherts as Arenig in age, a marked stratigraphical break separating the Arenig and the Caradoc, with the total absence of the Llanvirn and Llandeilo. Peach and Horne (1899) regarded the radiolarian cherts as abyssal deposits accumulated with great slowness, and claimed that in much of the Southern Uplands they are conformably succeeded by Nemagraptus gracilis shales, with interbedded chert. The latter view was more acceptable to Bailey (Bailey and Holtedahl, 1938), and confirmation of the transitionary passage between chert and black shales exists in the Leadhills-Wanlockhead area.

The four groups of rocks are of such marked lithological dissimilarity that identification is readily possible. For this reason, together with the paucity of fossils, the dating of the rocks by the fossil content was not attempted.

Throughout the district exposures are poor, and confined to discontinuous stream sections. The hillsides are obscured by heather, growing on thin peat. Boulder clay is largely restricted to the valleys.

a. The Volcanic Rocks.

Two outcrops of the Arenig Volcanic Series occur in the Leadhills-Wanlockhead area, one on the south-west side of Hunt Law by the side of the Leadhills path near the old dressing plant, the other on the south of Middle Muir. The latter exposure was described by Peach and Horne (1899, p.329) as "ophitic dolerite or gabbro". The exposure on the south-west side of Hunt Law was also recorded by Peach and Horne (1899, p.293). The rock is highly altered and consists mainly of carbonate, in which outlines of felspar phenocrysts are visible. The rock can be classified as a diabase porphyrite. No contact with the overlying chert is visible.

b. Radiolarian Cherts.

The chert outcrops in two distinct belts to the north and south of Leadhills and Wanlockhead. The northern belt runs from Cog Burn north-eastwards through Sowen Burn, Snar Water, Glenkip Burn, to the Glengonnar Water, and provides the majority of the chert outcrops in the district. The width of the belt varies, but is of the order of half to one mile, and consists of chert, overlying black shale, and infolds of the Lowther Group, with occasional occurrences of the Arenig Volcanic Series. Outcrops are largely restricted to discontinuous stream sections.

The southern belt is of limited extent, and the chert is restricted to outcrops in Mennock Water and its tributaries, and further to the north-east to the Leadburn Valley, and a small outcrop in Glen Aise Burn, a southerly tributary of the Elvan Water.

On the south-west side of Hunt Law, near the old dressing plant, a small cliff section shows banded cherts to be underlain by black shales with numerous intercalated chert bands and lenticles, which probably represent the lowest zones of the chert. The exposure occurs directly aligned in strike with the Arenig Volcanic outcrop, and forty-three yards to the south-west.

Over most of the area the chert presents a uniform banded appearance of blue-black chert in bands varying from one to four inches in thickness, and separated by narrow bands of black shale. Occasional detrital quartz grains occur in the chert; Radiolaria are common. The chert weathers to a grey soft shaley rock.

c. Black Shale (Glenkiln and Lower Hartfell).

The black shales outcrop with the cherts in the two belts described above. As the black shales overlie the cherts, they have a wider outcrop, particularly marked in the southern belt, where there are outcrops of black shale on the strike of the belt in Glen Franka Burn and the Windgate Burn.

The unweathered shales are black in colour, well bedded, plastic, and often contain graptolites. When weathered the shales become bleached to a khaki, grey, or white colour.

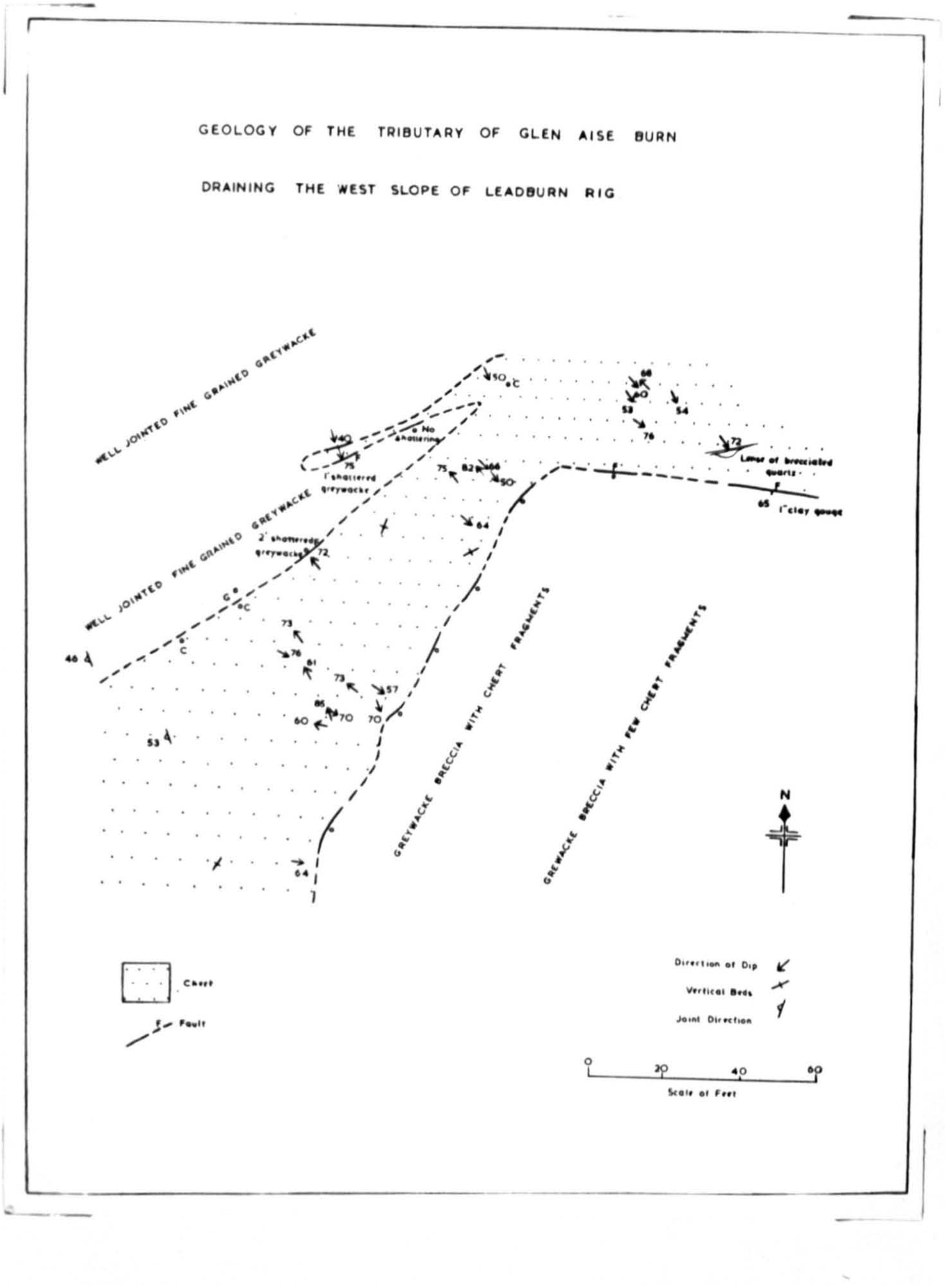


Figure 1.

The Geology of the tributary of Glen Aise Burn draining the west slope of Leadburn Rig.

In several areas the junction of the chert with the overlying rocks can be observed, and although in many places a normal chert-black shale sequence is present, discrepancies due to faulting and to local unconformity are common.

The normal chert-black shale junction is well exposed in a small scar draining westwards into Glenkip Burn, where the basal black shale contains irregular chert nodules which become less numerous with increasing distance from the massive banded chert. In Black Grain (Cog Burn), up to eighteen inches of the black shale is partly replaced by quartz at the junction, probably due to intrastratal solution of the chert and deposition in the black shale. A similar phenomenom is present in Whitestone Cleuch, where a microdiorite dyke has been intruded along the chert-black shale boundary.

The presence of discrepancies in the chert-black shale junction due to strike faulting has been widely recognized in the Southern Uplands (see Peach and Horne, 1899). In the Leadhills-Wanlockhead area two excellent examples are provided in Black Grain (Cog Burn), and in Glenmarchhope Burn. In both localities the chert is in contact with fine grained greywacke.

Local unconformities, as evidenced by breccias overlying the chert, were recorded by Peach and Horne from several localities (pp.296, 310, 325). A similar local unconformity (fig.1) occurs to the east of Leadhills at the head of the small tributary of Glen Aise Burn which drains the south-west flank of Leadburn Rig. The breccia is composed of angular chert fragments, up to several centimeters in length, with fragments of shale and greywacke in a quartz matrix. At the chert-breccia contact 90% of the breccia fragments are chert, this amount decreasing away from the contact.

d. Lowther Group.

The remainder of the area not covered by either of the three preceding formations is occupied by the Lowther Group, a series of greywackes and shales, estimated by the Geological Survey (Wilson, 1921, p.9) to be approximately 1000' in thickness. Outcrops are largely restricted to discontinuous stream sections, which, together with the absence of fossils, the rapid lateral variations, and the complicated structure, make it almost impossible to determine any vertical succession, the only datum line being the junction with the underlying black shale or chert.

The basal members of the Lowther Group exhibit transitional characteristics from the black shale to the massive greywacke type of sedimentation. One expression of this is the gradation from black shale into fine grained shaley greywackes, which are grey-green in colour, and weather to a limonitic shale. This type of greywacke often includes small lenticles of coarser greywacke, and is made up of graded bedding units, a typical example having alternating bands, 2 mm. wide, of average grain sizes .02 and .075 mm. Such rocks are well displayed in Mennock Water near the mouth of Wee Black Carli, and in Well Grain. Weathered representatives of this type are common in the northern belt, in Cog Burn, Sowen Burn, Snar Head, and the head of Glenkip.

In the southern belt part of the course of Meikle Arthur Grain runs along the junction between black shales and grey shaley fine greywackes.

In several localities a larger type of "graded bedding unit" overlies the black shale. The section in Mennock Water from slightly north of the entrance of Whitestone Cleuch down to the black shale anticline south of the mouth of Whitestone Cleuch shows massive greywacke beds, several feet in width, with interbedded black shale bands, varying from a fraction of an inch to several inches in width, the black shale bands becoming more numerous, and wider, on passing towards the black shale. The actual contact of this series with the black shale is not visible. Similar series of alternating greywackes and black shales outcrop in the Windgate Burn, Whitestone Cleuch, and the upper reaches of Glendyne Burn. At the latter locality the series is aligned near the strike of the chert and black shale which outcrops in Glendyne below the junction with Rough Cleuch (Peach and Hone, 1899, pp.301, 302).

The greywackes of the Lowther Group vary from coarse breccias to fine shaley greywackes, and are generally dark grey-green in colour. The most important constituent of the rocks is quartz, in angular or sub-angular grains, accompanied by felspar, which includes a little orthoclase, but consists, for the most part, of olicoclase and andesine, and is often decomposed. Fragments of various rock types are common, including greywacke, slate, quartzite, and fine grained igneous rocks. A notable feature is the presence of a considerable amount of hornblende, accompanied by a little augite, both of which exhibit euhedral outlines and "hacksaw" terminations which, in other cases, are ascribed by Pettijohn (1949, p.490) to intrastratal solution. Other constituents include white mica, chlorite, garnet, and zircon. These constituents are united by a dark chloritic cement with a considerable quantity of cryptocrystalline silica. Many of the greywackes effervesce freely with acid, and the carbonate is present in irregular patches in the cement. Many of the clastic quartz grains are fringed by an intergrowth of quartz with the matrix, due to replacement of the detrital by the matrix (Pettijohn, 1949, p.248).

Other Southern Upland greywacke has been described by Kennedy and Read from Newmains (1936, p.119), and was found to be rich in carbonate. An analysis showed 6.60% carbon dioxide.

For general description and purposes of comparison, the greywackes can be divided on average grain size into three groups; a) the fine greywackes, with an average grain size ½ mm. or less, in which individual fragments are not readily distinguishable in hand specimen without the use of a lens;

b) the medium greywackes, with an average grain size between 2 mm. and ½ mm., in which the individual fragments are easily distinguishable in hand specimen, and

c) the coarse greywackes, with an average grain size over 2 mm., comprising very distinctive rocks, often with fragments several centimeters in length.

The distribution of coarse greywacke is marked on the map (enclosure 1). Although obscured by lack of exposure, there appears to be a fairly continuous belt of coarse greywacke running slightly to the north of the southern chert-black shale belt, outcropping on the south side of Middle Muir, in Mennock Water, Glen Franka Burn, Glen Ea's Burn, and Glen Aise Burn. Occasional thin bands of coarse greywacke outcrop to the east of Leadhills in the streams draining southwards into the Elvan Water, whilst to the west of Wanlockhead outcrops of coarse greywacke are more numerous in Glenclach Burn, Bail Gill and Burgess Grain. The majority of the greywacke to the east of Leadhills is fine massive greywacke, with intercalated shaley fine greywackes, particularly well exposed in the streams draining southwards into Elvan Water. To the west of Wanlockhead the predominating greywacke is a massive medium grained variety, with occasional interbedded shaley fine greywackes, typically exposed in Glendyne Burn for half a mile above the junction with Rough Cleuch.

The comparison of greywackes to the east and to the west of Leadhills and Wanlockhead indicates a tendency for a slight coarsening in the sediments from east to west.

On the south side of the southern chert-black shale belt a series of finely laminated greywackes, the Lowther Shales, are exposed in the southern tributaries of Mennock Water, and in all the streams draining the Lowther Hills. The predominating rock type is a blue-grey, micaceous, finely laminated greywacke, which weathers to a brown colour. The rock has the composition of a typical greywacke described above, and is made up of units of varying grain size, a typical specimen having coarse bands with a width of 2 mm., and an average grain size of 0.09 mm., alternating with slightly narrower bands of average grain size, 0.04 mm. Gradations between the two sizes exist, and the rock is in effect made up of small graded bedding units. The rocks are slightly calcareous. The cement is very find grained quartz, which imparts the resistant quality giving rise to the distinctive "slatey" appearance. Interbedded in the finely laminated rocks are occasional beds of massive greywacke, generally of a medium to a coarse grain, which weather out as distinctive bands on the screes at the heads of most of the streams draining the series. /

The stratigraphical position of the Lowther Shales is indicated by the relationship to the chert-black shale rocks. In Big Black Carli, a southern tributary of Mennock Water, the distance between the Lowther Shales and the black shale is 1600', and to the east of this, in the unnamed stream between Whitestone Cleuch and Wee Black Carli, the distance is only 500'. If the Lowther Shales overlie the series of greywackes to the north, all the greywackes must be compressed into the small space between the black shale and the Lowther Shales. However, further to the south in Enterkin and Auchenlone Burns, cherts and black shales are directly overlain by the Lowther Shales (Peach and Horne, 1899, p.332). The Lowther Shales therefore appear to represent part of a lateral variation from the greywacke series of Leadhills and Wanlockhead towards the Barren Mudstones of the Hart Fell district.

THE STRUCTURE.

The principal structural elements of the Southern Uplands were caused by the Caledonian Orogeny, which gave rise to a series of folds and faults striking in a north-east to south-west direction. In the Leadhills-Wanlockhead area the general strike is 54° E. of N., an average of 100 measurements. The uniformity of the strike is illustrated by the fact that 48% of the measured strikes are within 5% of the average, whilst the maximum deviation from the average is only 21°.

a. Minor Folds.

Peach and Horne recognised (1899, p.71) three types of simple folds in the Southern Uplands, all of which occur in the Leadhills-Wanlockhead area. These comprise symmetrical folds, asymmetrical folds, and isoclinal folds.

Because of the restrictions by lack of outcrop on the area of folds exposed, symmetrical folds are classified for this description as folds which have the axial plane inclined at less than 10° from the vertical, excluding isoclinal folds. Folds restricted by this description predominate in the Leadhills-Wanlockhead area. The majority of the examples are in the chert-black shale belt, where the variation in rock type gives rise to easily recognizable folds, whereas bedding planes are difficult to determine in the massive greywackes, unless marked by thin shale bands. Near the Snar Head dressing mill four distinct chert anticlines are exposed in a distance of 800', the distance between the crests of the anticlines being of the order of 200'. In

Sowen Burn, and in the southerly scar draining the south-west slopes of Hunt Law, the junction of the chert with the black shale is exposed on the crest of two anticlines, the competent chert is brecciated and the black shale is highly contorted, both being heavily veined with quartz.

Asymmetric folds, characterized by an axial plane inclined at more than 10° to the vertical, excluding isoclinal folds, are particularly well exposed in the Lowther Shales, and in the upper reaches of Glendyne Burn. In Glendyne Burn the folded rocks are a series of greywackes with interbedded shales, and the general dip of the axial planes of the folds is to the south, varying in magnitude from 70° to 25° from the vertical. The Lowther Shales also have a general dip to the south, and folding is illustrated by the rapid changes in dip on the screes at the head of the streams draining the Lowther Shales, and by the duplication of coarse bands in the shales, as at the head of Glen Franka Burn, and the head of Whitestone Cleuch.

Isoclinal folds are characteristically developed in the incompetent black shales, though excellent examples of isoclinally folded chert are visible in Glen Aise Burn, and in Groops Scar on the west of the Glenconnar Water to the south of the Leadhills smelting mill. In both localities the folding of the competent chert has caused some brecciation, accompanied by quartz veining. The dip of the axial plane in Groops Scar is 70° to the south. Isoclinal folds with vertical axial planes are displayed in the black shales at the head of the tributary of Glenkip directly west of Groops Scar.

All the minor folds of the district are characterized by a considerable pitch, which may cause apparent anomalies in the succession, when stratigraphically higher beds occur at a topographically lower level than the stratigraphically lower beds on the same strike. In Cog Burn, greywacke at the junction of Burgess Grain with Cog Burn is topographically lower than the chert and black shale exposed in Black Grain. Similarly on the south-west side of Hunt Law at the old dressing mill, Volcanic rock is exposed on the side of the Leadhills path, whereas in the stream banded cherts outcrop. The inclination from the Volcanic rock to the lowest visible chert is $14\frac{1}{2}^{\circ}$,which can be taken to represent a minimum figure for the pitch of the anticline. A similar figure is given by the exposures of chert in Meikle Arthur Grain. This minimum figure for the pitch of the folds in the Leadhills-Wanlockhead area compares favourably with the figures of between 10° and 20° given by Jones (1922, p.7) for the folds in the Lower Palaeozoics of Cardiganshire.

b. Regional Folding.

The lowest stratigraphic zones in the Leadhills-Wanlockhead area are the northern and southern chert-black shale belts. The northern belt was described by Peach and Horne (1899, p.74) as "..... a striking example of 'fan structure' where in the centre of the primary fold the strata are folded on vertical axes, while the axial planes dip inwards on the north-west and south-east sides, thus producing a pseudo syncline ... along the

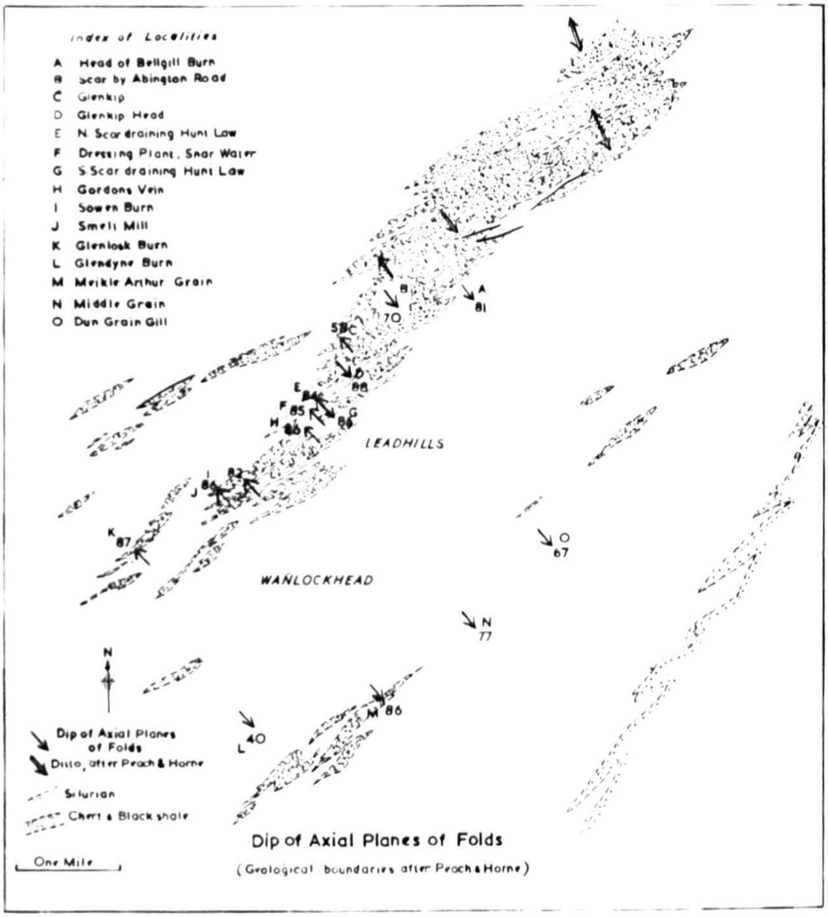


Figure 2.

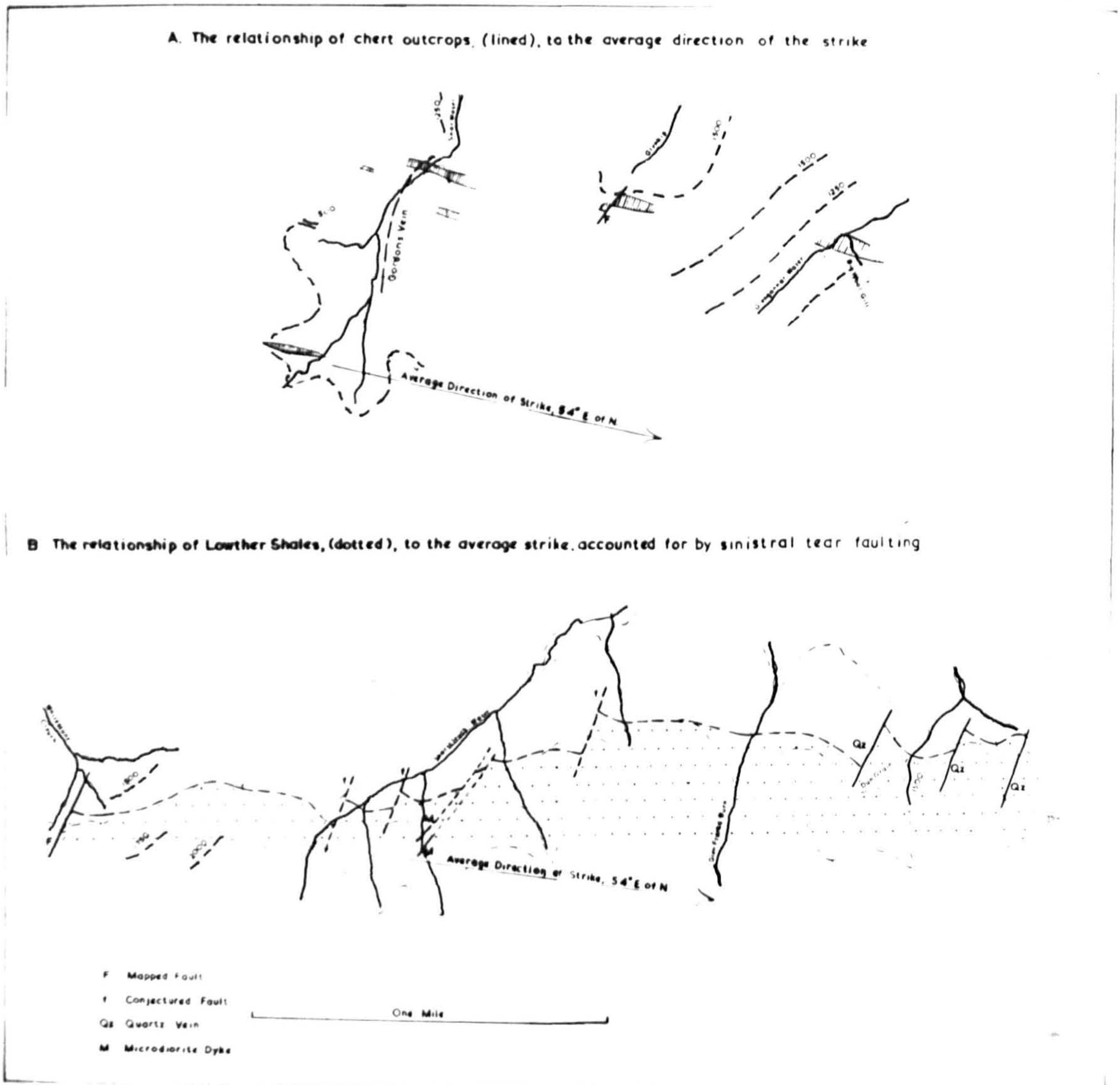
The dip of the axial planes of folds in the Leadhills-Wanlockhead area.

south-east side of the fan the Lowther Group (Upper Caradoc), plunge underneath the Arenig cherts and Glenkiln-Hartfell Shales with an inverted dip".

The majority of the axial planes in the northern chert-black shale belt are almost vertical (fig.2), with occasional lower inclinations in Groops Scar and Glenkip. To the west of Leadhills the axial planes of the folds are slightly inclined to the north, whilst to the north-east of Leadhills, between Leadhills and Abington, an almost uniform southerly dip prevails.

If a fan structure of the type described by Peach and Horne exists, its axial line may be traced along the Arenig outcrop, which swings slightly northward at Leadhills (enclosure 2), continuing north-eastwards, where it is truncated by the Southern Upland Fault, north of Peebles. This swing suggests a slight virgation, with the Leadhills-Wanlockhead area situated on the hinge of the virgation.

In the chert-black shale belt north of Leadhills, although exposures are poor, there is no doubt that a northerly stepping of the outcrop has taken place. The outcrops of the chert are shown in Fig.3. The projection of the most southerly chert at the head of Snar Water, along the average direction of strike, gives a discrepancy of half a mile with the most southerly chert in Glengonnar Water (determined in Gripps Level, oral communication by Mr. Borthwick). A similar displacement is shown by the Lowther Shales, although considerable uncertainty is introduced by poor exposure, and by the Lowther Shales being a facies change of the greywacke, which may be irregular with



A. The relationship of chert outcrops, (lined), to the average direction of the strike

B The relationship of Lowther Shales, (dotted), to the average strike, accounted for by sinistral tear faulting

Fig. 3.

A. The relationship of chertoutcrops, (lined), to the average direction of the strike.

B. The relationship of Lowther Shales, (dotted), to the average direction of the strike, accounted for by sinistral tear faulting.

respect to the strike.

The northerly movement of the northern belt can be explained by a combination of pitch with the swinging trend of the virgation. The chert exposed at the head of Snar Water could pitch to the north-east, without reappearing, which would account for the position of Gordons Vein. The general tendency in the whole district is for veins to be metalliferous in the Lowther greywacke, and non-metalliferous in the chert. Gordons Vein, though terminating at a chert anticline, is metalliferous to the south, which suggests that the line of the vein runs through a considerable proportion of greywacke, caused by the pitching chert. Alternatively, the line of the vein may represent a line of movement, which would account for the termination of the low angle strike thrust, described below, to the east of the Belton Grain vein. The discrepancies in the Lowther Shales can be accounted for by the swinging trend of pitching folds. The alternative explanation, of displacement by northerly trending tear faults, is illustrated in Fig.3. Northerly trending quartz veins, microdiorites, and a fault have been recorded in the Lowther Shale belt, and the brecciated character of the quartz vein is not inconsistent with movement.

The fact that a continuous axial line of the fan structure described by Peach and Horne can be envisaged traversing the whole area supports the suggestion that the northerly stepping of the rocks is due to the virgation of pitching folds, and that faulting is on a small scale.

c. Concordant Structures.

Peach and Horne recognized the existence of strike faults, of thrust type, generally formed by movement along one limb of an isoclinal fold, particularly where the rock series consists of interbedded competent and incompetent beds, such as the black shales interbedded between the competent cherts and greywackes. Examples of strike faults of this nature occur in the northerly scar draining the south-west flanks of Hunt Law, in Glenmarchhope Burn, and Black Grain (Cog Burn). This type of faulting is common in areas which have suffered intense compression and have deformed with the formation of a closely folded series.

An important low angle thrust strike fault has been proved on the levels driven north from the Glencrieff Shaft (MacGregor, 1929). In the 100 fathom and 160 fathom levels north of Linpen Burn, the plane of movement, with a dip of approximately 30° to the N.W., separates greywacke to the S.E. from black shales to the N.W. In the 160 fathom level over 700' of barren ground was proved beyond the plane of movement. Workings further south in the 40 and 80 fathom levels in the West branch of the New Glencrieff Vein also proved a plane of fracture inclined at 23° to the N.W. In the drainage level north of the Glencrieff Shaft the wide shatter zone is made up of completely crushed rock, laminated by the pressure, with inclusions of greywacke orientated along the plane of movement. The outcrop of the thrust fault passes through the Glencrieff Shaft, which was started in decomposed clayey material, and extends to the south-west, as evidenced by the crushed rock on the dumps of the levels driven on to the north end of the Shieling Burn Vein. To the north-east of the Glencrieff Shaft weathering along the outcrop has given the feature of Whytes Cleuch.

The effect of the shatter belt on the veins of the district is indicated by the Belton Grain Vein, which, in the north end of the stope above Taits Adit is reduced to a 4" zone of crushed rock, with a little barytes, whilst 30' to the south the vein is 30" wide, and carries galena and chalcopyrite, together with barytes. All the veins to the west of the Belton Grain Vein terminate against the fault, and it is an important structural control of the mineralization. The "damming" nature of the impervious shatter belt is illustrated by the numerous veinlets filled with galena and calcite in the greywacke directly below the shatter zone in the drainage level north of the Glencrieff Shaft. To the east of the Belton Grain Vein the fault must either die out or be displaced to the north, as several of the Leadhills veins cut across the conjectured continuation of the strike of the fault.

In connection with structures parallel to the strike, mention may be made of the development of "flaser" structure in the cherts in Mennock Water to the north of the Wee Black Carli tributary. This belt of cleaved rocks was noted by Peach and Horne (1899, p.76). The "flaser" structure could have been effected by a lateral movement, and the direction of the structure indicates a dextral movement, similar to that described by Blyth (1949), in the porphyrite dykes of Galloway.

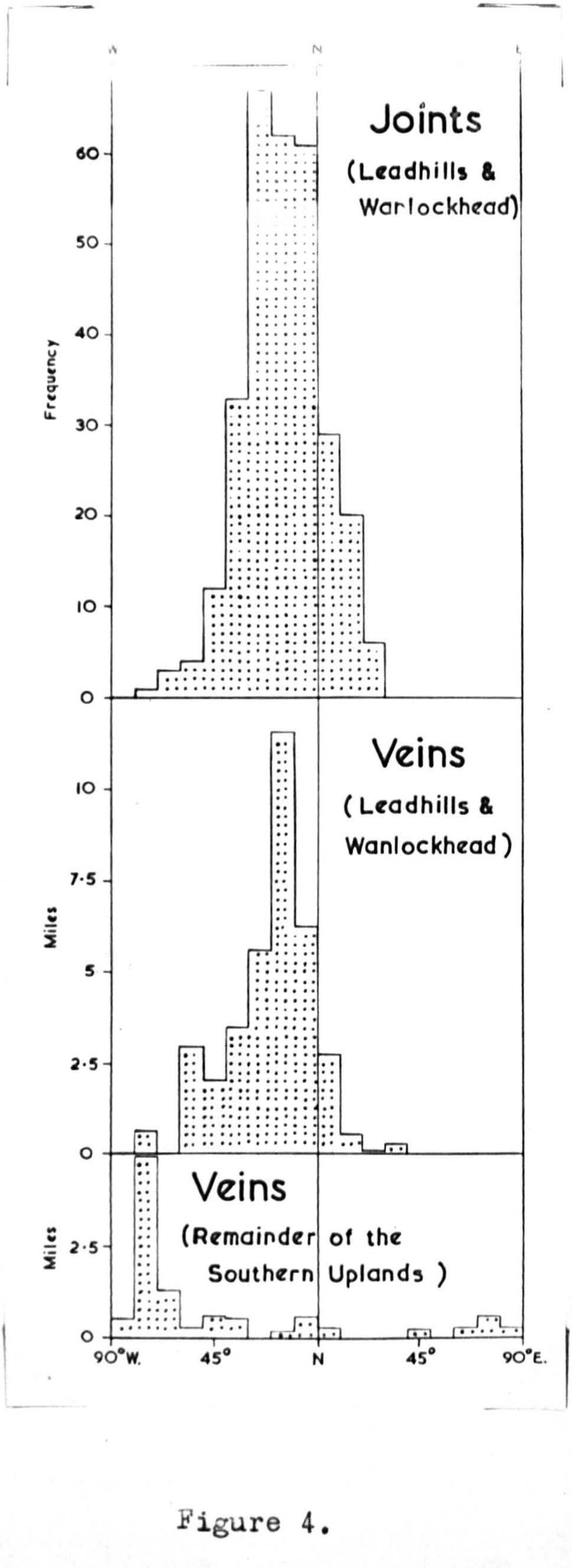


Figure 4.

Statistical analysis of structural trends.

d. Discordant Structures.

The discordant structures, cutting across the general strike of the country rocks, comprise joints, faults, and the veins.

A statistical analysis of the joint directions is presented in Fig.4, and it will be seen that the dominant direction of jointing is N.N.W. However, slight variations of the direction of jointing are common, and two dominant joint directions may be present together, deviating from one another by up to 40°, though in general the angle of deviation is less than this figure. 25% of the joints hade to the west, the remainder hade to the east, the magnitude of the hade varying from almost vertical to 40° from the vertical. To the east of Leadhills is a narrow N.N.W. trending area, including Glen Aise Burn, through Elvan Water to Scapcleuch Burn and the Long Cleuch, in which the hade of the jointing is to the west. Similar restricted areas of westerly hade may exist. Pseudo folds are produced by opposite hading joints, and in Nether Cleuch and the small quarry at Thief Slack Hass, the greywacke in the crest of the pseudo fold is highly jointed and brecciated.

The effect of the joints on the various rock types of the district varies considerably. In the Lowther Group, the jointing is the main structural feature of the massive greywackes, exposed over most of the area, whilst in the shaley members, including the Lowther Shales, jointing is developed, but is subordinate to the bedding planes. The competent cherts are jointed, but the joints are restricted by the narrow chert bands and the intervening thin black shales. The black shale group, because of its incompetency, deformed without the formation of joints. The intrusive rocks described below are well jointed.

Slight displacements of the joints are displayed in Taits Adit. Approximately 24' west of Belton Grain Vein a narrow calcite filled N.W. trending joint crosses, and slightly displaces, a wider calcite filled N.N.W. trending joint. To the west of New Cove Vein two joints are displaced, 3' and 4' respectively, by a strike fault, the fault plane being marked by quartz veining.

Other subordinate joint directions may be present, of which a low angle joint with a dip of the order of 30° towards the south, is the most common.

The detection of faults in the Lowther Group is difficult owing to the uniformity of the series. The majority of the faults have a strike direction similar to that of the dominant joints. Two faults occur in Middle Grain, displacing a microdiorite dyke over 200' in a sinistral direction, and having a marked topographic effect in the Middle Grain gully. In the Glencrieff Horse Level a microdiorite dyke is displaced 70' in a sinistral direction. Other N.N.W. trending faults, of small magnitude, were recognized in Cog Burn, Mossy Burn, and at the head of Whitestone Cleuch in the Lowther Shale.

Faults other than those with a N.N.W. trend have been recognized in the district. In the tributary of the Glen Aise Burn draining the south-west flanks of Leadburn Rig, a west-north-west trending fault separates chert from greywacke breccia (fig.1).

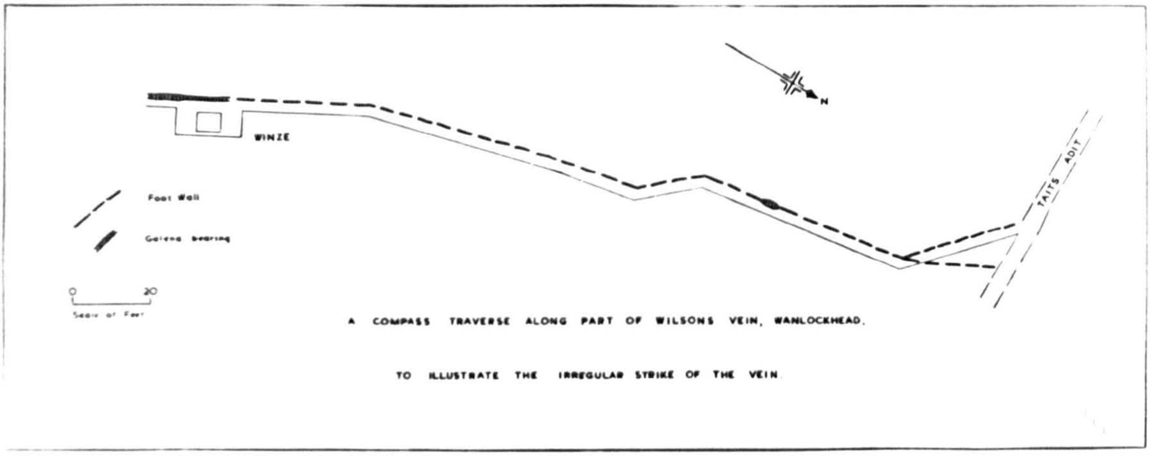


Figure 5.

A compass traverse along part of Wilsons Vein, Wanlockhead, to illustrate the irregular strike of the vein.

The fault is marked by a narrow clay gouge, and has a dextral displacement. Other W.N.W. trending faults can be invoked to account for the distribution of chert and greywacke near the head of Groops Scar, and the distribution of shale and greywacke at the head of the Long Cleuch.

The principal trend of the veins in the mining field is 15° W. of N., parallel to the main joint direction (fig.4), and the hade of this set of veins is to the east at varying angles, generally less than 30° from the vertical. A minor set of veins in the Leadhills area strike W.N.W., and are characterised by a south-westerly hade. The veins vary in thickness from a clay stringer to 18' (Wilston, 1921, p.14; Brown, 1926, p.61).

The N.N.W. trending veins in the Wanlockhead area, and presumably over the whole district, are characterised by an undulating course, with abrupt changes in direction. An extreme example of this is Wilsons Vein (fig.5). At the points of deviation minor veins are often given off, leaving the main vein in a northerly direction on the east side of the vein, and in a southerly direction on the west side of the vein. The minor veins are usually small and barren, but may be mineralized, and may extend for some distance, forming a branch vein, or a loop to the main vein. The vein walls are slickensided, mullion structure on the foot wall of the Lochnell Vein dipping 30° to the north, and slickensiding in the New Glencrieff Vein in the Glencrieff Horse Level also dipping to the north. As mentioned above, two veins, the Middle Grain and the New Glencrieff, have displaced microdiorite dykes in a sinistral direction.

The veins have been worked in the Lowther Group, and are filled with brecciated greywacke cemented by gangue minerals, particularly calcite and ankerite, with the sulphide mineral and barytes occurring in the filling, or usually being concentrated on either the foot or hanging walls, most commonly on the foot wall. Both the distinct foot and hanging walls are marked by a clay gouge, which, in a narrow vein, may form the matrix of the brecciated greywacke.

A relationship of the occurrence of minerals to the variations in strike of the veins is illustrated in the Lochnell Vein, in Williamsons Adit, where, to the south of an abrupt change in direction, the vein is a thin clay band, occasionally widening into impersistent lenses of brecciated greywacke cemented by calcite or quartz, with a thin veinlet of galena on the foot wall. The sharp bend of the vein from a N.N.W. to a N.W. direction entirely alters the character of the vein, a persistent 1" wide veinlet of galena appears on the foot wall of the 30" wide vein, largely filled with brecciated greywacke in calcite, with occasional lenses of barytes. In Wilsons Vein a similar relationship can be observed near the winze (fig.5), a persistent galena-barytes veinlet on the foot wall widening towards the south in the most westerly trending portion of the vein.

At the north end of the loop on Lochnell Vein, above Williamsons Adit, a strike fault displaces the vein in a dextral direction, a maximum distance of 10'. The fault has a small shatter belt which is veined with barytes. Other small strike faults laterally displacing the New Glencrieff Vein are mentioned

Diagram illustrating the formation of open spaces by the sinistral movement of an undulating fault.

Figure 6.

To illustrate the formation of open spaces by the sinistral movement of an undulating fault.

by Wilson (1921, pp.13, 23).

Apart from the N.N.W. trending dykes, described below, published evidence for the existence of N.N.W. trending structures in the rest of the Southern Uplands is meagre. Several N.N.W. trending faults were recorded by the Geological Survey, particularly in the coast section west of the Criffel "Granite", and to the south of the Loch Doon "Granite", the latter displacing a chert-black shale anticline in a sinistral direction. N.N.W. trending mineral veins were worked at Woodhead, Nutberry Hill, Dalleagles, and S.S.E. of Dalmellington.

Subsequent to folding, a pattern of intersecting joints was imposed by the later Caledonide compressive forces, the average bisecting line of the acute angle of the joint directions being N.N.W. to S.S.E. This pattern forms the principal discordant structure in the Leadhills-Wanlockhead district, and is best explained as due to a N.N.W. to S.S.E. compression. The generally accepted N.W. to S.E. compression of the Caledonian Orogeny, whilst explaining N.N.W. striking tear faults, is inadequate to account for the joint system. The intersecting joint pattern could thus be ascribed to a slight reorientation of the Caledonian stress from N.W.-S.E., to N.N.W.-S.S.E. Further reorientation towards a north-south stress would cause sinistral movement on the more northerly trending joints. The effect of this movement on the undulating veins formed from the intersecting joint pattern would be the production of open spaces on the more north-westerly courses of the veins (fig.6). The distribution of galena in the Lochnell Vein provides an example. The effect is probably of major importance in the localisation of ore in the whole district. A similar effect was described by Lovering from the Silver King Mine, Montezuma, Colorado (U.S.G.S. Prof. Paper 178, p.107).

The dextral shearing of the Galloway porphyrite dykes has been ascribed by Blyth (1949, p.417) to reorientation of the Caledonian north-west to south-east compression towards an east-west direction. A similar localised belt of dextral shear is visible in the chert and black shale of Mennock Water. It has been suggested (oral communication by T. N. Clifford) that dextral shear along localised belts could have taken place due to a torsional effect formed by the reorientation of the stress from N.N.W.-S.S.E. to N.-S., providing a logical transition from "Caledonian" to "Hercynian" stress.

THE CALEDONIAN MINOR INTRUSIVES.

The Caledonian minor intrusives of the Leadhills-Wanlockhead area can be divided into three groups on a combined structural and petrological basis, and it can be shown that the relationships of the three groups present a logical account of the general stress conditions towards the close of the Caledonian orogeny, applicable not only to this limited area, but at least to the whole of the Southern Uplands.

a. Group 1.

The strike of the first group of dyke rocks is parallel to the strike of the country rock, approximately N.E.-S.W. The dykes outcrop in many parts of the area, and the majority appear very limited in size owing to poor exposure. However, in the headwaters of Bellgill Burn one dyke can be traced up the slopes of Wellgrain Dod for a distance of 700 yds., and in several areas alignment in strike suggests that some dykes may persist over appreciable lengths.

As a whole the dykes of the group are small in width, the maximum observed in Whitestone Cleuch and Middle Grain being 7', whilst the average thickness over the area is 5'.

The dykes of the group are andesine-oligoclase rocks, with varying amounts of quartz. Phenocrysts are uncommon; occasional corroded quartz phenocrysts occur in the Middle Grain dyke but were not observed elsewhere in the area, whilst occasional micro-phenocrysts of andesine (two determined examples were Ab65An35 and Ab57An43) occur in the dykes of Whitestone Cleuch and at the head of Glen Franka. The quartz content of the rocks varies; in the Bellgill dyke, micropegmatitic intergrowths of quartz and felspar make up 44% of the rock, the remainder being quartz (31%), andesine-oligoclase (15%), and white mica, whilst in the Whitestone Cleuch example the rock has 42% andesine crystals, 17% micropegmatitic intergrowth, and only 2% free quartz.

Thus the rocks of group one are predominantly andesine-oligoclase rocks with variation in quartz from a minor to a major constituent. Accordingly the rocks fall into two classifications, the microdiorites, with accessory quartz, and the microgranodiorites.

The dykes have suffered deformation and show universal jointing in an approximate N.N.W.-S.S.E. direction, identical with the jointing of the adjacent greywackes. In the Middle Grain and Glen Franka dykes the joint planes of the greywacke are continued in the dyke without change of direction. An interesting feature reflecting on the incompetency of black shale against greywacke and dyke, is the jointing of the Windgate dyke, whereas the black shale into which it is intruded is not jointed.

The Middle Grain dyke has been displaced a distance of 210' in a sinistral direction by two N.N.W.-S.S.E. trending faults, whilst a 70' sinistral displacement of a dyke by the New Glencrieff Vein can be observed in the Glencrieff Horse Level.

b. Group II.

As in the case of group one, the group two dykes trend parallel to the strike of the country rock, N.E.-S.W. The outcrops of the group are limited in number, but an indication of the continuity of the dykes is given by the Elvan Water outcrops, two parallel dykes of similar composition and width outcropping in Melli Grain, Elvan Water and Scapcleuch Burn, if continuous, a distance of 1½ miles. The other two exposed dykes in Linpen Burn and Glenclach Burn both have limited outcrops, the latter appearing to strike E.-W. Further dykes of this nature must occur in the area, as evidenced by the waste heaps at Glencrieff Mine, Glenconnar Shaft, and Big Wool Gill.

In contrast with group one, the dykes are much wider, attaining a maximum of 50' in the case of the Glenclach representative. The width of the Linpen Burn dyke is indeterminable, but both of the Elvan Water dykes have a width of 15'-20'.

The rocks are distinguished by being markedly porphyritic with large phenocrysts of corroded quartz, plagioclase, and biotite. Alteration of the felspars to sericite, chlorite and carbonate, and the biotites to muscovite and carbonate, with development of rutile, is very common. The ground mass is predominantly quartz with oligoclase-andesine felspar. Unorientated white mica is plentiful. The mode of the Glenclach rock is quartz 47.31%, oligoclase-andesine 21.69%, othoclase 4.23%, white mica 20.78%, and carbonate 5.97%. The orthoclase (2V=72, negative, extinction on 001= 0 on 010 is 9^{o}-10^{o}) occurs as large crustals up to 6 mm. in length, and is poikolitic towards the quartz, plagioclase and biotite phenocrysts.

The abundance of quartz, and plagioclase felspars of the oligoclase-andesine range, together with the small amount of alkali felspar, indicates that the rocks should be termed porphyritic microgranodiorites, grading down to porphyritic dacites in the case of the Big Wool Gill rock.

The dykes have suffered similar deformation to group one, and are jointed in a direction parallel to that of the greywacke. An adit was driven along the joint direction of the Glenclach dyke on what is probably the continuation of the Shieling Burn Vein. The Linpen Burn dyke was probably faulted in a direction parallel to the joint, i.e. N.N.W.-S.S.E., the outcrop coming to an abrupt end in the burn. However, the limited exposure enforces considerable uncertainty on that supposition.

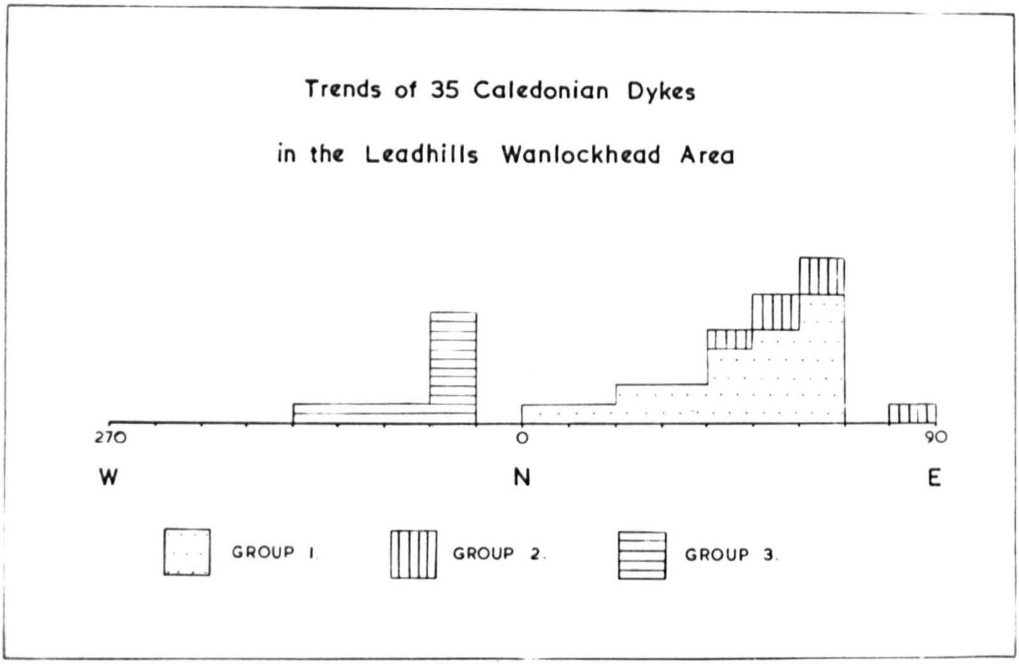


Figure 7.

Trends of 35 Caledonian dykes in the Leadhills-Wanlockhead area.

c. Group III.

In contrast to groups one and two, the dykes of group three strike approximately N.N.W.-S.S.E. (fig.7), that is parallel to the joint of the country rock. There are several outcrops of the group, none showing any traceable continuity. However, the Roanburn Vein was worked northwards from Moffats Shaft following a dyke for half a mile (Wilson, 1921), an indication that the dykes may be continuous for short lengths.

The width of these dykes is small and variable, the widest observed, in Black Grain, being 12' wide, whilst the smallest width, in the dyke at the head of the southerly scar draining Hunt Law, is 9".

Two typical rocks of this group show the variation in character in the group. The Black Grain is composed of quartz (57%) and oligoclase (30%), with occasional phenocrysts of corroded quartz, and microphenocrysts of oligoclase. In contrast the Shortcleuch representative is made up of quartz (34%), albite (28%), white mica and carbonate. No phenocrysts are present. The quartz is poikolitic towards the euhedral felspar laths, and both contain numerous opaque inclusions. The mica and carbonate appear to replace the quartz. The composition of two of the albites was determined as An_3 and An_2. The felspar presents a uniform appearance throughout the rock.

This group of dykes falls into the classification of microgranodiorites, being composed of quartz and plagioclase.

Dyke rocks rich in albite have been described from the Southern Uplands by King (1937), and from the Ards Peninsula by

Reynolds (1931). The former recognized two main types, those with albite which is a primary product of crystallization, and those which belong to a late phase in the history of the rocks. The chief criterion for the first type is the absence of any trace of more calcic plagioclase, a condition which is applicable to the Shortcleuch dyke. However, Leedal (1952, p.57) describes the albitization of tronjhemites in the Cluanie district, and observes that in the earlier stages of albitization (the quartz albitites), the plagioclase becomes more sodic, to An_{3-5}, and is clouded by numerous rods and granules of opaque material. This description, coupled with the texture of the Shortcleuch dyke, would serve to indicate that the dyke is a quartz albitite, an indication supported by its occurrence in a belt of shearing (Leedal, 1950).

The N.N.W.-S.S.E. trend of the dykes is not uncommon in the Lower Palaeozoics of the south of Scotland, Richey (1939) pointing out the N.N.W.-S.S.E. swarms associated with the Distinkhorn Granite of the Midland Valley (A. G. MacGregor, 1930), and the western part of the Criffel- Dalbeattie complex (M. MacGregor, 1937). Reynolds (1931) notes the occurrence of N.N.W.-S.S.E. dykes in the Ards Peninsula, Co. Down.

The group three dykes exhibit indications of deformation. A significant feature is the marked jointing of the Shortcleuch dyke in a N.W.-S.E. direction, making an acute angle of 12° with the wall of the dyke (fig.8). These joints do not extend into the greywacke with which the dyke is in contact. There is no

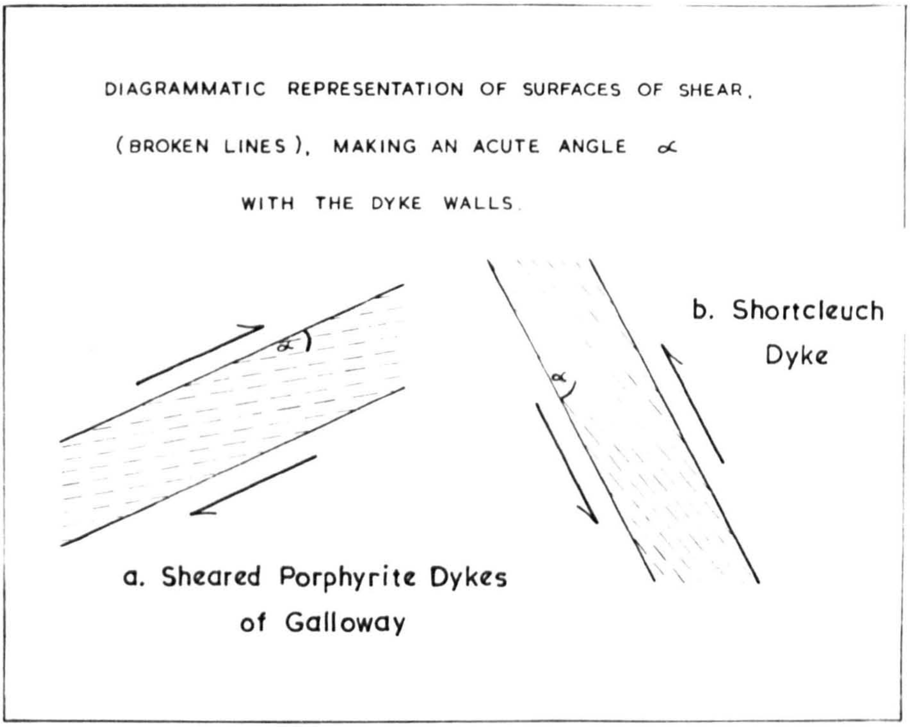


Figure 8.

Diagrammatic representation of surfaces of shear, (broken lines), making an acute angle with the dyke walls.

marked orientation of the white mica in the rock.

The significance of the minor joints was recognized by Blyth (1949, p.404) in describing the sheared porphyrite dykes of Galloway. He recognized in all sheared dykes, surfaces of shear striking parallel to, or making a slight angle with, the dyke walls (fig.8). He attributed this to emplacement of the dykes in a zone of dextral shearing or tear faulting, the shear surfaces parallel to the dyke walls being due to tear faults acting relatively early after the filling of the fissures and before the magma was fully consolidated, whilst the shear surfaces lying at an acute angle to the walls were due to the dextral shear affecting dykes which were almost, if not entirely, rigid.

The latter case is directly analogous to the Shortcleugh dyke, and indicates the dyke to have been affected by sinistral shear, either at a late stage in consolidation or when the magma was fully consolidated.

Other deformation of the group three dykes is illustrated by the small dyke in the south scar draining Hunt Law, a small displacement of the dyke having taken place along a rejuvenated strike fault, analogous to the displacement of the Lochnell Vein.

The three groups of dyke rocks are all characterized by the development of white mica. Its occurrence is characteristic of Caledonian dykes, not only in the Leadhills area, but elsewhere in Britain, e.g. Blyth (1941, p.401), in Galloway, and Leedal (1950), in Cluanie, noting its presence. Goldschmidt (1916, p.77) also recorded its widespread occurrence in Norwegian trondhjemites.

In the absence of data regarding its composition it is difficult to discuss the genesis of this mica. However, the white mica has been shown to occupy a very late stage in the dyke history, coating shear surfaces in the Galloway dykes, which lead Blyth (1949, p.403), to state that the derivation of the mica-forming materials from internal sources of intense shearing stress was very possible, though he did not discount an external magmatic source. In the Leadhills area the mica is not concentrated along the joint directions but disseminated throughout the rock. Its approximately equal order of magnitude in all three groups of dykes does not support an origin from areas of intense shearing stress, as the group three dykes are the only dykes which show evidence of having suffered shearing stress.

If the white mica is a potash mica, it would appear probable from its general abundance that potassium has either been introduced at a late stage in the crystallization of the magma, or hydrothermally at a later date, and in the case of the Galloway dykes migrated to loci of relief of pressure, the shear fractures, whilst in the Leadhills dykes it crystallized in the body of the rock. An introduction of potassium is indicated in the Glenclach dyke by a porphyroblastic orthoclase, which compares with orthoclase described by Leedal (1952, p.56), and ascribed as due to the growth of original orthoclase phenocrysts.

d. Relationships of the three groups of dykes.

First of all in considering the features of the dykes other than the mineral content, a picture of the general evolution of the area during the emplacement of the dykes can be visualized.

The dykes of groups one and two show similarities in directions of strike and jointing, both were jointed in continuity with the country rock into which they were intruded. As both can be traced for relatively long distances and do not exhibit any shear structures, it is suggested that both were intruded in conditions of relaxation of N.W.-S.E. compression. A difference between groups one and two is the greater width of the latter, and therefore it is further suggested that this is due to group two dykes being intruded when the conditions of relaxation were at a maximum.

In order to explain the jointing of the greywacke and dykes of groups one and two, and the displacements observed in the dykes and country rock, a further epoch of compression must be invoked, as described above, in a N.N.W.-S.S.E. direction, under conditions where the intermediate principal pressure was vertical (Anderson, 1951, p.15). The fact that the joints of groups one and two are in continuity with the joints of the greywacke necessitates the dykes being solidified in this phase of compression. The group three dykes were then intruded into a belt of shear, possibly, but not necessarily, in some minor relaxation of compression, and were later subjected to sinistral shear, giving rise to the shear joints of the Shortcleuch representative.

In connection with the epoch of compression separating groups one and two from group three, it is of interest to note that Reynolds (1931), recognizes two periods of dyke intrusion separated by a period of compression in the Ards Peninsula, Co. Down.

In consideration of the petrogenetical aspect of the dyke problem attention must be first of all directed towards the Southern Upland Caledonian Plutonic intrusives, as the dykes are considered upward expressions of the plutonites. Several of the Southern Upland intrusive masses have been described and all show a zoning, the outer zones being more basic than the inner zones (Deer, 1935; Gardiner and Reynolds, 1936, 1932; MacGregor, M, 1936; MacGregor, A.G., 1930).

The succession of rock types demonstrated illustrates that the formation of successively more acid types has taken place in the Southern Uplands, and it is suggested that the group three dykes of the Leadhills area are representatives of a more acid magma than that which gave rise to groups one and two. The basic to acid trend in the dykes is from the andesine-oligoclase (quartz) rocks of group one, through the quartz oligoclase-andesine group two, to the quartz oligoclase (albite) rocks of group three.

The basic to acid trend was probably the result of differentiation in the magma basin. MacGregor, A.G. (1930, p.51) states that the close association of similar rock types in the south of Scotland makes the assumption that the various members of the plutonic complexes are differentiation products of one magma basin, a certainty, and that the Distinkhorn complex has provided evidence of successive intrusion from one magma basin as opposed to differentiation in situ. Leedal (1950) considered that all the Caledonian Newer granites were the result of the crystallization of primary granitic magma derived by assuming melting of a mountain root during the main Caledonian orogeny, and shows that of the exposed plutonic rocks 99% are of rocks ranging from quartz diorite to granite, whilst diorite and more basic types account for only 1% of the total.

An investigation of the joint system of the Spango "Granite" to the north-west of Leadhills showed the principal open joint to be in a general E.N.E.-W.S.W. direction, with other joints in N.N.E.-S.S.W. and N.N.W.-S.S.E. directions. Under an application of Hartmann's Law ("Under non-rotational stress in ductile materials the obtuse angle between conjugate shears is bisected by the direction of compressive force"... Nevin, 1941, p.31), the first two sets of joints are not inconsistent with N.N.W.-S.S.E. compressive forces. The joints of the third set are parallel to the joints of the surrounding country rock, and were probably formed when the intrusive had reached consolidation indicating that the act of plutonic intrusion was completed, whilst a N.N.W.-S.S.E. stress was operative.

e. Age Relationships.

In the Geological Survey Memoir (1899, p.76), the age of the Southern Upland "Granites" is stated to have been post-Silurian and pre-Upper Old Red Sandstone. However, Richey (1939) points out that ~~where~~ there is no "top" evidence, as in the case of the Southern Uplands, the intrusives could be possibly of late Silurian age, and cites the case of a granite indistinguishable from Old Red varieties having been found in the basal Old Red conglomerates of the Oban district, and pebbles in the Downtonian conglomerates of Stonehaven.

OTHER MINOR INTRUSIVES.

On the railway embankment to the east of the Long Cleuch a 2' wide monchiquite dyke is exposed, which can be traced in a north-westerly direction, and outcrops in the Long Cleuch. A dyke of similar width and composition outcrops on the top of Wellgrain Dod, and may be the continuation of the Long Cleuch dyke. The dyke rock is typically alkaline, characterized by titanaugite, olivine, barkevikite, and analcite. Felspar of the andesine-labradorite range is present, but subordinate to the analcite.

A similar dyke outcrops at the head of Black Grain, (Cog Burn), and other monchiquite dykes have been recorded from the Southern Uplands (Walker, 1925, p.390). In the Midland Valley monchiquites have been assigned to the Permian volcanic period (MacGregor, A. & A.G., 1948, p.68), with a minor suite of Lower Carboniferous age.

A member of the Tertiary Mull Swarm, the Dalraith-Moffat-Eskdalemuir dyke (MacGregor, A. & A.G., 1948, p.81), traverses the north-eastern part of the Leadhills area. At the head of Wellgrain the dyke is 200' wide, and strikes W.N.W., hading to the south. A specimen taken from near the northern margin of the dyke in Wellgrain showed the rock to be a typical tholeiite, composed of augite, andesine, and iron ore, in a glassy mesostasis. In the rock are small rounded inclusions of a fine grained, closely packed mass of augite and andesine, with only minor amounts of glassy mesostasis. The inclusions probably represent material of the primary intrusion which was cooled quickly at the margin of the dyke, and was not wholly assimilated by the main intrusion.

SUMMARY OF TECTONIC HISTORY.

In the Table which follows, an attempt has been made to summarize the structural history of the Leadhills-Wanlockhead mining field. The exact date of the "Siluro-Devonian" movements cannot be fixed, and it is probable that several phases of Caledonian and Hercynian Orogenies, recognised elsewhere, are included. The age of the mineralisation is discussed later, when the evidence of the mineralisation can be taken into account.

PERIOD or OROGENY	EFFECT	PROBABLE REGIONAL STRESS
Siluro-Devonian	Folding, with virgation, accompanied by thrust faulting.	N.W.-S.E. compression, under conditions where the minimum principal stress was vertical.
ditto	Intrusion of the more basic members of the Southern Uplands Plutonic Complexes. Group 1 dykes Group 2 dykes	Relaxation of N.W.-S.E. compression. Maximum relaxation.
Siluro-Devonian (?Transition from Caledonian towards Hercynian).	Formation of intersecting joint system. Intrusion and consolidation of the more acid members of the Southern Uplands Plutonic Complexes. Group 3 dykes.	N.N.W.-S.S.E. compression, under conditions where the intermediate principal was vertical.
Ditto	Sinistral stress on the more northerly trending members of the joint pattern. Dextral shear along localised belts, e.g. Mennock Water, Galloway porphyrite dykes.	Reorientation of N.N.W.-S.S.E. stress towards a N.-S. direction. Torsional effect of reorientation.
?Carboniferous	Displacement of veins and joints and N.N.W. dykes along rejuvenated strike faults.	Dominantly vertical movements, under a ?N.-S. stress.
?Permian	Monchiquite dykes.	N.N.E.-S.S.W. tension.
Tertiary	Tholeiite dyke	ditto.

II. MINERALOGY OF THE LEADHILLS-WANLOCKHEAD DISTRICT.

INTRODUCTION.

The Leadhills-Wanlockhead area is a lead and zinc mining district, and the minerals common to most of the veins are galena, sphalerite, chalcopyrite, and pyrite, with a gangue of ankerite, calcite, barytes, and quartz. The area is renowned for the wealth of secondary minerals, and is a type locality for leadhillite, lanarkite, and caledonite.

In the following descriptions the minerals have been grouped as far as possible under the chief metals, namely lead, zinc, copper, and iron. The grouping of the remaining minerals is based on similarity of acid radicles, whilst the distribution of P, V, As, and Cr, is described separately.

The minerals were mostly collected from dumps in the district, and a full list of localities and their mineral content is given in Appendix II. The material collected was chiefly supplemented by minerals from the Scottish Mineral Collection, which are numbered, in brackets in the text, in accordance with the number in the collection. Reference was also made to collections in the Grant Institute, Edinburgh, the Hunterian Museum, Glasgow, and the Museum of Natural History, Dumfries, and specimens from these collections are named in the text.

Unless otherwise stated, all the minerals have been identified by X-ray powder photographs, and comparison of the diffraction patterns with standards in the departmental library.

Chemical formulae quoted are from Strunz (1949), and ionic radii from Rankama and Sahama (1950).

LIST OF MINERALS RECORDED FROM THE DISTRICT.

The sixty minerals recorded from the area are listed below in the order followed in the minerals descriptions.

Minerals not previously recorded from the locality are denoted by (1), whilst minerals not previously confirmed in Britain are denoted by (2). Minerals recorded from the locality, but not confirmed in the present investigation, are indicated by an asterisk.

Galena, PbS

Minium, Pb_3O_4

Plattnerite, PbO_2

(1)Cotunnite, $PbCl_2$

Cerussite, $PbCO_3$

Hydrocerussite, $Pb_3(CO_3)(OH)_2$

Leadhillite, $Pb_4(SO_4)(CO_3)_2(OH)_2$

Anglesite, $PbSO_4$

Lanarkite, $Pb_2(SO_4)O$

Linarite, $PbCu(SO_4)(OH)_2$

Caledonite, $(Cu_2Pb_5)(SO_4)_3(CO_3)(OH)_6$

Sphalerite, ZnS

Greenockite, CdS

Aurichalcite, $(ZnCu)_5(OH)_6(CO_3)_2$

(1)Hydrozincite, $Zn_5(OH)_6(CO_3)_2$

Hemimorphite, $Zn_4(OH)_2(Si_2O_7)H_2O$

Chalcopyrite, $CuFeS_2$

(1)Chalcosite, Cu_2S

(1)Covellite, CuS

Malachite, $Cu_2(OH)_2CO_3$

Brochantite, $Cu_4(SO_4)(OH)_6$

Chrysocolla, $CuSiO_3nH_2O$

Pyrite, FeS_2

(1)Marcasite, FeS_2

Hematite, Fe_2O_3

Goethite, $(HFeO_2)$

Gold, Au

Quartz, SiO_2

Psilomelane, basic oxide of, Ba, Mn^{2+}, Mn^{4+}

(1)Rutile, TiO_2

Fluorite, CaF_2

Ankerite, $(MgCO_3CaCO_3)(FeCO_3CaCO_3)(MnCO_3CaCO_3)(CaCO_3)$

Calcite, $CaCO_3$

Aragonite, $CaCO_3$

Witherite, $BaCO_3$

*Strontianite, $SrCO_3$

*Magnesite, $MgCO_3$

Barytes, $BaSO_4$

Gypsum, $CaSO_4.2H_2O$

(1)Albite, $Na(AlSi_3O_8)$

(1)Muscovite, $KAl_2(OHF)_2(AlSi_3O_{10})$

Chlorite, Fe,Mg,Al,Silicate.

Pyromorphite, $Pb_5(PO_4)_3Cl$

Polysphaerite, Ca rich pyromorphite.

?(2)Lead hydroxyapatite, $Pb_5(PO_4)_3(OH)$. Previously recorded only as an artificial mineral.

(1)Plumbogummite, $PbAl_3(PO_4)_2(OH)_5H_2O$

Niccolite, NiAs

*Cobaltite, CoAsS

(2)Rammelsbergite, $NiAs_2$

Mimetite, $Pb_5(AsO_4)_3Cl$

Olivenite, $Cu_2(OH)(AsO_4)$

(1)Beudantite, $PbFe_3(OH)_6(SO_4)(AsO_4)$

Erythrite, $Co_3(AsO_4)_2 \cdot 8H_2O$

Annabergite, $Ni_3(AsO_4)_2 \cdot 8H_2O$

Vanadinite, $Pb_5(VO_4)Cl$

Descloizite group, $(Cu\text{-}Zn)Pb(VO_4)(OH)$

Crocoite, $PbCrO_4$

(2)Phoenicochroite, $Pb_3(CrO_4)O$

(2)Chromian Leadhillite, a new variety.

(2)New Chromium mineral.

LEAD MINERALS.

As is suggested by the name "Leadhills", lead minerals are very common in the Leadhills-Wanlockhead district, and occur in all the veins. Galena is the only primary lead mineral, but nineteen secondary lead minerals have been recorded, of which the most abundant are cerussite, and pyromorphite.

Galena, PbS.

Galena is economically the most important mineral in the district, and up till the end of the nineteenth century was the only mineral worked. It is widespread throughout the area, and is associated with the majority of the other minerals, but particularly with sphalerite, chalcopyrite, calcite, barytes, quartz, and the lead secondary minerals.

In the veins galena is commonly found on the foot or hanging walls, the former predominating, and for this reason drives made along barren portions of the veins, followed the foot wall. The galena is generally in massive veinlets, varying in width from a fraction of an inch to several feet. Crystal faces are developed in vughs, and Heddle (1923, p.18) lists many of the magnificent forms which have been found.

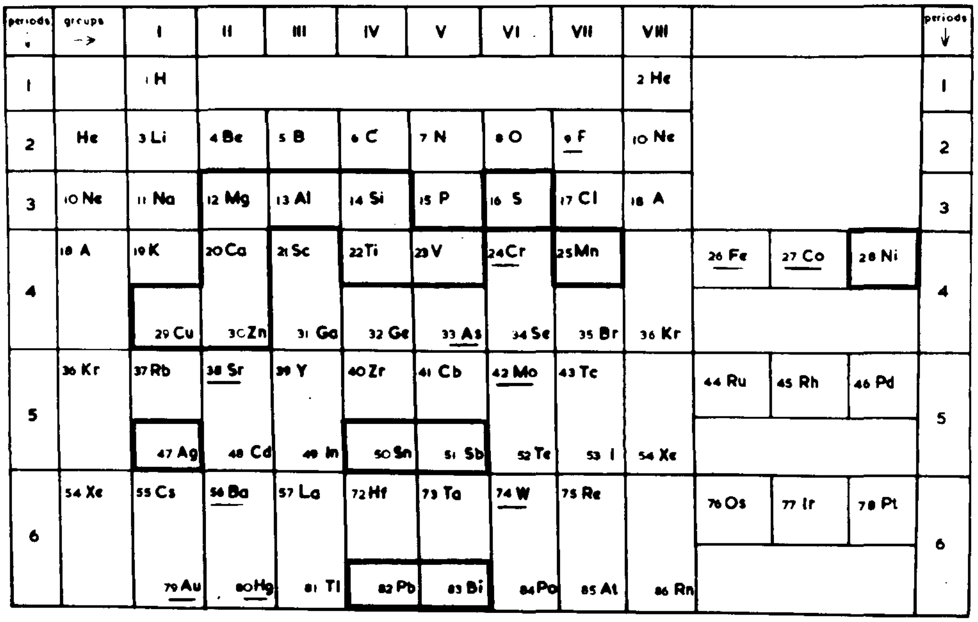
An interesting form of galena is that described by Brown (1925, p.134), as "spongy galena". Such galena is well named and consists of massive galena with numerous irregular columnar individuals formed along the cleavage, whilst the surface of the galena may be pitted, and present an appearance similar to that of smelted lead. Wilson (1921, p.15), describes crystals of galena with spongy interiors. The "spongy" galena could be due to a shortage of PbS in the vicinity of the growing mineral, but when the pitted surface of the galena is taken into account a solution effect better explains both phenomena.

Fine grained, or "steel" galena occurs in the oxidised portion of Cove Vein, and is due to partial replacement of the galena by anglesite. This is a common phenomenon in lead deposits (cf. Lindgren, 1933, p.854).

Specimens of "antimonial lead" were included in all the collections examined, and in every case the X-ray diffraction pattern indicated only the presence of galena. Wilson (1921, p.15) mentions such a variety of galena, and states that it approximates to jamesonite in composition. However, no jamesonite was recorded in the present investigation, although antimony was found to be universally present in the galena.

Silver is also universally present in the galena from the district, and was formerly extracted at the Leadhills and Wanlockhead Smelting Mills. According to Brown (1925, p.71), the silver in the Wanlockhead galena averages from 7 to 11 ozs. per ton. No silver minerals were observed in polished section.

Other elements included in the galena are listed below.



Elements in galena.

Although many of the large crystals have in the past been loosely termed "secondary", true secondary, or supergene galena has been recorded from the locality in the form of pseudomorphs after pyromorphite (1001.121), and cerussite (1001.209). In both cases the original crystal outlines are perfectly maintained, but the interior of the crystal is of black granular galena, with which may be admixed some of the original mineral.

Secondary galena has previously been noted (cf. Lindgren 1933, p.855; Brown, 1936). However, the occurrence of the variety is very limited, Dunham (1950, p.13) stating that except under special reducing conditions the mineral is unlikely to form above the water table, and little evidence exists to suggest the formation in the zone near the water table in which secondary copper sulphides originate.

The probable explanation of the Leadhills-Wanlockhead secondary galena was advanced by Wilson (1921, p.21), who suggested that the mineral owed its origin to local reducing conditions brought about by the influx of waters carrying H_2S.

Lead Oxides.

The two oxides of lead recorded from the district (Gregg and Lettsom, 1958; Heddle, 1923, pp. 101, 103), are minium (Pb_3O_4) and plattnerite (PbO_2). Although both are rare minerals, plattnerite is rather more abundant than minium.

Minium occurs in small scarlet masses associated with covellite, cerussite, and anglesite, from the Susanna Vein, Leadhills. Plattnerite occurs as black botryoidal aggregates from several veins, and is associated with mimetite from the High Pirn Mine on the Belton Grain Vein, with pyromorphite and cerussite from dumps at the head of Whytes Cleuch, and with leadhillite from the East Stayvoyage Vein.

Cotunnite, $PbCl_2$.

Cotunnite has not been previously recorded from the district, and is a very rare mineral. It was observed on only two specimens, one from the High Pirn Mine on the Belton Grain Vein, and the other from Locality 45 on the Hopeful Vein. In the High Pirn Mine specimen (1926.2.15), the mineral is associated with pyromorphite, mimetite and plumbogummite and is a white micro crystalline incrustation on the mimetite, which occasionally attains distinguishable elongated orthorhombic crystals, the largest being 0.08 mm. in length. Cotunnite from the Hopeful Vein is in elongated crystals, the largest half a millimeter in length, and is pale green in colour. It is associated with leadhillite, anglesite, and pyromorphite.

The cotunnite was confirmed by comparison of the spacing data with data published by Brakken and Harang (1928). The data are tabulated below. The diffraction pattern is also comparable with that of artificial lead chloride.

3472. High Pirn Mine		Cotunnite (Brakken & Harang, 1928)	
I	dA	I	dA
vw.	4.51	4	4.486
vw.	4.09	4	4.033
s.	3.88	8	3.884
s.	3.57	10	3.572
w.	2.91	6	2.904
m.	2.77	8	2.761
m.	2.49	8	2.501
vw.	2.36	4	2.370
m.	2.26	8	2.256
w.	2.21	6	2.209
m.	2.12	8	2.146
w.	2.09	8	2.091
w.	1.956	2	1.984
vw.	1.63		
vw.	1.578		
vw.	1.454		
vw.	1.422		
vw.	1.397		

Cerussite, $PbCO_3$.

Cerussite, together with pyromorphite, is the most common secondary mineral in the Leadhills-Wanlockhead district, and can be found on most of the old dumps. Brown (1918, p.134) described the occurrence of cerussite, associated with hydrocerussite, on the 120 fathom Level of the New Glencrieff Vein, and stated that cerussite was abundant between the 80 and 120 fathom Levels. A good locality is the High Pirn Mine on the Belton Grain Vein, where elongated crystals up to 1½" in length have formed in cavities in crystalline quartz. Many of the crystal forms occurring in the district have been listed by Heddle (1923, p.144).

The mineral may be massive, either white or black in colour, and associated with anglesite forming a pseudomorphous rim round cores of partly altered galena. The black colouration is due to small inclusions of galena. Cerussite may also be associated with pyromorphite, malachite, leadhillite, lanarkite, caledonite, and linarite.

A blue variety (Grant Institute, 1404), was associated with malachite, and qualitative analysis revealed the presence of copper, which presumably is the element causing the blue colouration.

Hydrocerussite, $Pb_3(CO_3(OH)_2$.

Hydrocerussite is a fairly rare mineral in the district, but has been found in several veins. According to Brown (1918, p.134), hydrocerussite is abundant in the West Branch of the New Glencrieff Vein down to the 120 fathoms Level.

The mineral generally forms a white, pearly coating on galena, but may be grey in colour and replacing galena along cleavage planes (polished specimen 134). Crystals of hydrocerussite, labelled as "cupreous calcite", (270.609), from the Susanna Vein, were up to 7 mm. in diameter, trigonal, and green in colour. The crystals were formed on a pseudomorph of pyromorphite and cerussite, after galena, which had been partly replaced by massive hydrocerussite. Encrusting on the hydrocerussite crystals were small groups of radiating malachite crystals, and the colour of the hydrocerussite can be attributed to copper.

Leadhillite, $Pb_4(SO_4)(CO_3)_2(OH)_2$.

According to Wilson (1921, p.17) and Heddle (1924, p.17), leadhillite has been found in all the veins of the district with the exception of the Belton Grain Vein. However, one specimen (740.3), localised from the "Belton Grain Mine, Wanlockhead", bears leadhillite crystals associated with chalcopyrite, galena, cerussite, and brochantite.

Leadhillite occurs in white or colourless to pale green hexagonal platy crystals, or less commonly in a rhombohedral form, which was known as susannite. X-ray investigation of the variety susannite demonstrated its identity with leadhillite. This rhombohedral variety has been recorded from the Susanna Vein (Heddle, 1924, p.174), and during the present investigation from the Brow, East Stayvoyage, and Old Glencrieff Veins.

Leadhillite is generally associated with massive varieties of cerussite, but only very rarely with cerussite crystals. Other associates are pyromorphite, lanarkite, hydrocerussite, and caledonite.

A chromium variety of leadhillite from the Hopeful Vein is described below.

Anglesite, $PbSO_4$.

Anglesite is not an uncommon mineral in the district, and has been recorded from many of the veins. Particularly fine crystals, up to several inches in length, at present exhibited in the Scottish Mineral Collection, were once collected from the Susanna Vein.

Anglesite is associated with caledonite, linarite, leadhillite and covellite.

Black, powdery, massive anglesite often pseudomorphously replaces galena, and may itself be replaced by cerussite. The black colour is due to finely divided galena included in the pseudomorph.

Lanarkite, $Pb_2(SO_4)O$.

Lanarkite is a rare mineral in the district, and although only recorded from the Susanna Vein by Heddle (1924, p.175), was found by Brown (1918, p.129) on the Margaret Vein, Crawfurds Vein, and New Glencrieff Vein, whilst to this list of localities may be added Cove Vein, and Hopeful Vein.

The mineral occurs in elongated white or pale greenish crystals, associated with leadhillite, massive cerussite, caledonite, and linarite. Dark, massive, powdery lanarkite was recorded from Whytes Cleuch, marginally replacing galena.

Linarite, $PbCu(SO_4)(OH)_2$.

Linarite is fairly common in the district, in oxidised mixed chalcopyrite-galena ores. It is associated with malachite, brochantite, caledonite, and anglesite, and generally occurs as small elongated blue crystals, particularly good localities being the dumps on the Scar and East Stayvoyage Veins, and the dumps by the side of the road near the Glencrieff Mine.

Caledonite, $Cu_2Pb_5(SO_4)_3(CO_3)(OH)_6$.

Caledonite together with leadhillite and lanarkite, was first described from the Leadhills-Wanlockhead district. The mineral is not uncommon in oxidised mixed chalcopyrite-galena ores. It is chiefly associated with anglesite, linarite and leadhillite, and only very rarely with malachite or brochantite. Excellent specimens were once collected from the Susanna Vein, but at present the best material is on the dumps of the East Stayvoyage and Scar Veins.

ZINC MINERALS.

Four zinc minerals have been recorded from the Leadhill-Wanlockhead district, of which sphalerite is the only primary mineral, and hemimorphite the only abundant secondary mineral.

Sphalerite, ZnS.

Sphalerite occurs in most of the principal veins, although it has not been recorded from the veins to the east of the area. It was worked chiefly from the Glencrieff and Glengonnar Mines during the latter years of the mining history, commencing about 1880. It commonly occurs as massive banded ore, which often contains inclusions of pyrite, or chalcopyrite, and is associated with galena, ankerite, calcite, barytes, and quartz. Massive sphalerite is generally found with galena on either the foot or hanging walls of the veins. When the mineral has crystallized in an open space, crystal faces are developed, fine examples being numerous on the dumps of the Bay Shaft, Wanlockhead. The crystals are tetrahedral, and in many cases the crystal faces are curved. Multiple twinning is common, both in the massive sphalerite, and in that with curved crystal faces. Massive intergrowths with galena are abundant on the large dumps at the Glencrieff Mine, and probably originated from the deeper parts of the Mine, Wilson (1921, p.31) noting that the ore from the lowest levels of the Brow Vein in Glengonnar Mine consisted of an intergrowth of galena and sphalerite in almost equal quantities.

As the minor elements incorporated in shpalerite may be used as indicators of the temperature of formation, several sphalerites were investigated, the iron content being estimated quantitatively, and the other elements determined qualitatively, by spectrochemical analysis. The results are tabulated below. To facilitate comparison with the sphalerites of the Leadhills-Wanlockhead area, examples from Cornwall (Vokes, 1950) and Skogbole, were taken as representatives of the Hypothermal Group (definition after Lindgren, 1933, p.637), and a specimen from the Carboniferous Limestone of County Dublin, together with an iron determination from Stonescroft Mine (Dunham, 1948, p.88), were taken to represent low temperature deposits.

The iron content of the Leadhills-Wanlockhead sphalerites is fairly uniform, which was to be expected from the uniform dark brown colour. The average iron content is 4.91% FeS, which is considerably lower than that of the hypothermal sphalerites. Of the elements typically present in sphalerite, cadmium and cobalt are uniformly present. Manganese is present in all, but is enriched in the Skogbole specimen, whilst gallium and germanium are present in all the examples excepting those of the hypothermal group. Indium was not detedted, and thallium was only recorded from seven of the sphalerites examined.

Qualitative Spectrochemical Analyses of Sphalerite.

No.	Cd.	Ga.	In.	Tl.	Ge.	Mn.	Co.	Cu.	Ag.	Mg.	Al.	Si.	Ti.	Sn.	Pb.	V.
1.	1	1	?	?	2	1	1	3	1	1	1	2	?	0	00	0
2.	1	1	?	0	2	1	1	3	1	1	0	2	?	0	0	0
3.	1	1	?	?	2	2	2	3	1	1	2	3	?	0	0	0
4.	1	1	?	0	2	0	1	3	1	1	0	1	?	0	0	0
5.	1	1	?	?	2	2	1	3	1	1	1	2	?	0	0	0
6.	1	1	?	?	2	2	0	3	1	1	1	1	0	0	0	0
7.	1	1	?	?	2	2	1	3	2	2	2	2	?	0	0	0
8.	1	1	?	?	2	1	1	3	1	1	1	2	?	0	1	0
9.	1	1	?	?	2	1	0	3	2	1	1	1	?	0	0	0
10.	1	0	?	?	2	0	0	3	1	1	0	1	?	0	1	0
11.	1	1	?	0	1	0	1	3	1	1	0	1	?	0	?	0
12.	1	1	?	0	2	2	0	3	2	2	1	2	0	0	1	0
13.	1	?	?	0	2	1	1	3	2	1	1	2	?	0	0	0
14.	1	?	?	?	0	2	1	3	0	2	1	1	?	0	?	0
15.	1	?	?	?	?	4	2	4	1	4	4	1	2	0	?	0
16.	1	1	?	0	2	2	0	3	1	1	0	2	?	0	0	0

1. Glencrieff Mine
2. ditto
3. ditto
4. Snar Head.
5. Mine Hill.
6. Big Wool Gill.
7. Susanna Vein.
8. Mill Vein.
9. Horners-Muirs Vein.
10. Moffats Shaft.
11. Lady Anne Shaft
12. Force Grag, Keswick.
13. Wood of Cree, Kirkcudbright.
14. New Consols Mine, Cornwall.
15. Skogbole.
16. Condalkia, Co.Dublin.

? not certain that element is present.
0 Element definitely present, numbers indicate relative abundance, estimated visually.

From the extensive literature on the minor elements in sphalerite the general variation of the elements in relation to the temperature of formation of the sphalerite may be summarised, although regional causes may influence the character of the minor elements. The sphalerites formed at high temperatures are characterized by a high percentage of iron, manganese and cobalt, with a low content of gallium and germanium, and an absence of thallium. Gallium and indium favour sphalerites of intermediate temperature. The content of germanium is high in low temperature sphalerites, and thallium is only present in sphalerites formed under conditions of low temperature. The content of cadmium appears to be independent of temperature (Borovick and Propenko, 1938; Oftedahl, 1940; Stoiber, 1940; Evrard, 1945; Gabrielson, 1945; Warren and Thompson, 1945; Rankama and Sahama, 1950).

It is possible, therefore, to designate the Leadhills-Wanlockhead sphalerites to the low or intermediate temperature groups, with the presence of gallium, germanium, and occasional thallium. The general absence of indium must be attributed to a regional cause, presumably the lack of indium in the parent magma of the vein solutions.

Confirmation of this estimation of the temperature of formation of the sphalerites is afforded by Kullerud (1953), who, by a study of the FeS-ZnS system was able to relate the iron content of sphalerites to an actual temperature of formation. Although pressure was not taken into account, its effects were shown to be fairly small, e.g., an error of a thousand atmospheres in the estimate of the pressure gives an error of plus or minus 25°C.

The iron content of the sphalerites examined in the present investigation, together with the approximate temperature of formation are tabulated below.

Temperature of formation of Sphalerites.

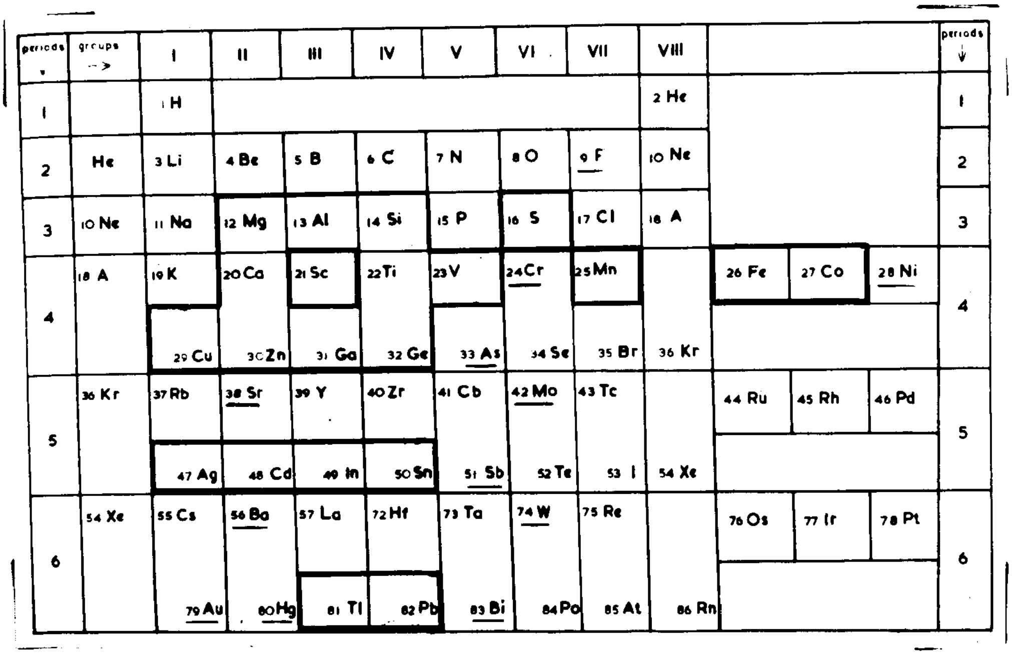
No.	FeS	Temp. °C.
1.	4.85	190
2.	7.11	281
3.	4.93	192
4.	3.88	147
5.	4.36	170
6.	5.26	207
7.	5.06	197
8.	3.83	143
9.	4.22	165
10.	4.44	172
11.	6.09	242
12.	6.69	265
13.	4.79	187
14.	14.12	480
15.	12.22	444
16.	1.88	138
17.	1.47	138

1. Glencrieff Mine.
2. ditto
3. ditto
4. Snar Head.
5. Mine Hill.
6. Big Wool Gill.
7. Susanna Vein.
8. Mill Vein.
9. Horners-Muirs Vein.
10. Moffats Shaft.
11. Lady Anne Shaft.
12. Force Crag, Keswick.
13. Wood of Cree, Kirkcudbright.
14. New Consols Mine, Cornwall.
15. Skogbole.
16. Clondalkia, Co. Dublin.
17. Stonescroft Mine (Dunham, 1948, p.88).

The average temperature of formation of the Leadhills-Wanlockhead sphalerite was 192°C. As pressure was not taken into account this is a minimum figure. Unfortunately, exactly localised specimens have not been available during the investigation as the mines were not opened, but from a study of localised specimens it may be possible to determine the direction of travel of the mineralising solutions, as the temperature should increase towards the source of the minerals. It is significant that the two highest temperatures (Nos.2 and 11), were recorded from the New Glencrieff and Brow Veins, the two veins in the district which have been worked to the greatest depth.

Other elements incorporated in the sphalerites include Cu, Ag, Mg, Al, Si, Ti, Sn, Pb, and V. Titanium was only present in three samples. With the possible exception of vanadium and tin, these elements could be present as impurities in the sphalerite, silica as quartz, or with magnesium, aluminium, and titanium as inclusions of country rock, whilst the lead and silver could be present as galena, and the copper as chalcopyrite.

Distribution of Elements in Sphalerite.



Greenockite, CdS.

Oxidized sphalerite from the Glencrieff dumps and the Bay Shaft (68.18), is encrusted by small radiating crystal aggregates of hemimorphite, covered by a yellow powder which proved to be greenockite. Greenockite was recorded by Brown (1918, p.137), in the list of minerals from the district, and it was stated that no greenockite in crystal form had been found.

Greenockite was noted by Rankama and Sahama (1950, p.712) to be frequently present on weathering sphalerites rich in cadmium, and was attributed to the difference in the ionic radii of zinc (0.73kX) and cadmium (0.97kX).

Carbonates of Zinc.

Zinc carbonates are rare in the district, Although smithsonite (calamine, $ZnCO_3$) was recorded from the area by Brown (1925, p.79), and Wilson (1921, p.16), Heddle (1923, p.141) stated that smithsonite had not been detected in Scotland. The present investigation confirms Heddle's statement in part, as no smithsonite was recorded from the Leadhills-Wanlockhead district.

A single specimen of aurichalcite ($(ZnCu)_5(OH)_6(CO_3)_2$), associated with smithsonite was localised as Leadhills by Gregg and Lettsom (1935, p.426), whilst Heddle (1923, p.146) describes groups of acicular crystals of aurichalcite from the Susanna Vein, associated with leadhillite, lanarkite, hydrocerussite, and malachite.

Investigation of the specimens probably described by Heddle (290.2; 290.3) proved the "aurichalcite" to be caledonite.

The only example of Aurichalcite observed was an unnumbered specimen in the Grant Institute, labelled "Calamine, Silicate of Zinc, Leadhills", which is probably the specimen referred to by Gregg and Lettsom. It consisted of rusty ankerite with small vughs lined with hemimorphite crystals surmounted by blue-green radiating crystalline aggregates of aurichalcite. The aurichalcite was sporadically encrusted by small, white, flattened, blade-like crystals of hydrozincite $(Zn_5)OH)_6(CO_3)_2)$. Hydrozincite is common in the district as a thin white coating on sphalerite, but has not previously been noted in crystal form.

Hemimorphite, $Zn_4(OH)_2(Si_2O_7).H_2O$..

Hemimorphite is a common secondary mineral in the district, and is present in most of the veins which carry sphalerite. It occurs in colourless or white radiating crystalline aggregates, and in massive botryoidal masses which vary from white to blue in colour. The mineral pseudomorphously replaces calcite and barytes, the workings on the Broad Law being rich in such pseudomorphs. Brown (1918, p.132) describes pseudomorphs of hemimorphite after calcite in the New Glencrieff Vein, between the 80 and the 120 fathom levels.

COPPER MINERALS.

Although not as abundant as lead minerals, copper minerals are widespread throughout the Leadhills-Wanlockhead area. The only primary copper mineral is chalcopyrite, and six secondary minerals have been recorded, excluding those included under the lead minerals.

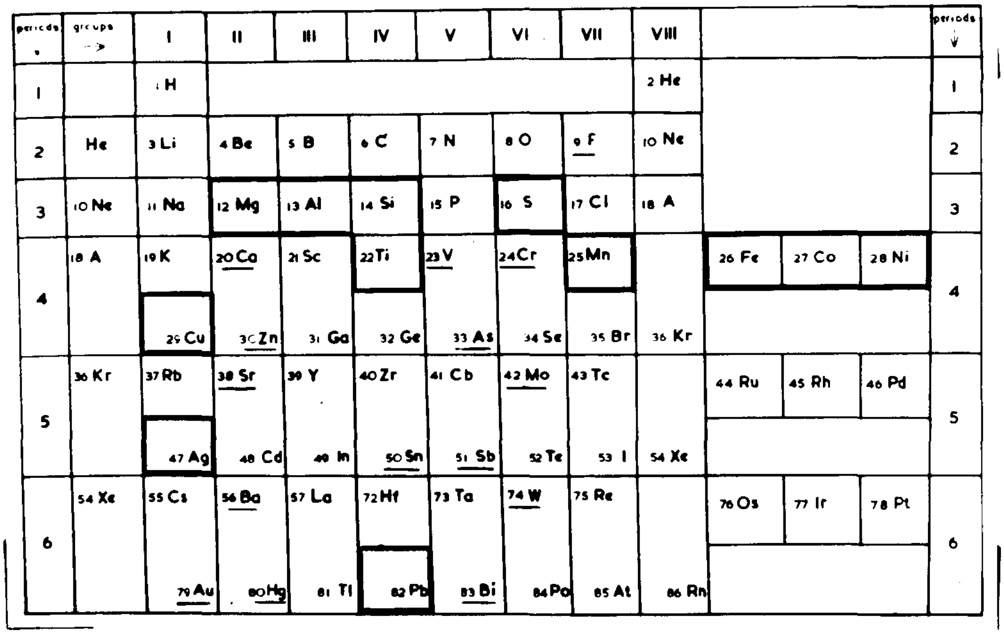
Chalcopyrite, $CuFeS_2$.

Chalcopyrite, although occurring in most of the veins of the district, has only been worked from two veins, the Long Cleuch, and Katystaklin Veins (Wilson, 1921).

The mineral is associated with sphalerite and galena, and is often present as inclusions in these minerals. It is generally massive, though occasional small, usually distorted, crystals may have formed in vughs.

Qualitative spectrochemical analysis revealed the presence, in trace amounts, of Ag, Pb, Mn, Co, Ni.

Elements in Chalcopyrite.



periods ↓	groups →	I	II	III	IV	V	VI	VII	VIII				periods ↓
1		1 H							2 He				1
2	He	3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	10 Ne				2
3	10 Ne	11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl	18 A				3
4	18 A	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn		26 Fe	27 Co	28 Ni	4
		29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr				
5	36 Kr	37 Rb	38 Sr	39 Y	40 Zr	41 Cb	42 Mo	43 Tc		44 Ru	45 Rh	46 Pd	5
		47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe				
6	54 Xe	55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re		76 Os	77 Ir	78 Pt	6
		79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn				

Chalcosite, Cu_2S.

Chalcosite has not been previously recorded from the locality, though it may be the mineral described by Wilson (1921, p18) as copper pitch, which appears to have a similar relationship to chalcopyrite as that observed for chalcosite, namely "...kernels of chalcopyrite, surrounded by copper pitch passing outwards to limonite and the whole veined with strings of crystalline malachite".

The mineral is abundant on the dumps by the side of the road near the Glencrieff Mine, and is associated with massive chalcopyrite, goethite, and sulphates and carbonates of copper. It replaces the margin of the chalcopyrite, and in polished section appears bluish-grey in colour and has small inclusions of deeper blue colour, which may be covellite (Uytenbogaardt, 1951, p.71). The identity of the mineral was confirmed by comparison of the diffraction pattern with that of chalcosite from Redruth, Cornwall, and with published data (Harcourt, 1942, p.76).

Covellite, CuS.

Covellite also has not been previously recorded from the locality, but is very common in oxidized mixed chalcopyrite-galena ores, usually replacing the galena, complete pseudomorphs after galena having been observed. When the galena has been removed, covellite is often associated with anglesite.

The mineral is a dark blue to green powder, and was confirmed by its properties in reflected light and by the X-ray diffraction pattern.

Malachite, $Cu_2(OH)_2CO_3$.

Malachite is a fairly common mineral in the zone of oxidation in the district, and is associated with chalcopyrite, and mixed chalcopyrite-galena ores. It forms tufts of radiating acicular crystals, and may occur as botryoidal masses encrusting on chalcopyrite.

A blue mineral associated with malachite has been identified as azurite by Wilson (1921, p.16), and Brown (1925, p.79). Heddle (1923, p.146) stated that the azurite recorded from Leadhills and Wanlockhead by Gregg was probably mistaken for linarite, and the present investigation failed to record any azurite from the area, the blue mineral associated with malachite being linarite in every specimen examined.

Brochantite, $Cu_4(SO_4)(OH)_6$.

Although the mineral is common in oxidised chalcopyrite and mixed chalcopyrite-galena ores, only one specimen (740.3), localised from the Belton Grain Vein, has previously been recorded from the district. However, several specimens labelled "Erinite" (568) also proved to be brochantite.

The mineral occurs in a massive form pseudomorphous after galena from the East Stayvoyage, Scar, and Marchbank Veins, and from the same localities, together with the dumps by the side of the road near the Glencrieff Mine, as green crystals associated with linarite, anglesite, and malachite.

Chrysocolla, $CuSiO_3.nH_2O$.

Chrysocolla is a common secondary mineral in the district, forming in chalcopyrite, or mixed chalcopyrite-galena ores. It is particularly abundant in Whytes Cleuch.

The mineral is associated with goethite, and replaces chalcopyrite, and galena, whilst pseudomorphs after malachite occur on the Brow and Long Cleuch Veins. It is bright blue or green in colour, and when not a replacement forms botryoidal aggregates.

THE IRON MINERALS.

Iron minerals are widespread throughout the Leadhills-Wanlockhead district, although generally subordinate in quantity to the lead and zinc minerals. Pyrite and marcasite, together with chalcopyrite, are the principal iron bearing primary minerals, the secondary minerals including the abundant oxides, hematite, and goethite.

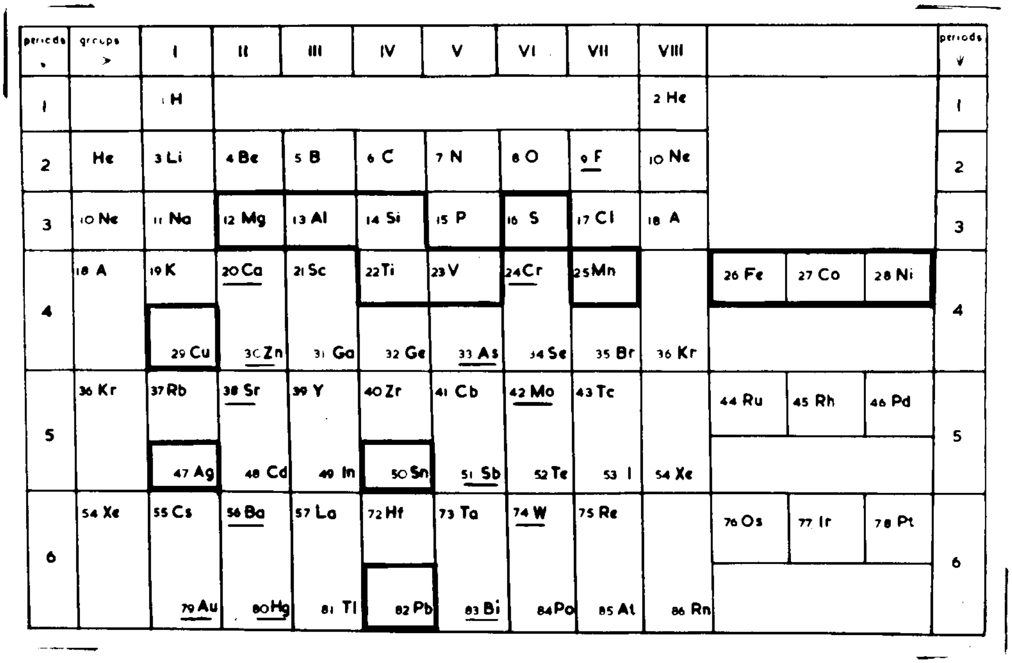
Pyrite, FeS_2.

Pyrite is a very common mineral in the district, occurring both in the country rocks and in the veins. In the veins two distinct generations of pyrite are apparent, the evidence of which will be presented later. The first generation generally occurs replacing ankerite, and is often massive. Pyrite of this nature is to be found in considerable quantities on the large dump at the Glencrieff Mine, and it is probable that it originated from the deeper parts of the vein. The later generation of pyrite is subordinate in quantity to the earlier generation, and often occurs in small pentagonal dodecahedra, encrusting upon sphalerite, calcite, and barytes. Inclusions in calcite give rise to the "ghost" structures of calcite, described below.

Euhedral pyrite crystals are often developed in the greywacke in proximity to the veins. The distribution of the pyrite through the rock is generally regular, and the pyrite crystals are orientated either in response to pressure or to the depositional characteristics of the country rock. An example of the first case is described in a later section. The pyrite is elongated with a diagonal plane parallel to the bedding of laminated sediments, and in a rock of alternating units of fine and very fine grained shaly greywacke, the long axis of the pyrite is generally in the coarser unit. As the pyrite may have inclusions of detritals, and is regularly spaced through the rocks, it is suggested that the mineral originates by reconstitution of the original iron in response to conditions during the commencement of the emplacement of the vein minerals. The orientated pyrite of the laminated rock can be ascribed to migration of iron governed by the bedding, and as the migration would have been facilitated by the coarser grain size, the pyrite was mainly developed in the coarser unit.

Pyrite is abundant in the Caledonian Minor Intrusives in proximity to the veins, and the formation may be genetically connected with the mineralisation, analagous with that of the greywackes. However, sparse pyrite occurs in the Caledonian Minor Intrusives away from the mineral veins, and this, together with the pyrite in the quartz veins of the Long Cleuch and the Lowther Hills, may be of an earlier age than the pyrite described above.

Qualitative spectrochemical analyses of several pyrites revealed the elements listed below. It is worthy of note that although the same elements are present in all, the pyrite of the first generation appears to be enriched in Ni and Co with respect to the pyrite developed in greywacke and Caledonian minor intrusives, and that of the second generation.



periods ↓	groups >	I	II	III	IV	V	VI	VII	VIII		periods ↓
1		1 H							2 He		1
2	He	3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	10 Ne		2
3	10 Ne	11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl	18 A		3
4	18 A	19 K 29 Cu	20 Ca 30 Zn	21 Sc 31 Ga	22 Ti 32 Ge	23 V 33 As	24 Cr 34 Se	25 Mn 35 Br	36 Kr	26 Fe 27 Co 28 Ni	4
5	36 Kr	37 Rb 47 Ag	38 Sr 48 Cd	39 Y 49 In	40 Zr 50 Sn	41 Cb 51 Sb	42 Mo 52 Te	43 Tc 53 I	54 Xe	44 Ru 45 Rh 46 Pd	5
6	54 Xe	55 Cs 79 Au	56 Ba 80 Hg	57 La 81 Tl	72 Hf 82 Pb	73 Ta 83 Bi	74 W 84 Po	75 Re 85 At	86 Rn	76 Os 77 Ir 78 Pt	6

<u>Marcasite</u>, FeS_2.

Marcasite has not been previously recorded from the district. The distribution is limited, and the mineral is not abundant. It was identified in polished section, and confirmed by the X-ray diffraction pattern. The mineral commonly occurs in a massive form. Several radiating structures, of typical marcasite appearance, proved to be pyrite, probably pseudomorphs after marcasite. The mineral was only observed associated with the first generation of pyrite, as inclusions in chalcopyrite and with massive pyrite.

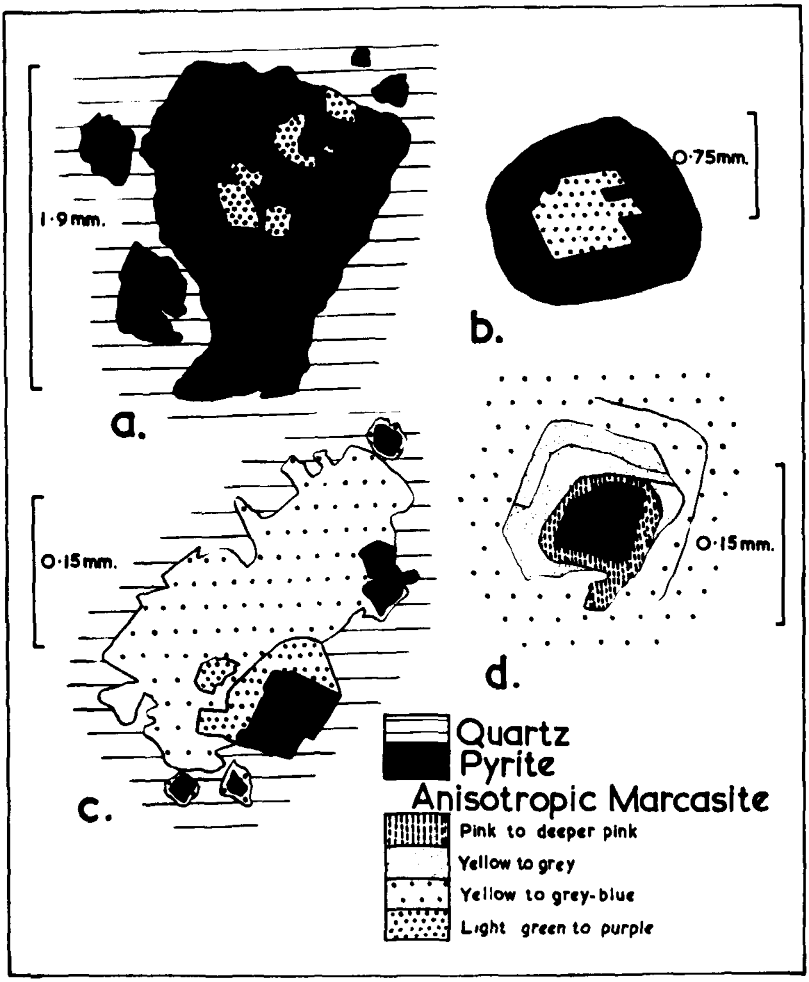


Figure 9. The pyrite-marcasite relationship.

a. Inclusions of marcasite in pyrite, the marcasites extinguishing simultaneously. Glencrieff mine, (P.S. 133).

b. marcasite in pyrite, the rhombohedral outline probably due to replacement of ankerite. Leadhills Dod, (P.S. 106).

c. Pyrite inclusion in marcasite, the degree of anisotropism varying from strong to weak away from the pyrite. Glencrieff mine, (P.S. 113).

d. Pyrite inclusion in marcasite, the degree of anisotropism varying from weak to strong away from the pyrite. Bay Shaft, (P.S. 104).

The anisotropism of the mineral varies, a full list of the variations, from strong to weak, including purple to green, grey-blue to dark yellow, grey to yellow, and light to deep pink.

The pyrite-marcasite relationship.

The relationship of pyrite to marcasite in the massive iron sulphides of the first generation is depicted in Fig.9. No uniform relationship exists. In Fig.9a the inclusions of marcasite in pyrite all extinguish simultaneously, which suggests that all were part of one marcasite crystal replaced by pyrite, whilst in Fig.9d the inclusion of euhedral pyrite in marcasite indicates the converse paragenesis. The latter case is particularly instructive as a change in the anisotropism of the marcasite takes place in well defined zones round the pyrite crystal, grading from a weak to a strong degree of anisotropism. A similar relationship is depicted in Fig.9c, but a zone of strong anisotropism followed by weak anisotropism surrounds the isotropic pyrite.

Laboratory investigations of the pyrite-marcasite relationship (Allen etc. 1912, 1941), have established the fact that acid solutions and low temperatures favour the precipitation of marcasite, whilst alkaline solutions and high temperature favour the precipitation of pyrite. Furthermore marcasite will precipitate even in the presence of pyrite, and at a given temperature the proportion of FeS_2 precipitating as marcasite is an almost linear function of the final acid concentration.

Buerger (1934) explained the relationship by showing marcasite to be more iron rich than pyrite, the acid solutions removing sulphur in the form of H_2S. Anderson and Chesely (1933) showed, by X-ray methods, the transformation of marcasite to pyrite to take place by the formation and growth of pyrite nuclei in the marcasite crystal.

The variations in anisotropism of the Leadhills-Wanlockhead marcasites cannot easily be attributed to variations in the orientations of several marcasite crystals, but can be accounted for by an application of the work of Anderson and Chesely. This would suggest that the variation in the number of pyrite nuclei formed in the marcasite was reflected in the degree of anisotropism, little pyrite being present in the strongly anisotropic marcasite, and considerable pyrite in the weakly anisotropic marcasite. X-ray studies of the various degrees of anisotropism, except the weakest, give a marcasite diffraction pattern without any trace of pyrite. Unless the concentration of pyrite reached a certain point the pyrite pattern would not be reproduced. However, the fact that the weakest anisotropism gives a pyrite pattern supports the work of Anderson and Chesely.

On the basis of the laboratory work of Allen etc., the interpretation can be carried a stage further, and the variations of anisotropism considered to be controlled by variations in the acidity of the depositing solution. Thus the strongly anisotropic marcasite would have been precipitated from a more acid solution that the weakly anisotropic marcasite. Local variation in the pH of the mineralising solution would account for the variation in sequence between pyrite and marcasite.

It would appear, therefore, that in the early stages of the mineralisation the mineralising solutions were partly acid in character, though the abundance of pyrite over marcasite in the first generation would point to the dominance of alkaline solutions. The absence of marcasite from the second generation of iron sulphide suggests precipitation from completely alkaline solutions.

Iron Oxides.

Hematite (Fe_2O_3) and goethite ($HFeO_2$) are extremely common in the gossan zone of the veins, and the hematite stained dumps in Whytes Cleuch and on the East Stayvoyage Vein form distinct features in the landscape. Hematite is generally earthy, but may occur in reniform masses, and has a marked tendency to replace calcite, penetrating into the calcite along the cleavage planes.

Goethite, which includes material formerly designated to "limonite", is to be found on the majority of the dumps, and is often associated with oxidised chalcopyrite, whilst pseudomorphs of goethite after pyrite are abundant throughout the district.

THE DISTRIBUTION OF GOLD.

Small quantities of alluvial gold are reputed to be widespread throughout the district (Watson, 1935), though the only localities where appreciable quantities are found at the present day are the Long Cleuch, and the Windgate Burn. During the strike of 1921 (Brown, 1925, p.76), the Windgate Burn was extensively searched, and the gold appeared to be in pockets, often away from the present course of the burn. The valley is filled with boulder clay, and the pockets of gold reported can be interpreted as the concentrations at meanders of the preglacial stream.

Nuggets of gold bearing quartz have been recorded, and include a specimen found by Mr. G. V. Wilson of the Geological Survey just below the confluence of the Windgate Burn and the Shortcleuch Water. Most of the gold from the Windgate Burn is associated with quartz, which suggests the possibility of gold bearing quartz veins in the area. However, the only gold bearing quartz vein of which mention is made in the literature was that worked at the head of the Long Cleuch by Bulmer, in the 16th century.

Gold associated with the lead-zinc mineralisation apparently does not occur in the district.

OTHER OXIDES.

Quartz, SiO_2.

Quartz is a very abundant gangue mineral in the Leadhills-Wanlockhead district, and is to be found on all the old dumps. The mineral occurs in two distinct varieties, which have a considerable age difference. The first variety is white, massive, and only rarely develops crystal faces. It is often slickensided, and occurs as joint fillings, attaining a width of several inches, and in the veins in brecciated form, or cracked and veined by ankerite, and other minerals. In the large quartz veins with inclusions of brecciated country rock, in the Lowther Hills, the quartz is similar to that described above, and may be of the same age, that is, pre-mineralisation.

The second variety of quartz is a common constituent of the veins, and almost invariably has crystal development. It does not show slickensiding, and is generally colourless, though in the gossan zone it may be yellow to black in colour, owing to inclusions and coatings of goethite and psilomelane. In a blue variety (R.S.M. Dunlop 53), the colour can be attributed to inclusions of galena which have been replaced by covellite, and to small crystals of linarite and caledonite interspersed in the finely crystalline calcite which is encrusting on the quartz.

Quartz replaces many of the earlier formed minerals, and pseudomorphs are abundant, particularly after ankerite and calcite. The replacement relationships of quartz will be discussed more fully in a later section.

Psilomelane.

Psilomelane, a basic oxide of barium, bivalent and quadrivalent manganese, is common in the gossan zone of the majority of the veins, forming hard, black, rounded masses. In Gripps Level, curtains of stalactitic psilomelane are in the process of formation (oral communication by Mr. G. Borthwick). Material from the High Pirn Mine on the Belton Grain Vein analysed by Heddle (1923, p.112), contained manganese, cobalt, copper, barium, potassium, sodium, and silica.

Oxidised ankerite is probably the main source of manganese.

Rutile, TiO_2.

Rutile is often developed in microdiorite dykes which have been affected by mineralising solutions, as in the case of the Wool Gill rock. It forms orientated microscopic needles in altered felspar and biotite, and is associated with carbonate and quartz.

The mineral has not been previously recorded from the locality.

OTHER HALIDES.

Fluorite, CaF_2.

Although a very careful search has been made, both in the present investigation and in routine investigation by the Mining Company, fluorite has not been observed in the district. The only specimen probably from the area was described by Heddle (1923, p.43). The specimen (175.56), presented by Wilson, consists of massive cubes of fluorite, purple at the base, with inclusions of pyrite. On the surface of the cubes are several brown botryoidal masses of vanadinite, similar to those found at the High Pirn Mine on the Belton Grain Vein, which presumably caused Wilson to localise the specimen as (?)Leadhills, and inspired Heddle to further localise the specimen as High Pirn Mine.

Thus there was some original doubt as to whether the specimen originated from Leadhills. Apart from this specimen no other fluorite has been recorded from the locality.

Dunham (1952, p.130), stated that the presence of fluorite had been confirmed by a chemical investigation of samples from mine and washery dumps, carried out by the Lanarkshire Steel Co. Ltd., and the analyses showed appreciable percentages of CaF_2 from localities in both Leadhills and Wanlockhead. However, it is suggested that there is a possibility that the results were calculated from normal oxide analysis, without an estimation of fluorine being made, and that the excess calcium was considered as fluorite. Carbon dioxide to satisfy the excess calcium oxide can be provided by considering the magnesium oxide as present in the mineral ankerite, and not magnesite, a mineral not abundant in the district.

OTHER CARBONATES.

This is an important group of minerals which constitute the greater part of the gangue of the veins. Ankerite and calcite are abundant throughout the whole district, but the remaining carbonates are relatively uncommon.

Ankerite.

Ankerite is an abundant and widespread gangue mineral in the Leadhills-Wanlockhead district. It commonly occurs as a vein filling, cementing fragments of brecciated country rock, and consists of a mass of interlocking rhombs with curved faces. When fresh, the mineral is white or pink in colour, but when

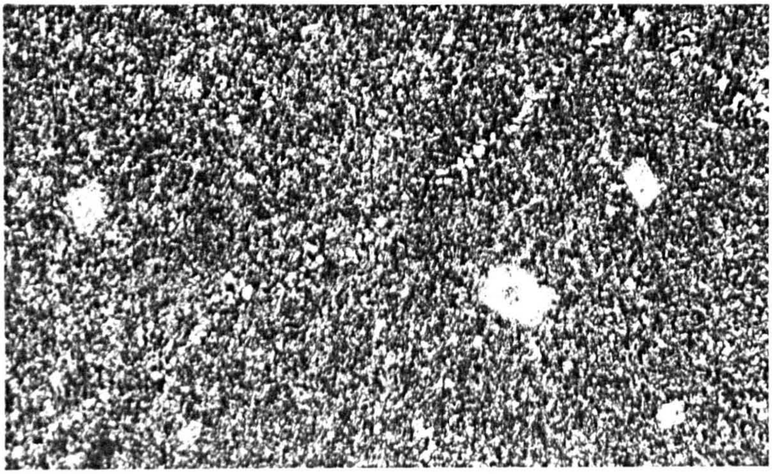


Plate 11.

Isolated rhombs of ankerite in chert, Gripps Level, Glengonnar Water, x90.

exposed to weathering it rapidly takes on a brown colouration. Apart from occurring in the vein fillings, ankerite is developed in country rock which has been exposed to the action of the mineralising solutions, the content of ankerite in the rock decreasing away from the contact with the solutions. This effect is particularly well demonstrated by some breccia fragments of fine grained greywacke, in which the zone of intense ankeritisation is up to a millimeter in width.

In some greywacke ankerite occurs as well developed rhombs, evenly spaced throughout the rock, and it is suggested that this ankerite could have formed by an isochemical change in the rock, the original carbonate in the greywacke.forming the ankerite. This would account for both the euhedral outlines and the regular spacing of the ankerite rhombs. Without chemical analyses this cannot be proved, but support is given by the occurrence of ankerite rhombs in chert (identified by radiolaria), from dumps on the course of Gripps Level on the Abington road, Leadhills. The rhombs in the chert are small and widely spaced, constituting only a slight percentage of the rock. As chert is essentially silica, and contains only a small proportion of admixed shaly material, the restriction of ankerite may be related to the small amount of carbonate originally present in the shaley material, whilst the abundant ankerite in altered greywacke can likewise be regarded as due to a relative abundance of original carbonate. However, in the altered greywackes distinction is difficult between the isochemical formation of ankerite, and introduced ankerite, the latter being dominant in close proximity to the channels of the mineralising solutions, whilst the former may become more dominant with increasing distance from the vein solutions.

The mineral described above was considered by Heddle (1923, p.138) to be dolomite, and he mentions no ankerite from the locality. Wilson (1921, p.17) also regarded the mineral as dolomite. However, analyses, tabulated below, show the mineral to contain appreciable amounts of iron and manganese, and as the minerals therefore belong to the isomorphous series represented by the general formula $(MgCO_3CaCO_3)(FeCO_3CaCO_3)(MnCO_3CaCO_3)(CaCO_3)$, the term ankerite is justified. (Smythe and Dunham, 1947; Dunham, 1948, p.91).

Chemical Analyses of some ankerites

No.	%FeO	%MnO	$\%FeCO_3$	$\%MnCO_3$
1.	4.57	1.25	7.38	2.02
2.	6.36	1.36	10.27	2.20
3.	9.25	2.48	14.92	4.03
4.	6.72	1.35	10.86	2.19
5.	7.36	1.82	11.88	2.95
6.	5.19	1.47	8.36	2.48
7.			5.72	1.37

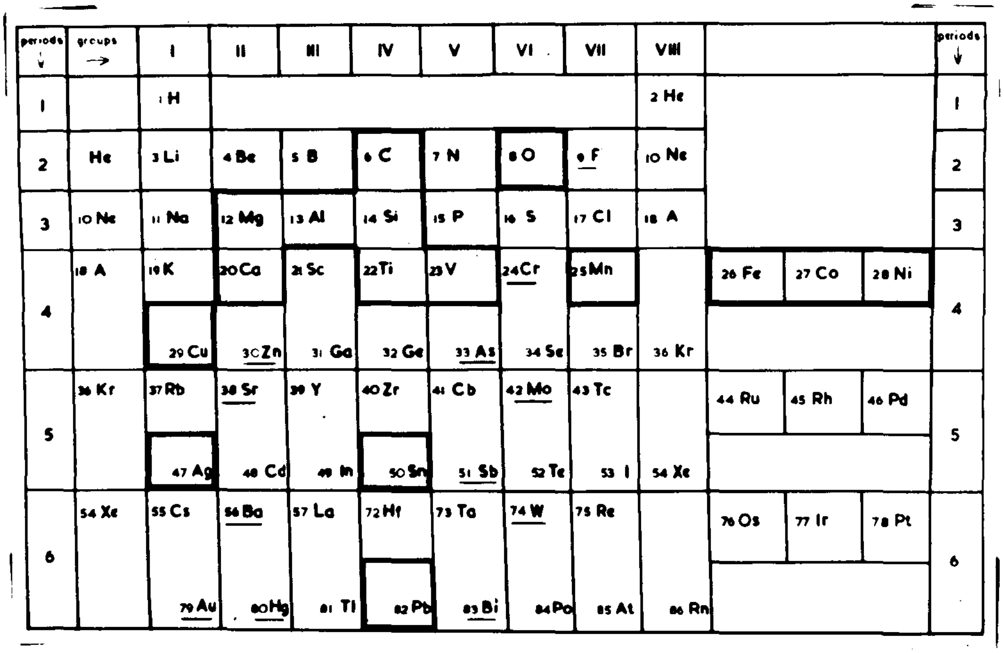
1. Pink, Meadowhead Vein.
2. Slightly pink, Wilsons Shaft.
3. Brownish-white, Glencrieff Mine.
4. White, Glencrieff Mine.
5. Brownish-white, Laverock Hall Vein.
6. Black Craig Mine, Kirkcudbright.
7. ditto.

from Heddle (1923, p.137).

A striking fact is the relative uniformity in the iron and manganese content over the whole of the Leadhills-Wanlockhead district, and the similarity with the ankerites from the Black

Craig Mine, Kirkcudbright. This similarity could be accounted for by two factors, one being a common, or similar, source of origin of the minerals, and the second being the similarity in rock type over a wide area, so that if the iron and manganese content is attributed to contamination by the country rock, the contamination would have been of a similar nature over a large area. Wager (1929, p.105) attributed the iron in the ankerites of the north Pennine orefield to contamination by the iron rich rocks formed by the metasomatic effect of the Whin Sill, this being supported by Smythe and Dunham (1947, p.72), who further suggested that magnesia was supplied from the same source.

Elements in Ankerite.



periods ↓	groups →	I	II	III	IV	V	VI	VII	VIII				periods ↓
1		1 H							2 He				1
2	He	3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	10 Ne				2
3	10 Ne	11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl	18 A				3
4	18 A	19 K 29 Cu	20 Ca 30 Zn	21 Sc 31 Ga	22 Ti 32 Ge	23 V 33 As	24 Cr 34 Se	25 Mn 35 Br	36 Kr	26 Fe	27 Co	28 Ni	4
5	36 Kr	37 Rb 47 Ag	38 Sr 48 Cd	39 Y 49 In	40 Zr 50 Sn	41 Cb 51 Sb	42 Mo 52 Te	43 Tc 53 I	54 Xe	44 Ru	45 Rh	46 Pd	5
6	54 Xe	55 Cs 79 Au	56 Ba 80 Hg	57 La 81 Tl	72 Hf 82 Pb	73 Ta 83 Bi	74 W 84 Po	75 Re 85 At	86 Rn	76 Os	77 Ir	78 Pt	6

Calcite, $CaCO_3$.

Calcite is a common gangue mineral in most veins of the Leadhills-Wanlockhead district. It occurs in massive form as a vein filling, cementing brecciated fragments of country rock, and, in cavities, crystal faces are developed. The mineral is associated chiefly with ankerite, barytes, galena, sphalerite, and chalcopyrite.

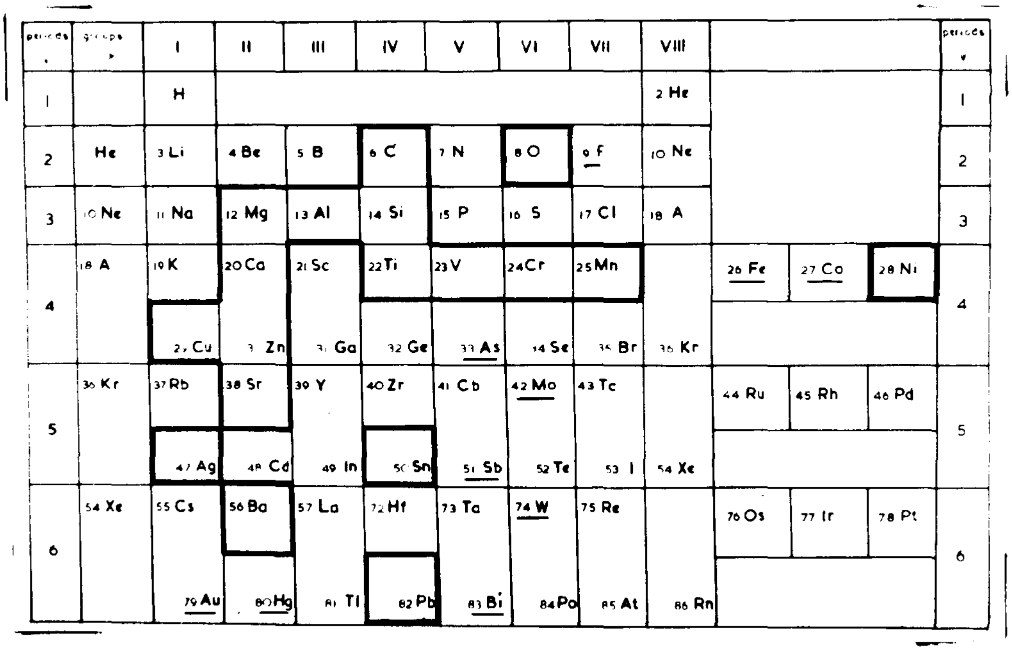
The variety of crystal types in the area is great, and many have been listed by Heddle (1923, pp.133-135). Two varieties may be mentioned, one being the superposition of a "nail head" type upon a "dog tooth" type (1923,3.8), the form of the latter being clearly visible as its surface is coated with small crystals of pyrite. The other form was not described from the locality by Heddle, though he did note a similar variety from Unst (1923, p.129). It was found on the dumps of the Bay Shaft, and is characterised by a flat termination and the dominance of the trigonal prism. The crystal belongs either to the 6m2 or the 3m symmetry groups, but as only one termination was visible assignation to either group is rendered difficult.

A large proportion of the massive variety of calcite is pink in colour, and analysis of an example from the Glencrieff Mine, Wanlockhead, showed the calcite to contain 0.76% MnO. Manganoan calcite has been recorded from numerous localities (Dana, 1951, p.153), manganese substituting for calcium in the structure.

Analyses of plumbocalcite from Leadhills and Wanlockhead have been given by Collie (1889, p.95), and Heddle (1924, p.136), the highest percentage of lead determined being 9.5% $PbCO_3$. Siegl (1936) records the presence of 26% $PbCO_3$ in plumbocalcite from Tsumeb, which consisted of an intergrowth of minute crystals of cerussite in calcite. Material labelled "Plumbocalcite" in the Scottish Mineral Collection (1952.6.1; 270.635) contained lead, and the diffraction pattern showed the mineral to have a slightly larger unit cell than normal calcite, which indicates the substitution of lead for calcium. The form of this variety was an aggregate of curved rhombs.

Other elements commonly present in calcite include Cu, Ag, Mg, Zn, Sr, Ba, Al, Si, Ti, V, and Mn.

Elements detected in calcites.



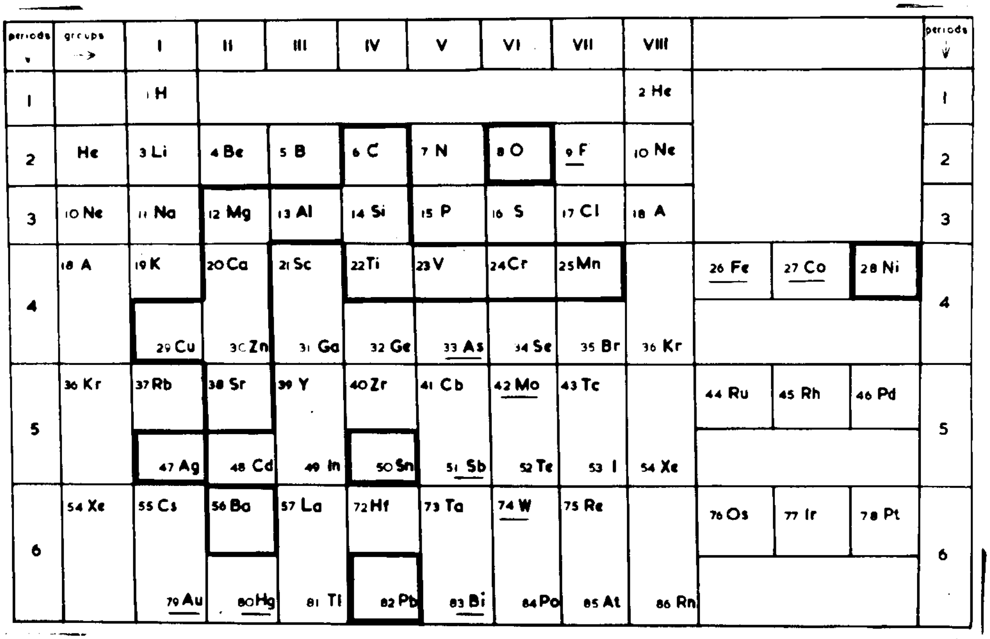
Aragonite, $CaCO_3$.

Aragonite is a relatively rare gangue mineral in the Leadhills-Wanlockhead area. The greatest abundance has been recorded from the New Glencrieff Vein, but the mineral has been collected from the dumps on several veins, notably Georges Roust and Laverock Hall Veins. Aragonite is commonly in the form of radiating groups of elongated white or colourless crystals, which have developed in vughs in the veins. Brown (1918, p.132) described a vugh 6' long, 6' deep and 2' wide, between the 80 and 120 fathom levels in the New Glencrieff Vein, in which the walls were covered with aragonite and cerussite. The mineral is associated with all the other primary minerals.

Varieties of aragonite include plumboaragonite, and blue aragonite (277.11). The latter was associated with chalcopyrite, and qualitative spectrochemical analysis revealed an appreciable amount of copper in the mineral, which presumably is the colouring agent. Plumbo aragonite was first described from the locality by Collie (1889, p.95), who in two analyses found the mineral to contain 0.8% and 1.8% of lead carbonate. A specimen of massive aragonite, named as plumboaragonite from the Brow Vein, was presented to the writer by Mr. J. Blackwood of Leadhills, and qualitative analysis confirmed the presence of lead. The diffraction pattern of the mineral was the same as normal aragonite. Siegl (1936) described plumbo aragonite, or tarnowitzite, from Tsumeb, with 3.12% lead carbonate isomorphously replacing calcium carbonate, and although the material varied considerable from aragonite in refractive indices and specific gravity, there was little variation in the unit cell measurements.

Other elements present in the Leadhills-Wanlockhead aragonites include Ag, Mg, Sr, Ba, Zn, and Al.

Elements in Aragonite.



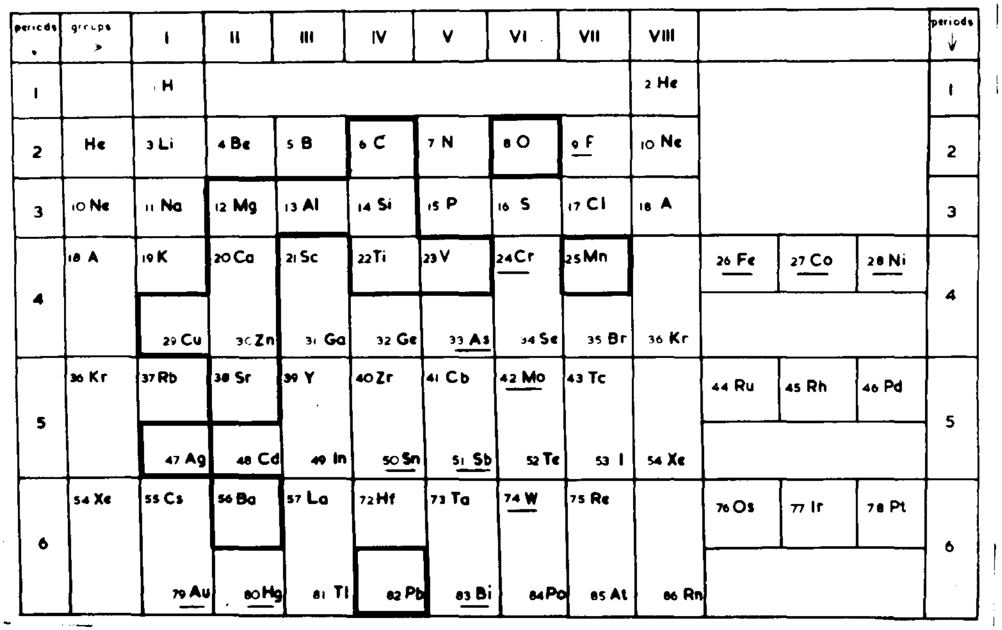
periods ↓	groups →	I	II	III	IV	V	VI	VII	VIII		periods ↓
1		1 H							2 He		1
2	He	3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	10 Ne		2
3	10 Ne	11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl	18 A		3
4	18 A	19 K 29 Cu	20 Ca 30 Zn	21 Sc 31 Ga	22 Ti 32 Ge	23 V 33 As	24 Cr 34 Se	25 Mn 35 Br	36 Kr	26 Fe 27 Co 28 Ni	4
5	36 Kr	37 Rb 47 Ag	38 Sr 48 Cd	39 Y 49 In	40 Zr 50 Sn	41 Cb 51 Sb	42 Mo 52 Te	43 Tc 53 I	54 Xe	44 Ru 45 Rh 46 Pd	5
6	54 Xe	55 Cs 79 Au	56 Ba 80 Hg	57 La 81 Tl	72 Hf 82 Pb	73 Ta 83 Bi	74 W 84 Po	75 Re 85 At	86 Rn	76 Os 77 Ir 78 Pt	6

<u>Witherite</u>, $BaCO_3$.

The first specimens of witherite recorded in Scotland were found in the West Branch of the New Glencrieff Vein in the early months of 1918 (Brown, 1918, p.128). The mineral occurred on the walls of a large vug, and was associated with calcite, barytes, and galena. Barytes was dominant near the top of the vug, witherite at the base, which, together with their appearance led Brown to suggest that the witherite was "pseudomorphous", and was formed by downward flowing solutions. The mineral formed globular masses, up to a foot in diameter, small pseudo hexagonal crystals sometimes having developed on the exterior of the globules. Witherite was also found in the Wembley Shaft, Leadhills, in massive crystalline aggregates.

Qualitative spectrochemical analyses of witherites from the Wembley Shaft revealed the presence of Ag, Mg, Ca, Sr, Zn, Al, Si, Pb, and V.

Elements in Witherite.



periods ↓	groups →	I	II	III	IV	V	VI	VII	VIII				periods ↓
1		H							2 He				1
2	He	3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	10 Ne				2
3	10 Ne	11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl	18 A				3
4	18 A	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn		26 Fe	27 Co	28 Ni	4
		29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr				
5	36 Kr	37 Rb	38 Sr	39 Y	40 Zr	41 Cb	42 Mo	43 Tc		44 Ru	45 Rh	46 Pd	5
		47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe				
6	54 Xe	55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re		76 Os	77 Ir	78 Pt	6
		79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn				

Strontianite, $SrCO_3$.

Strontianite has been recorded from the locality by Collie (1889, p.96) as solid brown crystalline masses, but Heddle (1923, p.143) observes that strontianite noticed by Walker in 1761 at Leadhills had unquestionably been brought by miners from Strontian. Watson (1937) also states that the presence of strontianite was recorded from the Wembley Shaft.

Although an intensive search has been made, it has not been possible to confirm the presence of strontianite in the district.

Magnesite, $MgCO_3$.

Similarly the presence of magnesite has not been confirmed, although Heddle (1923, p.139) states that the mineral occurs, very rarely, in the Bay Vein.

OTHER SULPHATES.

Barytes, $BaSO_4$.

Barytes is the only primary sulphate in the district, and occurs in most of the veins, with the exception of those to the east of the Risping Cleuch.

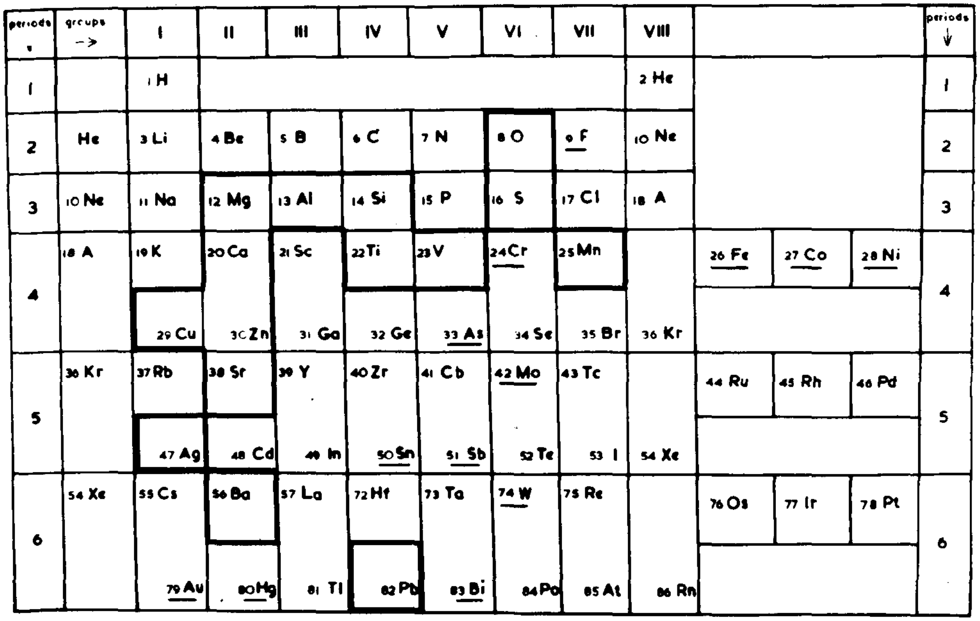
Massive barytes in the veins is associated with galena or sphalerite on either the foot or hanging walls, or may be filling small fissures in the bulk of the vein. Crystal faces are commonly developed in vugs, and many of the considerable number of variations in form have been listed by Heddle (1924, pp.168, 169). The dump at the Wembley Shaft, Leadhills, affords excellent examples of barytes crystals.

Variations of colour in barytes include colourless, white, green, yellow, and blue. Barytes from the Bay Shaft (719.134) is associated with sphalerite, and the barytes crystals have yellow tips, which may be due to either iron or cadmium derived from small inclusions of sphalerite in the barytes.

Iron as the colouring agent is supported by yellow barytes encrusting upon calcite and pyrite (719.149). Green varieties from the Wembley Shaft, associated with calcite, were found to contain more strontium than colourless barytes, and the green colour may be a function of the strontium content. Blue tabular crystals from the New Glencrieff Mine (719.140) have minute inclusions of either galena or pyrite. If the former, the blue colouration may be analogous to that described for blue quartz, namely attributed to copper, derived from the replacement of galena by covellite. Blue varieties of barytes formed by the action of sunlight on yellow barytes have been described by Sweet (1931).

The minor elements incorporated in barytes from the district include Cu, Ag, Mg, Ca, Sr, Ba, Zn, Pb, and V.

Elements in Barytes.



periods ↓	groups →	I	II	III	IV	V	VI	VII	VIII		periods ↓
1		1 H							2 He		1
2	He	3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	10 Ne		2
3	10 Ne	11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl	18 A		3
4	18 A	19 K 29 Cu	20 Ca 30 Zn	21 Sc 31 Ga	22 Ti 32 Ge	23 V 33 As	24 Cr 34 Se	25 Mn 35 Br	36 Kr	26 Fe 27 Co 28 Ni	4
5	36 Kr	37 Rb 47 Ag	38 Sr 48 Cd	39 Y 49 In	40 Zr 50 Sn	41 Cb 51 Sb	42 Mo 52 Te	43 Tc 53 I	54 Xe	44 Ru 45 Rh 46 Pd	5
6	54 Xe	55 Cs 79 Au	56 Ba 80 Hg	57 La 81 Tl	72 Hf 82 Pb	73 Ta 83 Bi	74 W 84 Po	75 Re 85 At	86 Rn	76 Os 77 Ir 78 Pt	6

Plate III.

Albite and white mica in vein with quartz,
Glencrieff Mine, Wanlockhead, x90.

Thin, colourless, hexagonal plates of barytes were observed from the Brow Vein, encrusting on malachite crystals associated with chrysocolla. This barytes must be of a secondary, or supergene, origin.

Gypsum, $CaSO_4 . 2H_2O$.

Brown (1925, p.79) includes gypsum in the list of minerals from the locality, but does not describe its occurrence. The only gypsum observed was small, white, elongated, striated crystals, on ankerite, from the Glencrieff Mine. The Mineral is probably of secondary origin.

OTHER SILICATES.

Silicates in the veins associated with other gangue minerals are very rare in the district. Albite and white mica (Plate 3), occur in a specimen from the Glencrieff Mine, and are associated with quartz and ankerite. The albite has a 2V of 77°, albite twinning, and approximates to the composition $Ab_{96-98}An_{4-2}$. Owing to the small amount of material, the composition of the mica could not be determined, and from its optical properties could be either muscovite (potash bearing), or paragonite (soda bearing) (Winchell, 1951, p.370).

Albite occurs in some, and white mica in all, of the Caledonian dyke rocks in the district, fully described in an earlier section, whilst small quantities of muscovite (checked by the diffraction pattern), occur in the quartz veins outcropping in the Lowther Hills and the Long Cleuch.

As all the above mentioned occurrence of albite and white mica are associated with quartz of pre-main mineralisation age (see description of quartz, above), the minerals may be of an earlier date than the main mineralisation.

Finely divided white mica, or sericite, is a common constituent of country rocks which have been altered by the mineralising solutions.

Chlorite is also commonly developed in country rocks which have been subjected to the effects of mineralising solutions, and varies from a massive green variety, to euhedral crystals, which are brown in colour.

One particular occurrence of chlorite may be mentioned. The mineral was collected from a dump on Gripps Level on the Abington Road, and is associated with pyrite and quartz, in chert. The minerals are in nodular forms, the largest nodule being 15 mm. in diameter. The centre of the nodule is made up of radiating pyrite, the chlorite being on the periphery of the pyrite, and orientated in such a manner that the chlorite crystals appear to continue the pyrite lamellae. Quartz pseudomorphously replaced the chlorite. The chlorite is white in colour, and the diffraction pattern closely resembles that of chlorite described from Ducktown, Tennessee (McMurchy, 1934). Qualitative spectrochemical analysis revealed that the mineral contained abundant magnesium, little calcium, and abundant aluminium, silica, and iron, with trace amounts of copper and nickel.

Similar rounded cavities containing remnants of pyrite and quartz were observed in chert from the south-west flanks of

Hunt Law, and it is considered probable that they represent altered concretionary bodies.

THE DISTRIBUTION OF PHOSPHORUS.

Phosphorus, in the form of phosphates, is abundant, and widely distributed throughout the area in the pyromorphite group. Other phosphates have been recorded, but are rare.

The Pyromorphite Group.

Pyromorphite, together with cerussite, is the commonest secondary mineral in the district, and is present on the majority of the old dumps, particularly good localities being the High Pirn Mine on the Belton Grain Vein, and the shallow workings on the Sarrowcole Vein. The pyromorphite occurs in two forms, one having hexagonal crystals and being either green, yellow, or orange in colour, generally formed in small cavities, and associated with galena and cerussite, whilst the second form is usually massive, varying in colour from black to white, and often pseudomorphously replacing galena or cerussite. The latter variety may crystallize in small radiating aggregates of hexagonal crystals, white to yellow-green in colour, numerous examples occurring on the dumps in Whytes Cleuch.

X-ray examination of over a hundred pyromorphites demonstrated that on structural grounds the group was divisible into two, and that the two groups corresponded to the two varieties mentioned above. A typical member of each variety was selected for further investigation, the first variety, or group one, being represented by aggregates of orange hexagonal crystals,

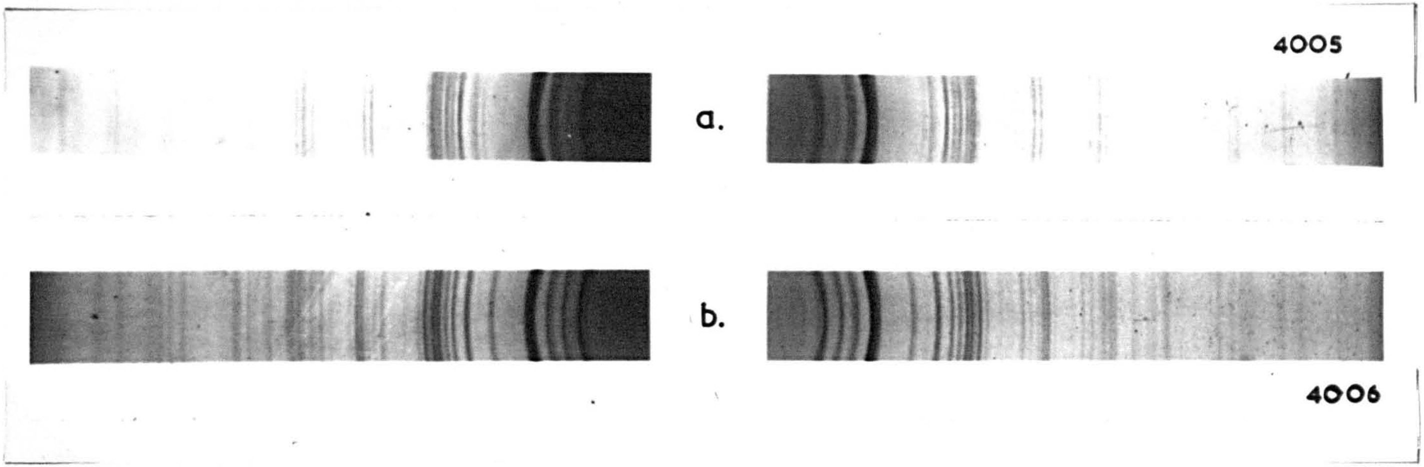


Plate IV.

The Pyromorphite Group.

a. Group 1, Pyromorphite, Susanna Vein, Leadhills,
Film No.4005.

b. Group 2, Polysphaerite, Whytes Cleuch, Wanlockhead.
Film No.4006.

up to a centimetre in length, from the Susanna Vein. The massive variety, or group two, was represented by a pseudomorph after cerussite which had originally pseudomorphously replaced galena, from Whytes Cleuch. In thin section the mineral was massive, almost isotropic, and green in colour, the cubic cleavage of the original galena being discernible. Around the edge of the massive mineral were numerous small closely packed, hexagonal crystals, white in colour, with high relief, weak birefringence, and uniaxial negative.

Group 1.
3632. Orange Hexagonal crystals, Susanna Vein.

1.	dA
vw.	4.97
fs.	4.28
fs.	4.10
vw.	3.67
fs.	3.36
fs.	3.14
vs.	2.95
fs.	2.86
vw.	2.25
w.	2.19
vw.	2.11
fs.	2.05
m.	1.99
m.	1.95
m.	1.90
m.	1.87
m.	1.85
w.	1.82
vw.	1.69
vw.	1.67
w.	1.62
w.	1.59
m.	1.53
m.	1.50
vw.	1.35
m.	1.33
m.	1.31
m.	1.29

Group 2.
2254. Massive variety, Whytes Cleuch.

1	dA
vvw.	4.95
vvw.	4.22
fs.	4.07
m.	3.57
vw.	3.30
vw.	3.19
vs.	2.92
vvw.	2.83
w.	2.37
m.	2.12
w.	2.02
w.	1.96
m.	1.91
m.	1.88
m.	1.81
vvw.	1.70
vvw.	1.64
vvw.	1.60
vw.	1.59
vvw.	1.55
w.	1.50
w.	1.48
vvw.	1.45
vvw.	1.38
vw.	1.36
vw.	1.33

Occasional inclusions of cerussite, distinguished from other carbonates by the high relief, were present in the pyromorphite.

The X-ray diffraction patterns of the two groups are listed above, and although the spacing of some lines is similar, the intensities are at variance, a characteristic difference being the strength of the line 3.57 in group two, as compared to the corresponding line in group one. A comparison of the spacing of corresponding lines establishes the fact that the unit cell of group two is slightly smaller than that of group one (e.g., the strongest line, 2.95 dA(1), against 2.92 dA(2)).

Chemical Analyses of some Pyromorphites.

	1	2	3	4	5
PbO	81.76	81.33	70.12	52.64	72.70
CaO			9.51	12.30	7.82
P_2O_5	16.34	16.11	18.15	19.80	13.22
As_2O_5		0.13		4.06	
V_2O_5					2.93
Cl	2.60	2.71	2.44	1.95	2.30
Cr_2O_3	0.20				
CuO					1.60
CO_2			tr.		
Rem.				9.64	0.60
	100.80	100.28	100.22	100.39	101.17
O=Cl	0.59	0.61	0.56	0.44	0.52
	100.21	99.67	99.76	99.95	100.65

1. Gp.1, Orange crystals, Susanna Vein, Leadhills (A.K.T.).
2. Wissen, Germany (Dana, 1951, p.892).
3. Gp.2, Massive green, and white crystals, Whytes Cleuch (A.K.T.).
4. Polysphaerite, Nussieres (probably impure. Dana, 1951, p.892).
5. Colleite, Leadhills, calculated from Collie (1899).

The chemical analyses (listed above) show a major difference in the groups, the group two representative (no.3), containing 9.51% of calcium oxide. Examination in thin section reveals the absence of calcium minerals, whilst the trace of carbon dioxide is accounted for by the interstitial cerussite, which may slightly affect the accuracy of the lead determination. Pyromorphite rich in calcium has been previously described, the varieties "colleite" from Leadhills, by Collie (1899), and "polysphaerite" from Mussieres by Barruel (1836). Both analyses are given for comparison with the Wanlockhead specimen. Colleite (522.10) proved to be a member of the descloizite group, and was not the material analysed by Collie.

Qualitative Spectrochemical Analyses of Pyromorphites.

No.	Cu.	Ag.	Mg.	Ca.	Zn.	Al.	Si.	V.	As.	Cr.	Mn.
1.	1	0	2	1	?	0	2	00	0	1	1
2.	0	0	1	0	?	0	1	?	?	0	1
3.	0	0	1	1	?	0	2	0	0	2	1
4.	0	0	2	0	?	1	1	1	0	0	1
5.	0	0	1	0	?	0	1	0	?	0	1
6.	0	0	1	0	?	0	1	0	?	?	1
7.	3	0	1	3	?	0	1	0	?	?	2
8.	4	0	2	4	0	1	1	0	0	?	3
9.	5	0	2	5	?	1	2	0	0	0	1
10.	5	0	2	5	?	2	1	0	0	0	1
11.	3	0	1	3	?	0	2	0	0	1	1
12.	3	0	1	3	?	0	2	0	?	?	1

1.	Gp.1.	Orange crystals, Susanna Vein.
2.	"	Yellow-green crystals, High Pirn Mine.
3.	"	Orange crystals, Susanna Vein.
4.	"	Pseudomorph after cerussite, Hopeful Vein.
5.	"	Green crystals, East Stayvoyage Vein.
6.	"	Yellow crystals, Glencrieff Mine.
7.	Gp.2.	White crystals, Whytes Cleuch.
8.	"	Massive black, Whytes Cleuch.
9.	"	Massive green, Whytes Cleuch.
10.	"	Massive green, High Pirn Mine.
11.	"	Massive orange-green, Broad Law.
12.	"	Yellow-green crystals, Glencrieff Mine.

? = not certain that element is present.
0 = element definitely present, numbers indicate relative abundance, estimated visually.

The group one pyromorphite appears in its major constituents to approximate closely to the calculated formula, and is compared with a pyromorphite from Wissen, Germany (Dana, 1951, p.892). The Chromium variety is common in the Leadhills-Wanlockhead district. Other chromium bearing pyromorphite has been reported from Beresovsk, by Chirva (1935), who did not note any relationship between colour and chemical composition.

Further minor variations in the diffraction patterns of the two groups were noticed, and accordingly qualitative spectrochemical analyses of 12 pyromorphites were made, tabulated above. Differences in the minor element content between the two groups, and in each individual group were apparent, the most striking result being the enrichment of copper, with calcium in the group two representatives. Copper was estimated by Collie in the calcium rich pyromorphite from Leadhills, and the presence of copper was also recorded by Chirva in a light green-blue pyromorphite. Arsenic and vanadium show sporadic distribution in and between both groups. The occurrence of chromium is likewise independent of either group, and is significantly present in the orange coloured variety, suggesting that chromium is the colouring agent of such pyromorphites. Manganese is enriched in the black massive specimen and in the white crystals of group two, but in the first case may be partly due to the presence of psilomelane. Barium and silver are present in trace amounts in all the minerals examined. Aluminium, silica, and magnesium are probably impurities, though all three can substitute in the apatite group, of which pyromorphite is a member. The presence of zinc in one case can be attributed to impurity.

Calcium must be present in substitution for lead, whilst the similarity in the ionic radii of calcium (1.06 kX) and copper (0.96 kX), together with the general sympathy in occurrence, suggests that copper substitutes for calcium in the structure. As calcium has a smaller ionic radius than lead (1.32 kX), the substitution of calcium for lead may be the major factor in the structural differences between the two groups, and accounts for the smaller unit cell of the calcium rich group two. Subordinate variations in the structure may be attributed to the substitution of arsenic, vanadium, chromium, and possibly silica, for phosphorus, whilst manganese, magnesium, and barium may also affect the structure.

This brief survey of the pyromorphites therefore reveals that the group is divisible on a structural basis, into two groups, one characterised by hexagonal crystal form, the other commonly massive but also present as hexagonal crystals. The structural difference between the two groups is attributed to the presence of calcium in the second group, whilst minor structural variations are due to several other elements, of which arsenic and vanadium are predominant.

A complete series between pyromorphite ($Pb_5(PO_4)_3Cl$.), and calcium rich pyromorphite probably exists. The name polysphaerite (Breithaupp, 1832, in Dana, 1951B, p.892), has priority in the nomenclature of the calcium rich variety, and it is suggested that the structural differences between the two groups allow the retention of the name polysphaerite as the end member of a series in which calcium substitutes for lead in pyromorphite.

The exact limit of the series is not easily defined, the Ca:Pb ratios of the Leadhills mineral being 1:1.71, that of Collie, 1:2.16, whilst the impure material from Nussieres is 1:1.1. With increase of calcium beyond Ca:Pb = 1:1, mimetite passes into hedyphane ($(PbCa)_5(AsO_4)_3Cl$), but the phosphate analogue of hedyphane has not been described, and, according to Dana (1951, p.891), a complete series apparently does not exist in natural material between calcium varieties of pyromorphite and chlorapatite ($Ca_5(PO_4)_3Cl$). It will be seen, therefore, that without further knowledge, the limit of the calcium for lead substitution in the pyromorphites cannot be defined. The association of polysphaerite with apatite may indicate that the ultimate end of the calcium for lead substitution in pyromorphite is a calcium phosphate, the chloride group having been lost.

A white mineral from Whytes Cleuch, Wanlockhead (loc.26), on examination proved to be a further lead phosphate. Small quantities of the mineral are associated with polysphaerite, forming a pseudomorph after galena. The diffraction pattern, listed below, compares closely with that of basic lead phosphate ($2(Pb_5(PO_4)_3(OH))$), named by Hey (1950, p.219), as lead hydroxyapatite, and recorded only as an artificial mineral. The mineral appears to represent a further substitution in the pyromorphite group, the hydroxyl group substituting for chloride.

3296. Whytes Cleuch. $2(Pb_5(PO_4)_3(OH))$, A.S.T.M. index.

1	dA	1	dA
fs.	4.06	24	4.03
vw.	3.56	16	3.61
vw.	3.18	16	3.18
vs.	2.92	100	2.91
vw.	2.82	8	2.82
vvw.	2.68*		
vw.	2.37*		
w.	2.20*		
w.	2.13	8	2.15
w.	2.02	16	2.02
vvw.	2.01*		
vw.	1.96	8	1.96
w.	1.91	16	1.91
vw.	1.88	8	1.86
vw.	1.82	16	1.82
vvw.	1.77*		
vvw.	1.75*		
vvw.	1.68*		
vw.	1.56	8	1.57
vw.	1.51	16	1.51
vvw.	1.47	8	1.48

"A.S.T.M." is the "American Society of Testing Materials".
* Probably impurities.

Plumbogummite $(PbAl_3(PO_4)_2)OH)_5H_2O)$, not previously recorded from the Leadhills-Wanlockhead district, was the only other phosphate found. It occurs as a blue botryoidal crust associated with pyromorphite, mimetite, and cotunnite (1926.2.15), from the High Pirn Mine on the Belton Grain Vein, and also as a brown botryoidal mineral associated with plattnerite from the dumps of the Raik Vein to the north of Mine Hill.

THE DISTRIBUTION OF ARSENIC.

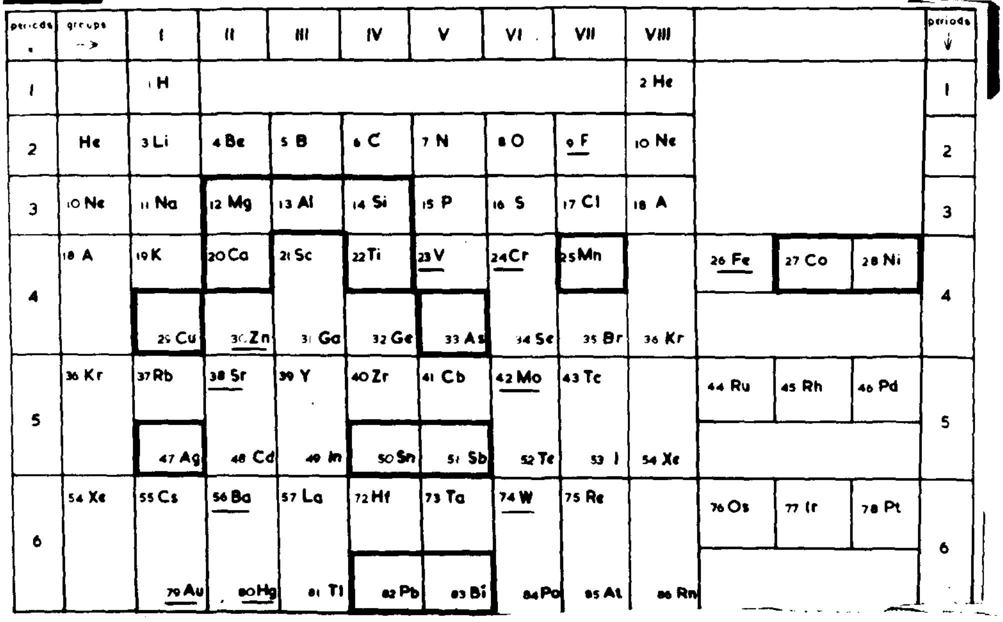
Although arsenic is a rare element in the Leadhills-Wanlockhead district, several minerals have been recorded in which arsenic is a major constituent. Such minerals occur only in small quantities, but include both primary arsenides, and secondary arsenates.

The only arsenides previously noted from the area are Niccolite (NiAs), and cobaltite (CoAsS). Niccolite was mentioned by Heddle (1923, p.27), whilst Brown (1925, p.75) reported the mineral to come from number four level on the West Branch of the New Glencrieff Vein. He further recorded the presence of cobaltite in the dressing floors of the Glencrieff Mine. Owing to the inavailability of material, cobaltite was not confirmed in the present investigation.

Niccolite from the Glencrieff Vein (1952.5.18), has a rounded or "pseudo conglomeratic" form, and is in contact with brecciated fragments of country rock, a fine grained, shaley greywacke. Niccolite from Cassencarrie, Kirkcudbrightshire (71.4), has a similar form.

A qualitative spectrochemical analysis of niccolite from the Glencrieff Mine revealed the presence of Cu, Ag, Mg, Ca, Al, Si, Ti, Sn, Pb, As, Sb, Bi, Mn, Co, and Ni. Of these elements, all except Ni, Co, As, Sb, Bi, and Sn, could be impurities.

Elements in Niccolite.



periods	groups -->	I	II	III	IV	V	VI	VII	VIII				periods ↓
1		1 H							2 He				1
2	He	3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	10 Ne				2
3	10 Ne	11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl	18 A				3
4	18 A	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn		26 Fe	27 Co	28 Ni	4
		29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr				
5	36 Kr	37 Rb	38 Sr	39 Y	40 Zr	41 Cb	42 Mo	43 Tc		44 Ru	45 Rh	46 Pd	5
		47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe				
6	54 Xe	55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re		76 Os	77 Ir	78 Pt	6
		79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn				

In polished section a mineral on the edge of, and partly veining the niccolite is visible. The mineral has a clearly defined, irregular, junction with the niccolite. The mineral is of a strong white colour, against which galena appears light grey. It is of similar hardness to niccolite, and is anisotropic. Although the maximum width of the mineral is only 0.1 mm., successful etch tests were made (method of Short, 1940). The mineral effervesced, and was stained brown with nitric acid, slightly stained brown with ferric chloride, slightly tarnished with mercuric chloride, and had no reaction with hydrochloric acid,

Glencrieff Mine		Rammelsbergite (Peacock & Dadson, 1940).	
I	dA	I	dA(Calc.)
vw.	3.65	m.	3.68
w.	3.01	vw.	3.01
vs.	2.84	s.	2.84
m.	2.65		
vs.	2.54	s.	2.55
s.	2.45	s.	2.47
vvw.	2.36	vw.	2.39
vw.	2.18	w.	2.21
w.	2.01	w.	2.03
m.	1.96		
s.	1.85	s.	1.87
w.	1.80	w.	1.79
w.	1.76	m.	1.76
m.	1.68	m.	1.69
w.	1.61	m.	1.63
w.	1.58	m.	1.59
vw.	1.51	m.	1.54
m.	1.43	s.	1.44
vw.	1.37	vw.	1.38
vw.	1.32		
vvw.	1.26		
vvw.	1.24		
vw.	1.22	m.	1.24
w,	1.15	m.	1.16
vvw.	1.11	w.	1.12
vvw.	1.09	w.	1.10
vvw.	1.06	w.	1.07
vw.	1.05	w.	1.05
vw.	1.03	w.	1.04
vw.	1.01	m.	1.02
vw.	1.00	m.	1.01

potassium cyanide, or potassium hydroxide. The description of the mineral resembles that of either rammelsbergite or pararammelsbergite (Uytenbogaardt, 1951, p.154), and rammelsbergite ($NiAs_2$) was confirmed by the X-ray diffraction pattern, which compares favourably with that given (above) by Peacock and Dadson (1940).

Rammelsbergite has not been previously confirmed as occurring in the British Isles, although in Heddle (1924, p.195) it is pointed out by Goodchild that on one of the tickets of the Scottish Mineral Collection (602.3), rammelsbergite is stated to occur with niccolite at "Menimuir Burn, Cassencarrie". From an investigation of some Scottish Mineral Collection specimens, rammelsbergite was recorded in three instances, viz., 71.4 (Cassencarrie, Kirkcudbrightshire), 602.3 (queried locality Hilderston, Linlithgowshire), and 602.4 (queried locality Cassencarrie). In all three cases rammelsbergite is associated with Niccolite, and has the same relationship towards it as has been described above.

Both niccolite and rammelsbergite from the Glencrieff Mine are cut by narrow veinlets, 0.01 - 0.02 mm. in width, occupied by a light grey-brown mineral, which is probably similar to galena in colour, though direct comparison cannot be made. The mineral is isotropic. It is slightly harder than niccolite and rammelsbergite, and has a lamellar structure, with imperfectly developed cleavage, which appears to have a rhombic outline. Etch reactions were attempted, and the mineral stained brown with nitric acid and mercuric chloride, there being no reaction with hydrochloric acid, potassium cyanide, pottassium hydroxide, or ferric chloride. The description resembles that of Gersdorffite (NiAsS), and further likeness is supplied by the effect of saturated potassium permanganate, which stains the mineral dark brown, a reaction given by Utyenbogaardt (1951, p.159) as typical of gersdorffite. However, owing to the small amount of the mineral, confirmation by the X-ray diffraction pattern could not be obtained.

Arsenates, though rare in the district, are rather more widely distributed than arsenides, and include mimetite, olivenite, beudantite, annabergite and erythrite.

Mimetite, $Pb(AsO_4)_3Cl$, has been recorded from two localities the High Pirn Mine on the Belton Grain Vein, and the dumps by the side of the road near the Glencrieff Mine. A specimen (551.7) from the former locality exhibits barrel shaped crystals of mimetite (var.campylite), associated with pyromorphite and plumbogummite.

Heddle (1924, p.161) mentions small yellow crystals of mimetite from Leadhills, but all the yellow members of the pyromorphite group examined were pyromorphite. However, a massive orange mineral (564A.1), from the High Pirn Mine, labelled "dechenite", proved to be mimetite.

Only two specimens of olivenite, $Cu_2(OH)(AsO_4)$, (561.4, and unnumbered in Natural History Museum, Dumfries), have been observed, both from "Browns Vein, Glengonnar". The olivenite is brown in colour and occurs as vitreous, short prismatic crystals, and globular masses with a fibrous habit.

Beudantite, $PbFe_3(OH)_6(SO_4)(AsO_4)$, has not been previously recorded from the district, and was found on the High Pirn Mine as a red-brown botryoidal incrustation on quartz.

Erythrite, $Co_3(AsO_4)_2.8H_2O$, and Annabergite, $Ni_3(AsO_4)_2.8H_2O$ were first recorded by Brown (1925, p.79), and are restricted to the Glencrieff Mine. On one specimen (1951.8.4), the minerals are associated with niccolite and rammelsbergite. Erythrite coating greywacke occurs on the main dump at the Glencrieff Mine.

Several specimens of a green mineral (568), were labelled "erinite", $Cu_5(OH)_2(AsO_4)_2$. The mineral is associated with linarite, or is pseudomorphous after galena, and in every case proved to be brochantite, $Cu_4(SO_4)(OH)_6$.

Arsenic has been recorded in minor quantities in the pyromorphite group, where it has probably replaced phosphorus. Qualitative spectrochemical analyses failed to detect arsenic in galena, sphalerite, chalcopyrite, pyrite, calcite, aragonite, barytes, and witherite, but this may be due to the low spectrochemical sensitivity of the element, the lower limit of detection being about 0.01% (Ahrens, 1950, p.208). Trace amounts of arsenic may be present accompanying antimony and bismuth in galena. According to Oftedahl (1940), the presence of arsenic has not been established in sphalerite.

The source of the aresnic found in the oxidised zone of the mineral deposits may therefore be attributed to primary arsenides, together with trace amounts in galena, and possibly other primary minerals. As no country rocks were examined, this source cannot be discounted.

THE DISTRIBUTION OF VANADIUM.

Although vanadium is a common trace element in many of the primary and secondary minerals of the district, vanadates are quite rare, and have only been recorded on occasional veins, of which the most important is the Belton Grain Vein. The only vanadates found in the district are vanadinite and the descloizite group.

Heddle (1924, p.161) mentioned the presence of vanadinite ($Pb_5(VO_4)_3Cl$) at the High Pirn Mine on the Belton Grain Vein "... only in one spot, about six fathoms in length", whilst Brown (1918, p.130) noted the presence of vanadinite on the Belton Grain Vein. The latter vein was a stringer cutting the Belton Grain Vein, and appeared to be particularly rich in vanadinite. The present investigation confirmed Brown's localities, all the dumps on the Belton Grain Vein, both at the head of Whytes Cleuch, and the High and Low Pirn Mines, having numerous examples of the mineral. In addition it was found on the dumps at Glengonnar Mine, and at locality 129 on the Brow Vein.

The mineral occurs as brown botryoidal aggregates, and brown hexagonal crystals. It is commonly associated with massive green pyromorphite, pseudomorphous after galena, and may be associated with the descloizite group, or, in occasional cases from the High Pirn Mine, with hemimorphite. On the dumps in Whytes Cleugh the mineral is generally encrusting on quartz.

A calcium bearing variety of vanadinite was described from Wanlockhead by Frenzel (1881, in Dana, 1951, p.897), 3.25% calcium oxide being present.

Members of the descloizite group were recorded from the same localities as vanadinite, with the addition of Scar Vein. The minerals are often associated with vanadinite, or may be encursting on pyromorphite or quartz. The colour varies from reddish-brown, on the Belton Grain Vein, to green, from Glengonnar Mine.

Brown (1925, p.74) recorded the presence of "psittacinite or mottramite" from the Belton Grain Vein and the Scar Vein. Bannister (1933, p.385) stated that the powder photographs of descloizite, cuprodescloizite, mottramite, psittacinite, chileite, eusynchite, and dechenite, from type localities are identical with each other, but recent work by Mr. J. Hartley (to be published in the near future) has disproved Bannister's statement. Slight variations in the powder data of several of the Leadhills-Wanlockhead specimens confirms Hartley's work. In the absence of further knowledge all the Leadhills-Wanlockhead examples have been broadly assigned to the descloizite group, $(Cu-Zn)Pb(VO_4)(OH)$, without attempting to differentiate between descloizite and mottramite, the names applied to the halves of the series with zinc greater than copper, and copper greater than zinc, respectively (Dana, 1951, p.813).

A massive orange mineral (564A.1), associated with plattnerite, from the High Pirn Mine, was labelled by Heddle as dechenite $(PbZn)_2(OH)(VO_4)$, formula after Heddle (1924, p.162). On examination the mineral proved to be mimetite.

Apart from occurring in vanadates, vanadium is a common trace element in the district, being present in galena, sphalerite, five out of six pyrites, calcite, aragonite, barytes, and witherite. It was not detected in niccolite, and chalcopyrite. The presence of vanadates from several localities has been previously described, and the source of the vanadium attributed to either the country rocks or the primary minerals. In the case of the Rhodesian Broken Hill, and Otavi, vanadium was not detected in the primary minerals, but was detected in the sulphide ores, calcite, and dolomite, from Tsumeb (Skerl, 1934; Moritz, 1933; Newhouse, 1934; Schwellnus, 1946). The presence or absence of vanadium in the primary minerals must be a reflection on the composition of the parent magma, and the source of the vanadium for the Leadhills-Wanlockhead vanadates could be the primary minerals, whilst, as no country rock was examined, this source cannot be discounted.

THE DISTRIBUTION OF CHROMIUM.

Chromium is a rare element in the district. It is chiefly concentrated in the pyromorphite group, in which it has a sparse, though widespread occurrence. Only four other chromium bearing minerals were recorded, all in minute quantities from the same locality.

The only chromate which has been previously recorded is Crocoite ($PbCrO_4$). This mineral was stated by Brown (1925, p.74) to have been found in 1920 on an old dump on the Hopeful Vein. Mr. J. Blackwood, of Leadhills, who first found the mineral, kindly pointed out the exact locality (loc.45), and donated a small specimen for investigation. Crocoite was confirmed by the diffraction pattern, and is associated with massive cerussite and leadhillite.

Two further specimens of chromium bearing minerals from the same locality were obtained from the Leadhills collection in the Grant Institute, Edinburgh, and two other specimens were unearthed from the old dump. Investigation of the specimens revealed the presence of four chromium bearing minerals, excluding crocoite. These included a mineral new to the British Isles, a new variety, and a new mineral.

On two of the specimens a small massive red mineral was found, associated in one case with massive cerussite and leadhillite, and in the other with pyromorphite and leadhillite. The diffraction pattern of this mineral closely resembles that of Phoenicochroite)$Pb_3(CrO_4)O$), from the type locality of Beresovsk. The spacing data for both minerals are listed below. Unfortunately further confirmation of the Leadhills phoenicochroite by chemical analysis was precluded owing to lack of material.

Phoenicochroite has not been previously recorded from the British Isles and, according to Dana (1951, p.650) has only been described from Beresovsk and the Adelaide Proprietary Mine, Dundas, Tasmania.

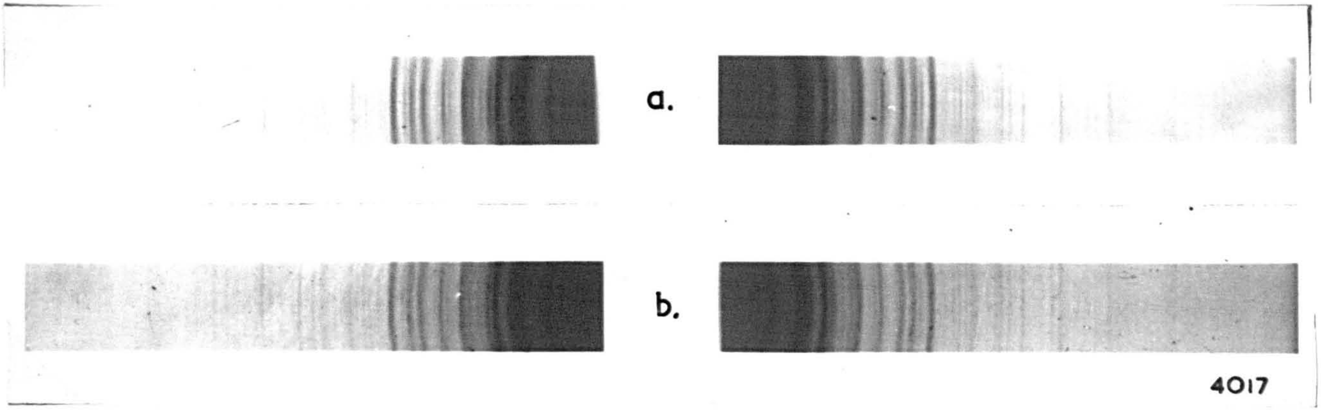


Plate V.

a. Phoenicochroite, Beresovsk, Urals.
Film No. 986.

b. Phoenicochroite, Hopeful Vein, Leadhills.
Film No. 4017.

Small, elongated orange crystals, associated with pseudo-hexagonal leadhillite, occur on two of the specimens.

Spacing data for Phoenicochroite.

1101. Phoenicochroite, Beresovsk.		3805. Hopeful Vein.	
I	dA	I	dA
vw.	6.42	w.	6.48
vw.	6.02	vw.	6.02
vw.	5.40		
w.	4.94	w.	4.94
m.	4.36	m.	4.36
vw.	3.75	vw.	3.74
vs.	3.58	s.	3.58
vs.	3.46	s.	3.46
fs.	3.36	fs.	3.36
s.	3.26	s.	3.26
s.	2.99	s.	2.98
w.	2.87	w.	2.87
w.	2.83	w.	2.83
w.	2.69	vw.	2.70
m.	2.57	w.	2.57
fs.	2.51	m.	2.51
fs.	2.46	m.	2.46
w.	2.31	w.	2.30
fs.	2.25	m.	2.25
w.	2.19		
fs.	2.07	w.	2.07
vw.	2.04	vw.	2.04
fs.	1.99	w.	1.99
fs.	1.96	w.	1.96
m.	1.92	vw.	1.92
fs.	1.84	m.	1.85
vw.	1.79		
w.	1.68	vw.	1.68
vw.	1.65		
w.	1.62	vw.	1.61
vw.	1.58		
vw.	1.55		
vw.	1.50	vw.	1.49
vw.	1.46	vw.	1.46
vw.	1.42		
w.	1.41	w.	1.41
vw.	1.39		
vw.	1.33		
w.	1.30	w.	1.30

The diffraction pattern of the orange mineral is identical with that of leadhillite ($Pb_4(SO_4)(OH)_2(CO_3)_2$), with the exception of a slight spacing difference, illustrated below by six accurately measured lines. It can be seen that the orange mineral has a slightly larger unit cell than that of leadhillite.

3690. Orange mineral.	1575. Leadhillite, Leadhills.
dA	dA
4.550	4.520
2.3130	2.3100
2.0598	2.0511
1.7313	1.7286
1.5505	1.5480
1.3349	1.3319

As a qualitative spectrochemical analysis revealed the presence of chromium in the mineral, 6 mg. of the mineral were picked, and subjected to a quantitative spectrochemical analysis. The mineral contains approximately 0.5% Cr.

This chromium mineral has a slightly larger unit cell than leadhillite, and therefore it may be inferred that Cr^{6+}, (0.35 kX), has partly replaced S^{6+}, (0.34 kX), in the sulphate group of leadhillite, and as no structural differences other than change of unit cell size have taken place, the mineral may be regarded as chromian leadhillite, a variety which has not been previously described.

A red crystal was observed occupying a small cavity in massive greenish-white cerussite on one of the specimens from the Grant Institute (unnumbered). The crystal, which had been partly broken, was 2 mm. in length, and weighed slightly over 1 mg. It was elongated, and twinned in a cyclic manner.

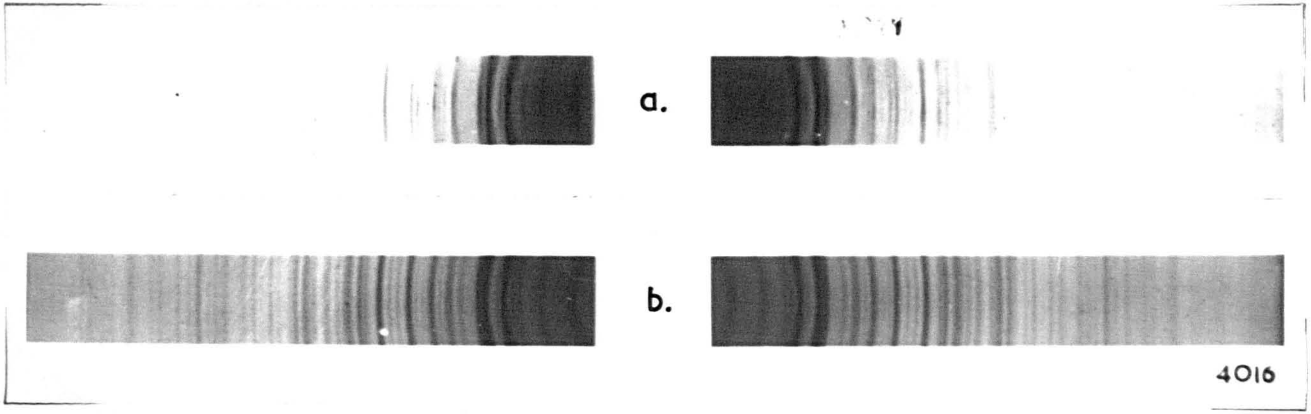


Plate VI.

a. New chromian mineral, similar to lanarkite,
Hopeful Vein, Leadhills. Film No.3599.

b. Lanarkite, Susanna Vein, Leadhills.
Film No.4016.

The diffraction pattern of the mineral (listed below), is similar to that of lanarkite ($Pb_2(SO_4)O$), but the unit cell is larger than that of lanarkite (plate 6). However, apart from the cell dimensions, several minor structural variations are apparent in the diffraction patterns.

Spacing data for new mineral.
Film No.3599.

I	dA	I	dA
m.	6.49	fw.	1.45
w.	6.00	w.	1.42
fw.	4.44	w.	1.37
fw.	3.77	w.	1.32
w.	3.56	w.	1.30
vs.	3.38	vw.	1.28
fw.	3.23	w.	1.22
vs.	2.98	vw.	1.21
s.	2.86	w.	1.19
w.	2.65	vw.	1.18
w.	2.56	w.	1.16
fs.	2.48	w.	1.14
fs.	2.39	vvw.	1.12
fw.	2.37	vvw.	1.11
fw.	2.31	vvw.	1.07
fs.	2.26	vvw.	1.06
w.	2.19	vvw.	1.05
fs.	2.12	vvw.	1.04
fw.	1.99	vw.	1.03
fw.	1.94	vw.	1.02
s.	1.87	vvw.	1.01
vw.	1.82	vvw.	1.00
m.	1.77	vw.	0.98
w.	1.75	vw.	0.95
m.	1.72	vw.	0.94
w.	1.69	vw.	0.93
m.	1.66	vw.	0.91
vw.	1.58	vw.	0.90
vw.	1.56	w.	0.892
m.	1.52	w.	0.886
m.	1.49	vw.	0.878
fw.	1.47	vw.	0.870
m.	1.46		

A quantitative spectrochemical analysis was attempted, and, allowing for all errors, the percentage of chromium in the mineral can be stated to lie between 6% and 15%. As the unit cell of the red mineral is larger than that of lanarkite, an analogy may be drawn between this mineral and the chromian leadhillite described above, in that the unit cell difference may be accounted for by the replacement of S by Cr in the sulphate group. However, this red mineral has structural differences with lanarkite other than unit cell size, which could have been brought about by the large percentage of chromium, or by the introduction of some other element or group into the structure. The mineral therefore cannot be regarded only as chromian lanarkite, but, as no such mineral has been previously described, must be considered as a new mineral.

The fourth variety of chromium bearing mineral from the dump on Hopeful Vein is pyromorphite, orange in colour, which is fairly common throughout the district, and has been fully described in the section on the "Pyromorphite group".

Vauquelinite, a chromate-phosphate of lead and copper of uncertain formula, was recorded from the New and Hopeful Veins by Brown (1925, p.74), and also from the Bay Vein (727.6). The latter mineral proved to be goethite, and vauqelinite has not been confirmed from the locality in the course of the present investigation.

The source of chromium in oxidised lead-zinc deposits has been discussed by Newhouse (1934, p.220), and attributed to chromium in solid solution in galena and sphalerite. However, qualitative spectrochemical analyses of galena and sphalerite from the Leadhills-Wanlockhead district failed to detect chromium, but it was present in calcite (var. "plumbocalcite"), and aragonite (var. "plumboaragonite").

III. PARAGENETICAL MINERALOGY OF THE LEADHILLS-WANLOCKHEAD AREA.

For the purpose of the description of the paragenetical mineralogy, the minerals occurring in the district are divided into two groups, namely the early stage, and the main stage of mineralisation. The latter term refers to the lead-zinc mineralisation, which can be subdivided into the metasomatic minerals developed in the country rocks, and the primary and secondary (or hypogene and supergene), minerals of the veins.

THE EARLY MINERALISATION.

Massive white quartz is widespread in the area, veining the greywackes and occurring in the lead-zinc veins in either vein breccias, or slickensided on the walls of the veins. The shattered quartz is often veined by ankerite or calcite, and is unmistakably of a pre-main mineralisation age.

Minerals probably associated with the quartz include pyrite, white mica, albite, gold, and galena. Both pyrite and muscovite are common in the larger quartz veins of the district, particularly in the Lowther Hills and the Long Cleuch, whilst white mica, accompanied by albite, were observed in quartz from the Glencrieff Mine.

The evidence for the association of gold with the quartz veins is not conclusive. However, Bulmer, in the latter part of the sixteenth century, erected a stamping mill, and worked a "little string or vein powdered with small gold" at the head of the Long Cleuch, (Porteous, 1876), and small quantities of alluvial gold can be obtained from most of the burns in the district. A large specimen of gold bearing quartz was found by Mr. G. V. Wilson of the Geological Survey in the Shortcleuch Water, and small fragments of gold associated with quartz can be found in the Windgate Burn. The occurrence of gold bearing quartz, combined with the absence of gold in the lead-zinc veins, make it appear feasible that the quartz veins carry gold which may have no genetic relationship with the main mineralisation.

The quartz vein on the side of Dun Grain has been worked by a small trial adit, and the quartz on the dump carries small veinlets of galena, no other gangue or sulphide mineral being present. This small amount of galena may have a genetic connection with the quartz veins, but the possibility of a relationship with the main mineralisation cannot be dismissed.

The age of the quartz mineralisation cannot be stated with certainty, but the inclusion of white mica, a diagnostic mineral of the Caledonian minor intrusives, together with small amounts of albite, which also occurs in some of the dykes, suggests that the quartz may be related to the end stages of the Caledonian Orogeny.

MINERALS OF THE MAIN MINERALISATION.

A. THE METASOMATIC MINERALS.

In proximity to the veins, the originally dark green country rock is bleached to a light grey colour, due to a change in mineral composition. The prominent mineral in the altered rock is pyrite (plates 14-15), which is generally euhedral, and often contains inclusions of the greywacke detritals, consistent

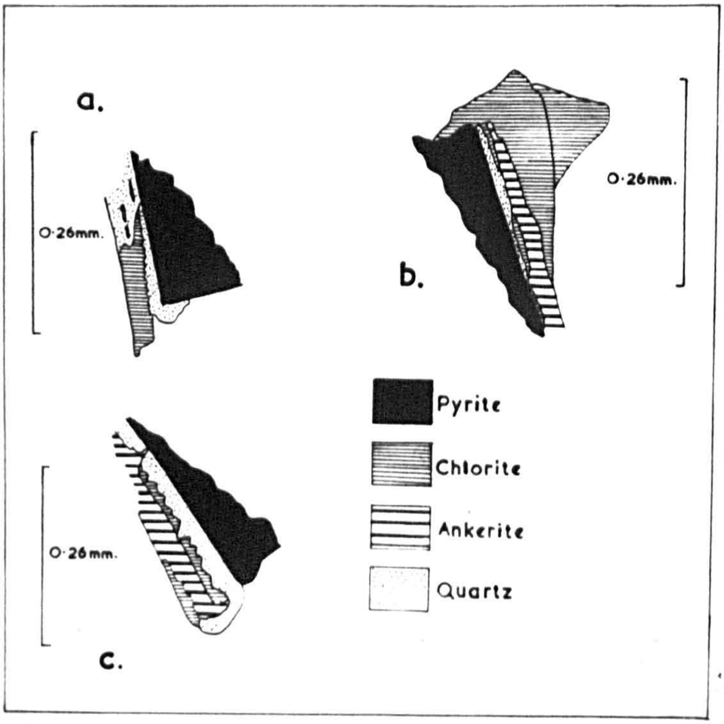


Figure 10. Metasomatic minerals in pressure fringes round pyrite crystals. Glencrieff Mine.

a. Inclusion of chlorite in quartz indicates that quartz was the later mineral.

b. Ankerite replacing chlorite along the cleavage.

c. Quartz infiltrating along the pyrite-chlorite junction.

with a formation by preferred replacement of the greywacke matrix. The pyrite is accompanied by abundant ankerite, which tends to form euhedral rhombs, a tendency less marked towards the channels of mineralising solutions. Chlorite is also common in the altered rock, and occurs both in a massive green form, and as brown crystals. Small amounts of sericite were present.

The relationships of these minerals is well exhibited in a specimen from the Glencrieff Mine, in which euhedral crystals of pyrite are partly surrounded by cavities filled with ankerite, chlorite, and quartz. The formation of the cavities is discussed in a later section. The mineral relationships are depicted in Fig.10, and may be interpreted as the successive deposition of pyrite, chlorite, ankerite, and quartz. Ankerite appears to be replacing the chlorite along the cleavage, and confirmation of this relation is afforded by irregular veinlets of massive green chlorite cut by ankerite. The quartz partly occurs in a comb structure along the edge of the pyrite, and the only indication of its relative age is the inclusions of chlorite (fig.10a). From general experience of the occurrence of quartz in the vein minerals, described later, it is considered probable that the quartz is later than chlorite and ankerite.

It would appear therefore, that the light colour of the altered rock is due to a reconstitution of the dark chloritic and calcareous matrix, and the detrital biotites and amphiboles of fresh greywacke, with the resultant formation of sericite, pyrite, chlorite, ankerite, and probably quartz. However, pyrite, ankerite, and quartz could have been wholly, or partly introduced from the channels of mineralising solutions. Anticipating the following section, the paragenetical relations of the three minerals in the veins are ankerite, pyrite, and quartz, and it therefore may be deduced that the pyrite in the altered rock is due to a reconstitution of the iron originally present, that the chlorite and sericite are chiefly derived from the rock, and that the ankerite may have been partly, and the quartz wholly, introduced.

B. PARAGENESIS OF THE PRIMARY VEIN MINERALS.

The following sections will be devoted to descriptions of the paragenetical relationships of the vein minerals. The illustrations are mainly drawn from a study of polished sections, but were fully confirmed by a macroscopic study of several thousand specimens, the majority of which were collected from the mining,area, supplemented by material from collections, in particular the Scottish Mineral Collection.

The criteria used in the determination of the paragenesis include the encrustation of one mineral upon another, the relative positions in veinlets, and replacement phenomena, the latter as evidenced by pseudomorphism, either wholly or in part, and the presence of inclusions.

The descriptions are arranged in order to describe all the mineral relationships necessary to build up the paragenetical sequence, with the minimum of overlap.

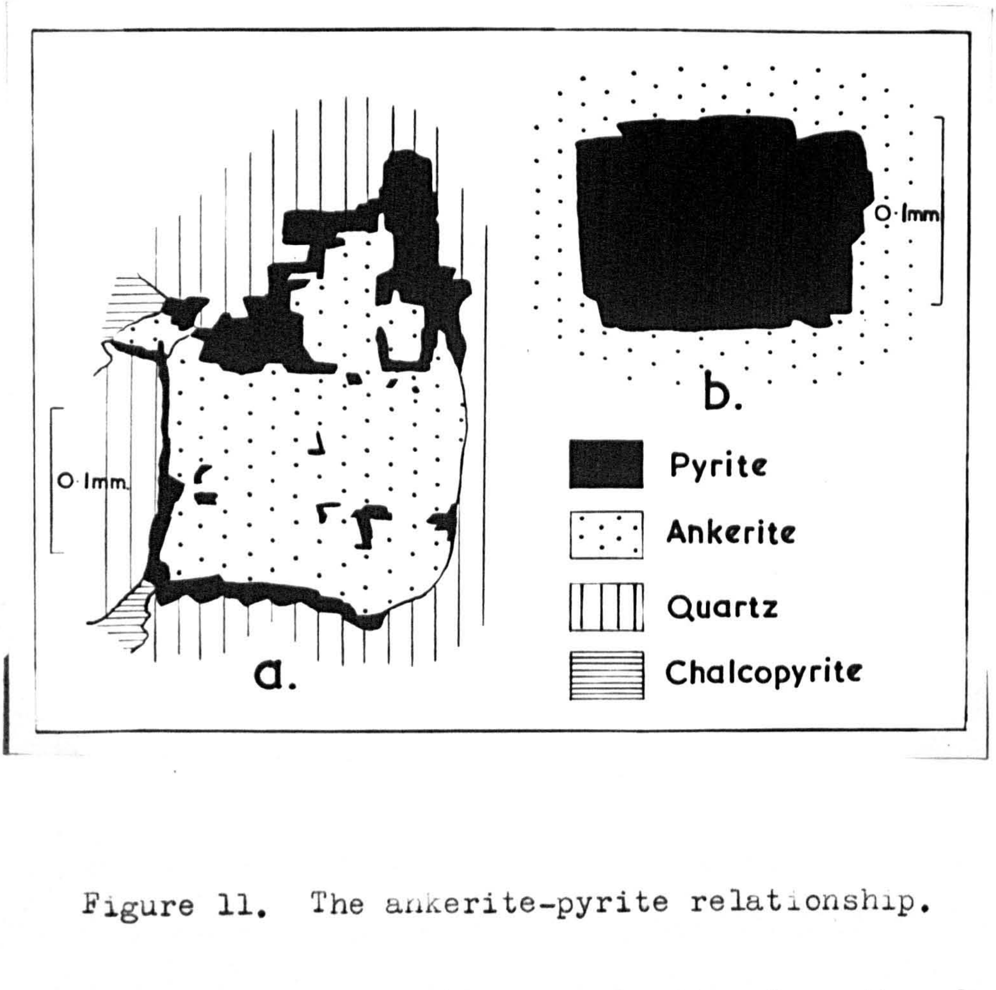


Figure 11. The ankerite-pyrite relationship.

a. Pyrite replacing ankerite along the cleavag
Glencrieff Mine, (P.S. 119).

b. Pyrite with rhombohedral outlines, due to
replacement of the ankerite.
Wilsons Shaft, (P.S. 109).

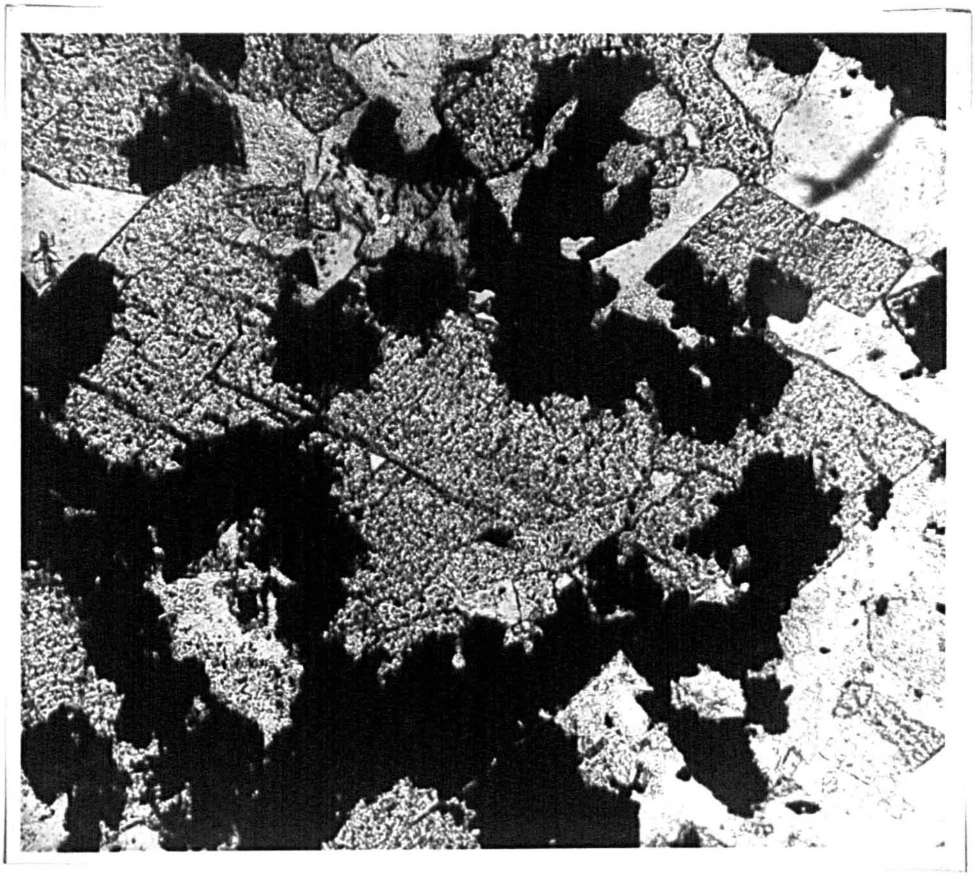


Plate VII.

Pyrite, (black), replacing rhombs of ankerite, x90.

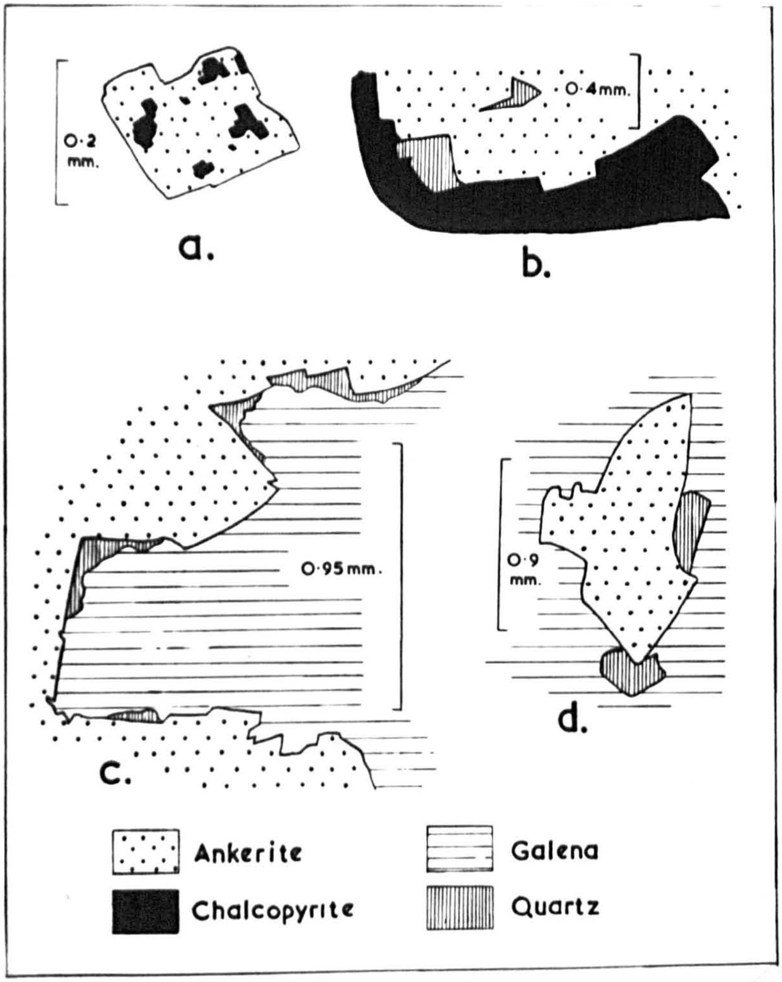


Figure 12. The relationship of ankerite towards chalcopyrite and galena.

a. Chalcopyrite replacing ankerite along the cleavage.
Wilsons Shaft, (P.S. 109).

b. Ankerite euhedral towards chalcopyrite.
Wilsons Shaft, (P.S. 109).

c. Ankerite euhedral towards galena, with quartz replacing galena along the ankerite-galena junction.
Gordons Vein, (P.S. 126).

d. Inclusion of ankerite in galena.
Laverock Hall, (P.S. 108).

a. Relationships of Ankerite.

The relationships of ankerite are visible in the majority of the veins, other minerals, particularly gangue minerals, encrusting upon, and veining the ankerite, which, together with the replacement by the sulphide minerals, gives strong indication that ankerite was the first mineral in the veins.

The ankerite-iron sulphide relationship illustrates well the general paragenesis of ankerite. Iron sulphide does occasionally vein ankerite, but is generally disseminated through the mineral where two types of iron sulphide form can be distinguished, namely euhedral, and pseudomorphic. In the latter case the sulphide replaces the carbonate along the cleavage planes (fig.11a), and all stages of replacement have been observed, from small tongues along the cleavage to complete rhombs of sulphide after the carbonate (plate 7). All the iron sulphide which has formed in ankerite has traces of rhombohedral outline when examined under high magnification (fig.11b), and the only true euhedral sulphide is that which has developed in vugs in the ankerite.

The relationship of chalcopyrite to ankerite is similar to that of pyrite, in that chalcopyrite may replace the carbonate along the cleavage (fig.12a), further replacement being indicated by occasional inclusions of ankerite in the chalcopyrite. However, the predominating relationship between the two minerals is one where the ankerite exhibits euhedral crystal faces towards the irregular masses of chalcopyrite (fig.12b).

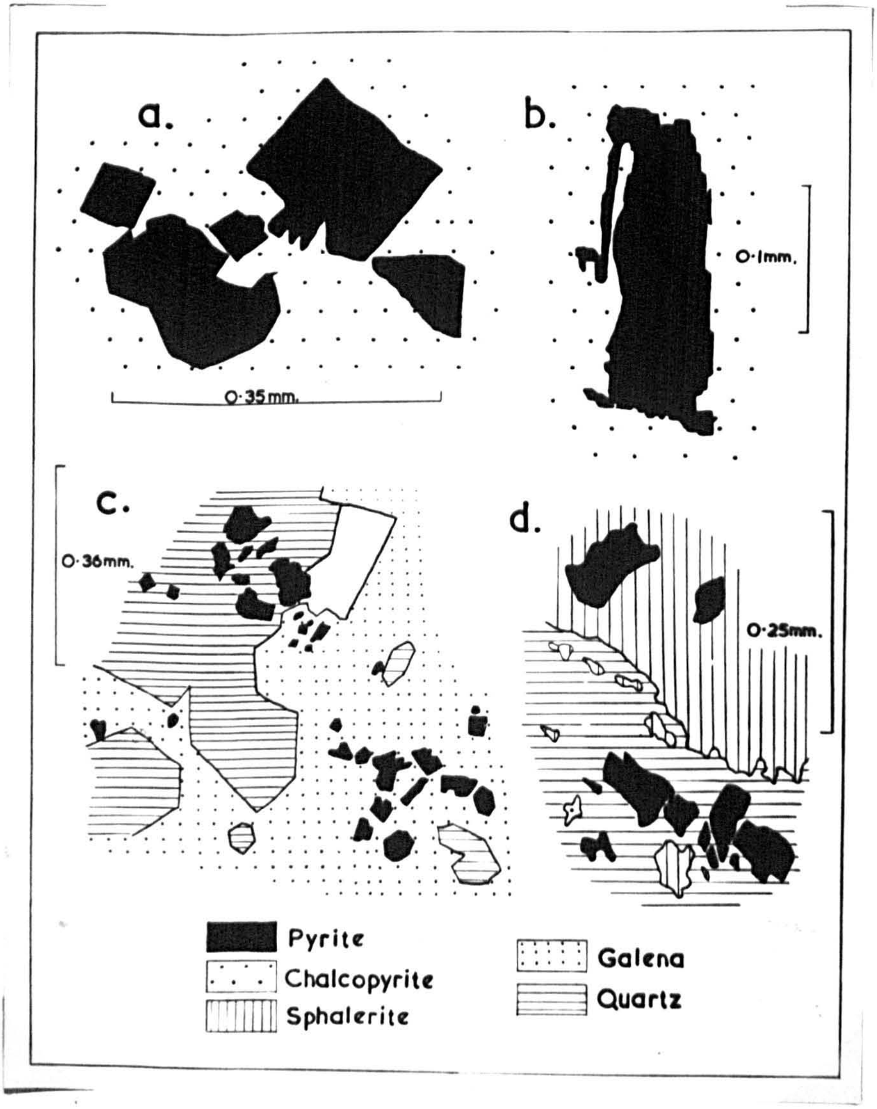


Figure 13. The relationship of first generation pyrite to the other sulphides.

a. Inclusions of euhedral pyrite in chalcopyrite. Wilsons Shaft, (P.S. 109).

b. The pyrite, included in chalcopyrite, exhibits rhombohedral outlines, probably due to replacement of ankerite. Wilsons Shaft, (P.S. 109).

c. Inclusions of euhedral pyrite in galena. Bay Shaft, (P.S. 145).

d. Inclusions of pyrite in sphalerite, both minerals being partly replaced by quartz. Glencrieff Mine, (P.S. 127).

Sphalerite and galena generally occur encrusting, or as small veinlets in contact with, the ankerite, and in both cases the ankerite exhibits euhedral outlines towards the sulphide minerals (fig.12c). Both the ore mineral replace ankerite to some extent, inclusions of ankerite being fairly common (fig.12d).

The relationships of ankerite towards all the sulphide minerals is, therefore, of a similar nature, excepting that pyrite exhibits a strong tendency to replace the ankerite, a tendency which appears to decrease through chalcopyrite to sphalerite and galena.

The other gangue minerals, calcite, barytes, aragonite, and witherite, commonly occur encrusting on ankerite, or occupying a central position, with respect to ankerite, in veinlets. Calcite may replace the ankerite.

b. The relationships of the Iron Sulphides.

Two generations of iron sulphide occur in the veins of the district, the first being characterised by both pyrite and marcasite (whose inter-relationships have been described in an earlier section), whilst marcasite was not observed in the second generation.

The first generation is usually massive and is widely distributed through the ore. It replaces ankerite, and is included in chalcopyrite (fig.13a, b), in galena (fig.13c), and in sphalerite (fig.13d). These inclusions vary in shape from euhedral to subhedral, and may be of a rhombohedral shape, pseudomorphous after ankerite. The first generation of sulphide

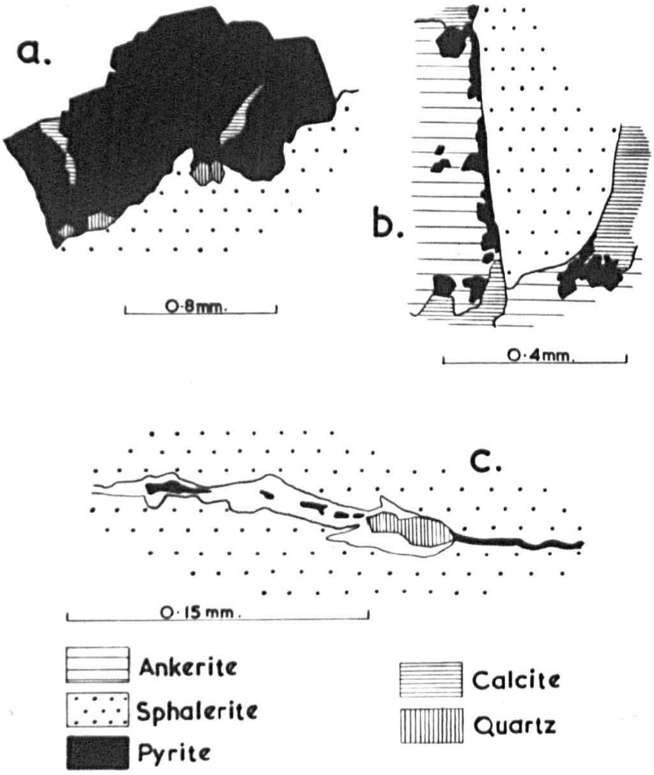


Figure 14. Second generation pyrite later than sphalerite.

a. Crystals of pyrite encrusting on sphalerite.
Gordons Vein, (P.S. 99).
b. Pyrite round the margin of sphalerite, partly replacing ankerite and calcite.
Big Wool Gill, (P.S. 120).
c. Pyrite infiltrated along crack in sphalerite.
Susanna Vein, (P.S. 121).

was therefore deposited before the other sulphide minerals.

The second generation of pyrite may crystallise as small pentagonal dodecahedra, commonly encrusting on sphalerite (fig.14a), on barytes, in extreme cases forming a pseudomorph after barytes, and on calcite. The inclusions in calcite which give rise to the "ghost" features are the second generation of pyrite, and may be either massive and intergrown with the calcite, or exhibit crystal form, the two forms probably being dependent on whether or not the pyrite was deposited simultaneously with the calcite. The second generation of pyrite may be massive, filling cracks in chalcopyrite, and in sphalerite (fig.14c).

c. The relationships of Chalcopyrite.

From the above descriptions, it can be established that chalcopyrite is later than ankerite and the first generation of iron sulphide. The relationships of chalcopyrite to the other sulphides, galena and sphalerite, is demonstrated throughout the district, the chalcopyrite occurring as inclusions in both minerals (fig.15a), and in one case exhibiting euhedral crystal outlines towards sphalerite (fig.15b).

With the exception of ankerite, contacts between chalcopyrite and the gangue minerals are infrequent, but the relationships may be inferred from the relationships of associated galena and sphalerite to the gangue, and in this respect the association of chalcopyrite with galena in the Belton Grain Vein, and the relationships to the calcite and barytes suggests that the sulphides were later than the gangue minerals.

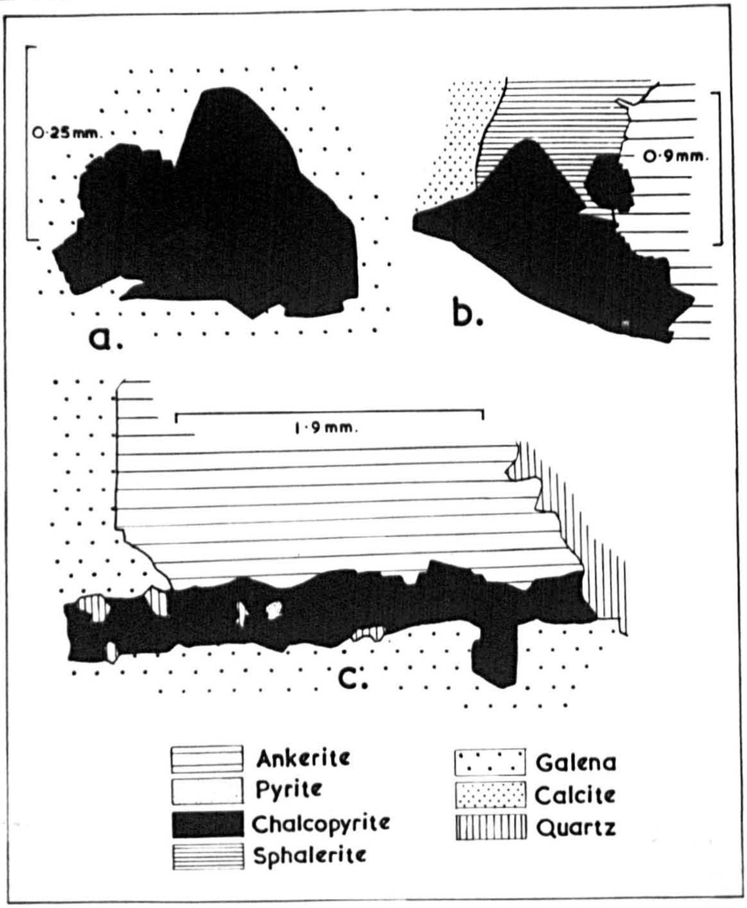


Figure 15. The relationship of chalcopyrite to sphalerite and galena.

a. Inclusion of chalcopyrite in galena. Glencrieff Mine, (P.S. 119).

b. Chalcopyrite euhedral towards sphalerite, calcite encrusting upon both minerals Moffats Shaft, (P.S. 114).

c. Chalcopyrite later than quartz, infiltrating along the cleavage, with quartz cross-cutting both minerals.
Glencrieff Mine, (P.S. 119).

Furthermore three cases of discrepancies in the normal chalcopyrite-galena relationship were noted, all from the Glencrieff Vein. The first case was an intergrowth of galena and chalcopyrite, in which the galena is unmistakable included in the chalcopyrite. Secondly was an example showing chalcopyrite present along the cleavage of galena (fig.15c), and thirdly, crystals of chalcopyrite resting on a pseudomorph of quartz after calcite, which is itself resting on galena and chalcopyrite, the latter two minerals being in the normal paragenetical sequence (83.42).

d. The Sphalerite-Galena relationship.

Sphalerite and galena may occur together, both as separate veinlets in massive banded ore, and as intergrowths, the latter probably from the deeper parts of the veins (e.g., Wilson, 1921, p.31). Investigation of therelations of the two minerals revealed that whereas in most specimens a sequence can be obtained, that sequence cannot be applied to every contact between the two minerals, not even from the same locality.

Thus in many of the massive intergrowths galena has replaced sphalerite along the crystal boundaries (fig.16a), whilst examples of the converse relationship are given by sphalerite crystals on galena (fig.16b), and by crystals of sphalerite along the cleavages of galena (1001.170), (plate 8).

Sphalerite and galena must therefore be regarded as of a similar age, both being later than ankerite, the first generation of iron sulphide, and chalcopyrite.

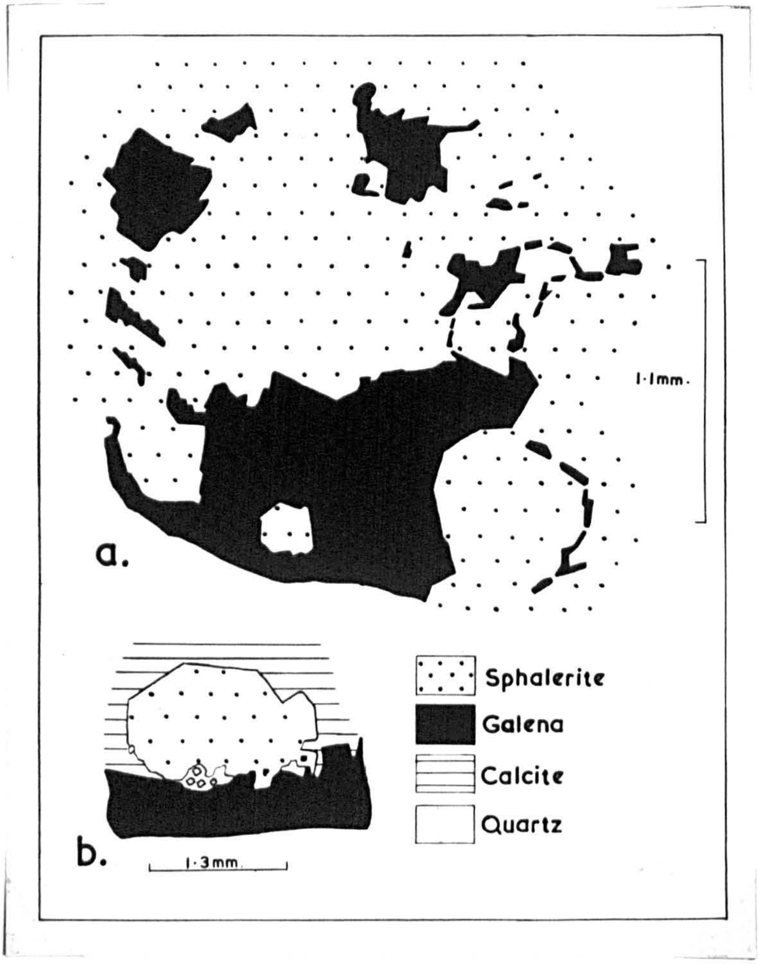


Figure 16. The sphalerite-galena relationship.

a. Galena replacing sphalerite along the grain boundaries.
Glencrieff Mine, (P.S. 143).

b. Crystal of sphalerite on galena, calcite later than both minerals.
Gordons Vein, (P.S. 126).

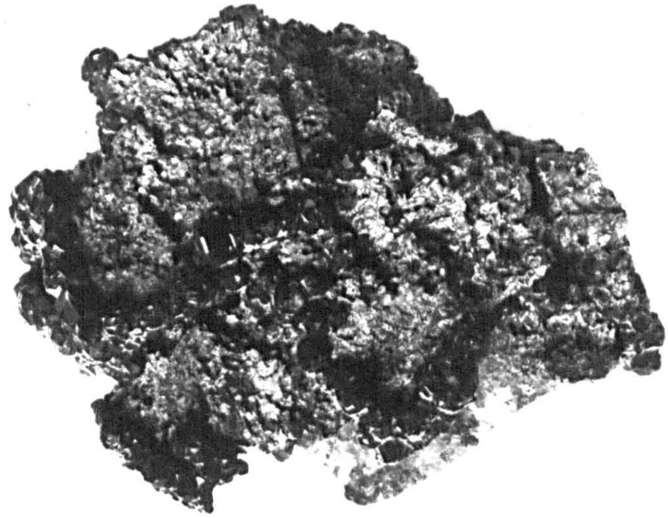


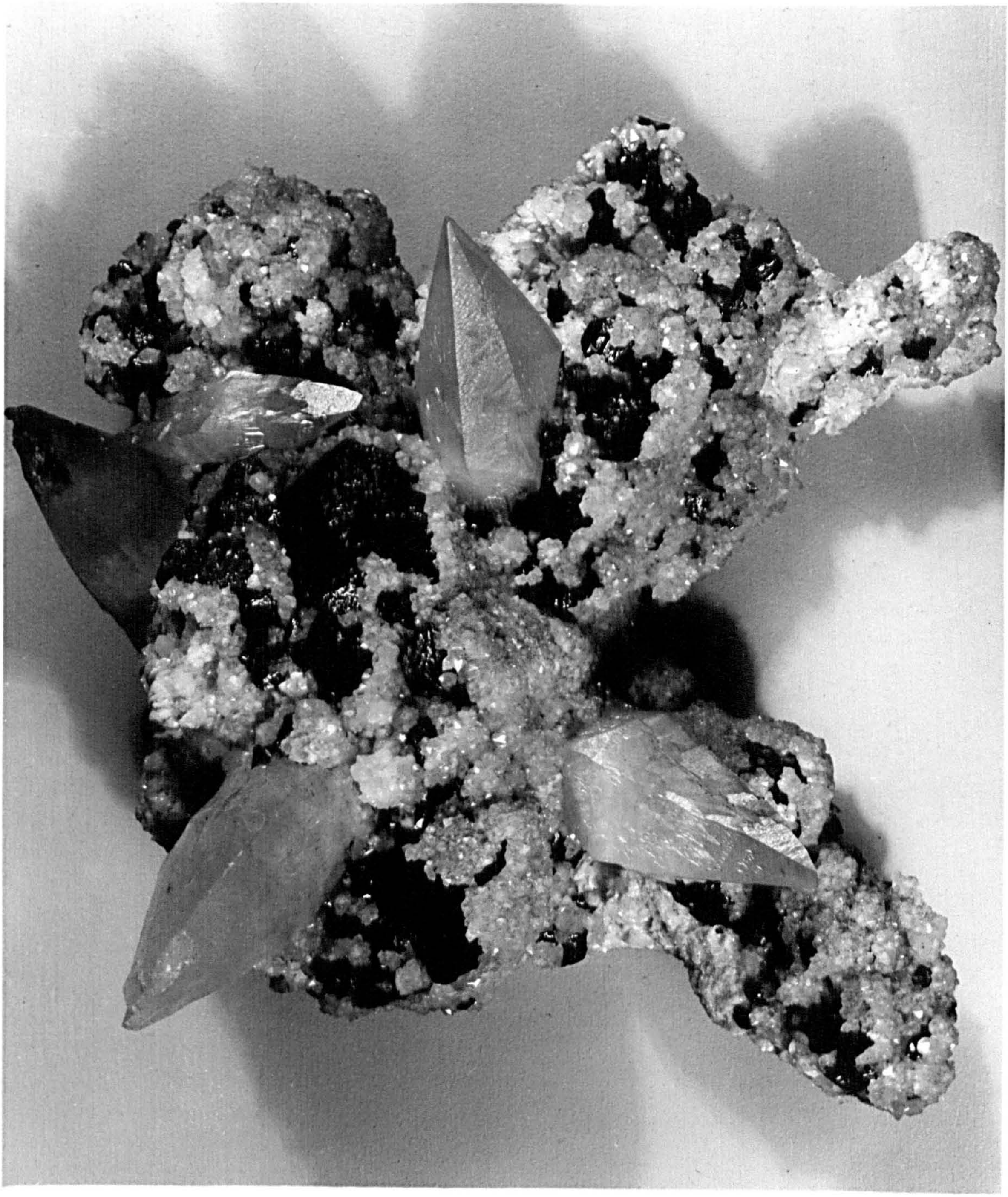
Plate VIII.

Crystals of sphalerite, (black), encrusting on, and replacing galena along the cleavages. Scottish Mineral Collection No. 1001.170, x0.5.

Plate IX, (opposite).

Calcite, associated with sphalerite and quartz,
Glencrieff Mine, Wanlockhead; Scottish Mineral
Collection, 1926.2.4., xl.

The specimen shows the paragenesis of sphalerite, calcite, quartz. Calcite is encrusting upon the sphalerite, and also contains inclusions of that mineral. Quartz encrusts on the sphalerite and the base of the calcite crystal.



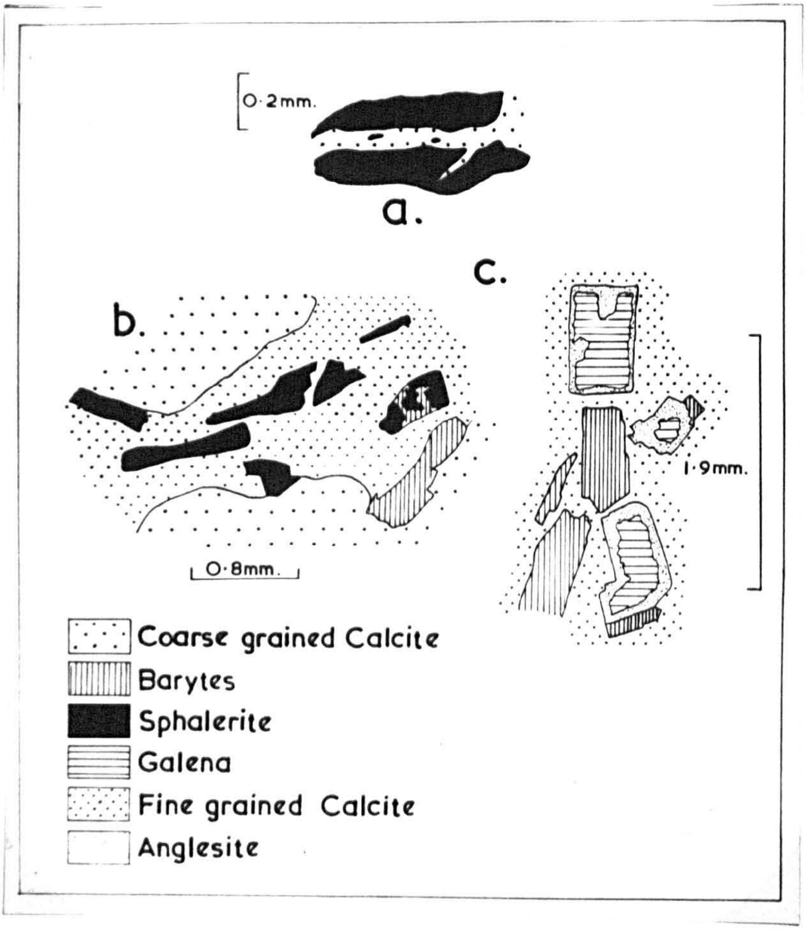


Figure 17. The relationship of sphalerite and galena towards calcite and barytes.

a. Crack in sphalerite filled with calcite.
Moffats Shaft, (P.S. 114).

b. Coarse grained calcite, with barytes, partly replaced by sphalerite, and later brecciated by the introduction of fine grained calcite.
Brow Vein, (P.S. 132).

c. Barytes partly replaced by galena, and later brecciated by the introduction of fine grained calcite.
Broad Law, (P.S. 137).

e. The Calcite-Barytes relationship.

Calcite and barytes are often associated together in the veins, particularly good relationships being exhibited on the dumps of Laverock Hall, and the Wembley Shaft, where barytes invariably encrusts on calcite. A similar relationship exists in the Belton Grain Vein above Taits Adit, the massive white calcite filling of the vein being cut by veinlets of barytes.

However, on material from several veins both massive barytes and calcite are brecciated, and the fragments cemented by finely crystalline calcite. It is considered probable that this brecciation is not caused by movement, but by replacement due to the introduction of a second generation of calcite along the cleavage planes of barytes and the crystal boundaries of calcite, all gradations of the replacement being visible. This second generation of calcite is common in the district, generally occurring as small "nail head" crystals encrusting on other minerals particularly galena and barytes.

f. The relationship between Sphalerite-Galena and Calcite-Barytes.

From a study of the relationship of sphalerite-galena to calcite and barytes, it appears that two generations of sphalerite and galena are present in the veins.

Sphalerite and galena are earlier than massive white calcite and barytes, both of the gangue minerals encrusting upon the sulphides, and occupying a central position, with respect to the sulphides, in veinlets. Further evidence is provided by inclusions of sphalerite in calcite, and cracks in sphalerite

Plate X.,(opposite).

Galena associated with calcite, barytes and pyrite, Glencrieff Mine, Wanlockhead, Scottish Mineral Collection No. 45.83, x0.3.

The specimen shows the paragenesis of galena, calcite, barytes, pyrite, and second generation calcite. The large calcites are encrusting on galena, and barytes on both galena and calcite. Pyrite is present on barytes, and on the surface of the first generation calcite, the later calcite crystallising in continuity with the early calcite, and so giving rise to inclusions of pyrite,(black), near the facesof the calcite. Some second generation calcite is encrusting on barytes.

Plate XI, (opposite).

Galena, associated with barytes, calcite, and pyrite, Glencrieff Mine, Wanlockhead; Scottish Mineral Collection No. 1953.8.5., x1.5.

The specimen shows the paragenesis of galena, barytes, pyrite, calcite. The pyrite occurs as small black crystals encrusting on barytes, and the calcite as "nail-head" crystals encrusting on both barytes and pyrite.

filled with calcite (fig.17a).

However, in numerous specimens from the Bay Shaft and Glencrieff Mine, both galena and sphalerite encrust upon massive calcite, whilst in the brecciated calcite and barytes, the sulphides are present in the second generation calcite matrix. Polished sections of these breccias reveal fragments of sulphide and barytes, both cemented by the second generation calcite. From the shape of the sulphides, which are elongated and often rhombohedral in outline, together with inclusions of barytes in the sulphide fragments (fig.17b, c), it would appear that the sulphides replaced the barytes.

Thus sphalerite and galena occur both earlier and later than the first generation of calcite and barytes. A notable feature of the second generation of sphalerite and galena is the absence of pyrite and chalcopyrite. The paragenetical relationship of the second pyrite to the second sphalerite and galena can be suggested as the pyrite encrusts upon barytes, but is encrusted upon by the second generation of calcite. It therefore has analogous relationships with the second sphalerite and galena, but as no specimens carrying second pyrite, sphalerite and galena were observed, and as no further evidence can be presented, the minerals can only be tentatively regarded as of a similar position in the paragenetical sequence.

g. Niccolite and Rammelsbergite.

From its position veining, and on the periphery of niccolite, rammelsbergite was slightly later than the niccolite.

The position of the minerals in the paragenesis is rather obscure owing to the restricted amount of specimens available for study. However, the arsenides were in contact with ankerite (1952.5.20), and have a rhombic outline along the contact, consistent with the niccolite having replaced the ankerite (fig.18b). Also the relationship with galena was observed (fig.18a). The galena is partly in contact with niccolite, and the remaining portion is enclosed in rammelsbergite. The junction of the galena with the niccolite is irregular, and occasional small fragments of galena are included in the margin of the niccolite. From the occurrence of the galena, it is suggested that niccolite replaced galena, and that the formation of rammelsbergite took place after the niccolite had started replacing the galena. Whether this particular time of formation of rammelsbergite is conicidence, or is genetically connected with the contamination of niccolite by galena, cannot be stated with any certainty.

The arsenides are therefore later than ankerite and galena, but no evidence is present to identify the galena as first or second generation.

h. The position of quartz in the paragenesis.

Of the two types of quartz occurring in the veins, one is brecciated and is of Early mineralisation, and is therefore not considered further, whilst the other quartz is common to the veins, is colourless or white in colour, and generally exhibits crystal faces. The manner of occurrence, with regard to the paragenetical position, is misleading, as the mineral has a strong

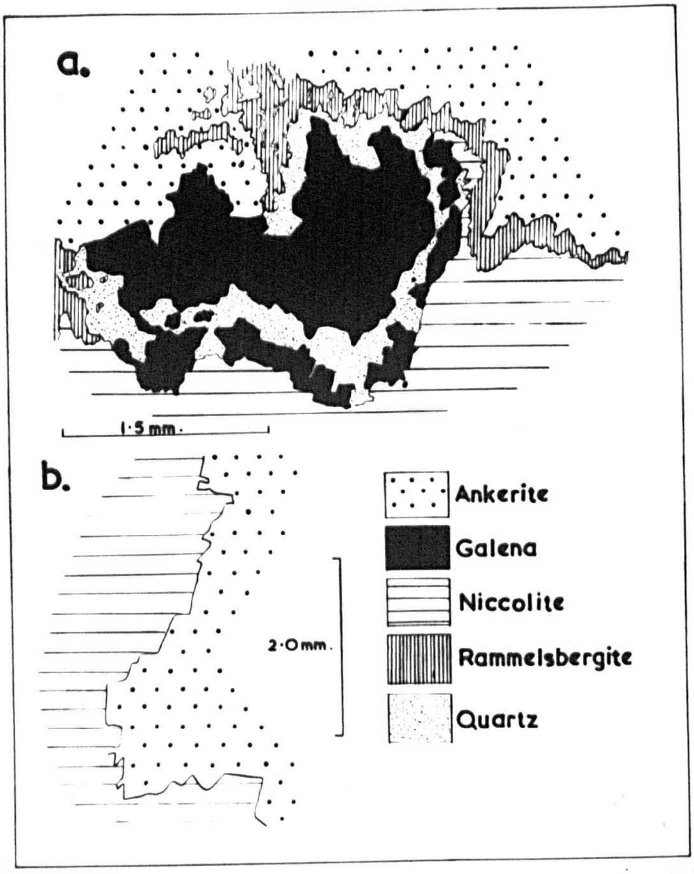


Figure 18. The relationships of niccolite.
Glencrieff Mine.

a. Small inclusion of galena in the niccolite indicates that niccolite was the later mineral. Rammelsbergite is on the periphery of niccolite, and in contact with galena. Quartz is interpreted as the last crystallised mineral.

b. Niccolite with rhombohedral outlines, due to replacement of ankerite.

tendency towards the formation of euhedral crystals, and to replace other minerals. Replacement is particularly marked along mineral junctions, and results in the impression that the uppermost mineral, against which the quartz usually exhibits euhedral faces, is of later formation than the quartz. However, when the relationships of quartz with all the other minerals are examined in detail, the paragenetical position of quartz becomes apparent.

The relationship with massive pyrite and marcasite often gives rise to a "boxwork" formation of quartz infilled with iron sulphide. That the quartz replaced the iron sulphide is evidenced by similarity in polarisation colours and extinction of marcasite which is separated by quartz (fig.19a). The mode of formation of such a "boxwork" is probably the replacement of ankerite by the iron sulphides, supported by the rhombohedral outlines of inclusions of marcasite in pyrite, and vice versa, followed by the infiltration of quartz along the approximate position of the original ankerite cleavages.

Quartz also infiltrates along cracks in chalcopyrite (fig.19b), and replaces sphalerite. Pseudomorphs after galena are common, the quartz replacing the galena along the cleavage (fig.19c).

Quartz forms pseudomorphs after all the gangue minerals excepting witherite. Perfect pseudomorphs after ankerite occur on the High Pirn Mine, and after calcite scalenohedra on the Stayvoyage Vein. The most common form of pseudomorph after

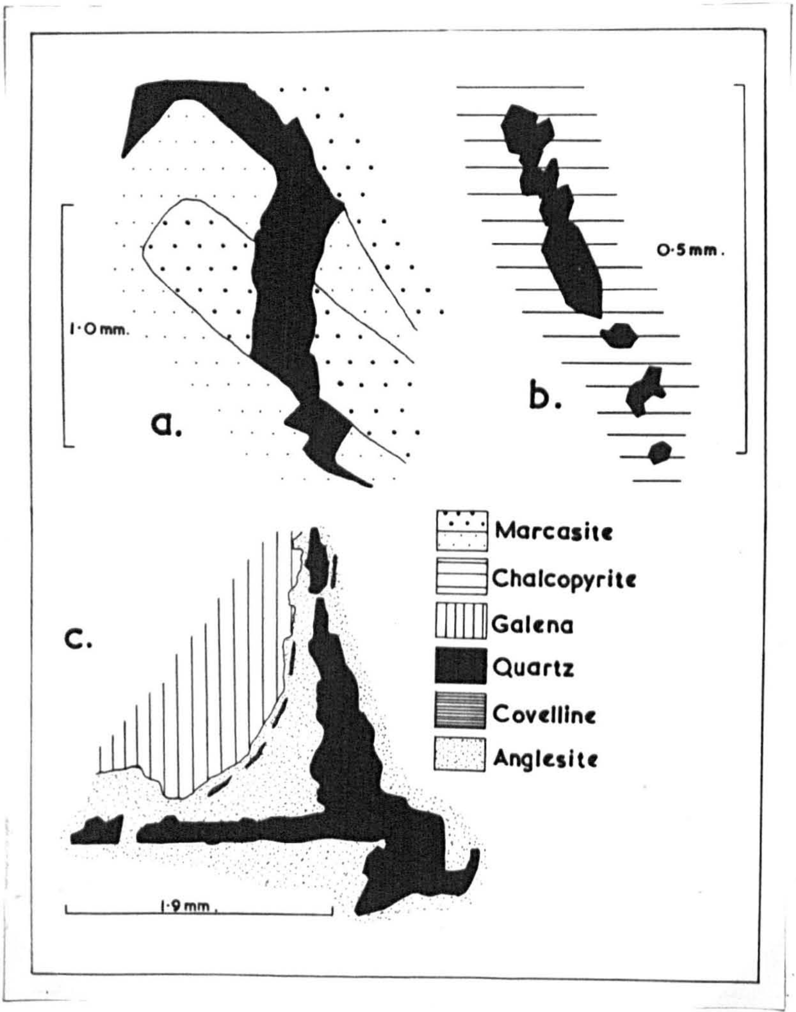


Figure 19. The relationships of quartz.

a. Quartz filling crack in marcasite.
Moffats Shaft, (P.S. 114).
b. Quartz filling crack in chalcopyrite.
Wilsons Shaft, (P.S. 109).
c. Quartz infiltrated along the cleavage
of galena.
High Pirn Mine, (P.S. 131).

Plate XII.

Calcite scalenohedra, and chalcopyrite crystals, (black), encrusting upon quartz.

Scottish Mineral Collection, 83.42, x0.5.

ankerite, calcite, and barytes, is an interlocking mass of quartz plates, often of a rhombohedral pattern, which are abundant over most of the district. Perfect pseudomorphs of quartz after massive radiating aragonite were found on the dumps at Wilsons Shaft.

Quartz later than the gangue minerals was confirmed in microscopic examination, an example being the replacement of barytes along the junction with chalcopyrite in the Belton Grain Vein.

Other primary minerals encrusting on quartz have been observed, two examples of which include the pseudomorph (83-42), described above (plate 12), crystals of chalcopyrite and calcite resting on a quartz pseudomorph after calcite, and secondly small crystals of barytes encrusting on quartz which has partly replaced massive barytes. Such occurrences are, however, rare, and may be explained by assuming a later generation of the encrusting minerals, but the small quantity, and association of the minerals, favours the explanation that in both cases the mineral removed by replacement has recrystallised on top of the quartz.

i. Summary and discussion of the paragenesis of the primary vein minerals.

The paragenetical relationships of the primary vein minerals are diagrammatically illustrated below.

Plate XIII, (opposite).

a. Inclusions of pyrite, (strong white), in galena, (light grey). Euhedral quartz partly replacing the galena.
Bay Shaft, Wanlockhead, x30.
Polished section 145.

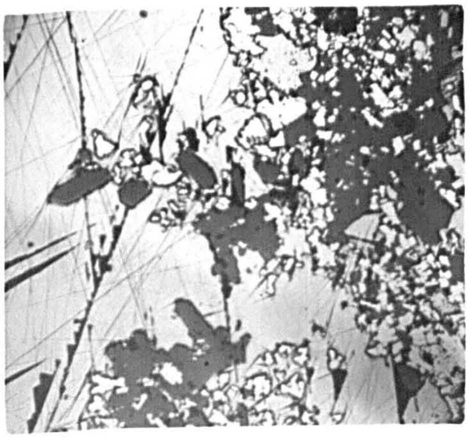
b. Chalcopyrite, (white), euhedral towards sphalerite, (light grey). The occurence of rhombohedral outlines indicates that both chalcopyrite and sphalerite partly replaced the ankerite, (dark grey on the right of the field). The euhedral outlines of sphalerite and chalcopyrite to calcite, (dark grey on the left of the field), demonstrates that calcite was the later mineral.
Moffats Shaft, Leadhills, x30.
Polished section 114.

c. Galena, (scratched grey mineral), in contact with niccolite on the upper and left hand sides of the field. Rammelsbergite, (white), partly replacing ankerite, and occuring in contact with galena and on the periphery of niccolite. The dark grey mineral near the upper limit of the field is quartz, replacing galena on and near the galena-niccolite junction.
Glencrieff Mine, Wanlockhead, x30.
Polished section 117.

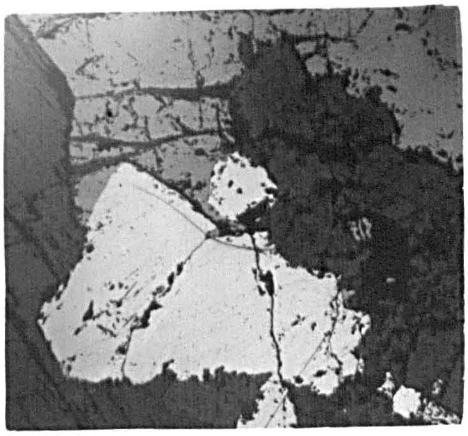
d. Pyrite crystals, (white), encrusting upon sphalerite.
Gordons Vein, Lamb Knowes, Leadhills, x30.
Polished section 99.

e. Crystal of sphalerite, (light grey), encrusting on galena, (white). Calcite, (dark grey), was later than both sulphide minerals.
Gordons Vein, Lamb Knowes, Leadhills, x30.
Polished section 126.

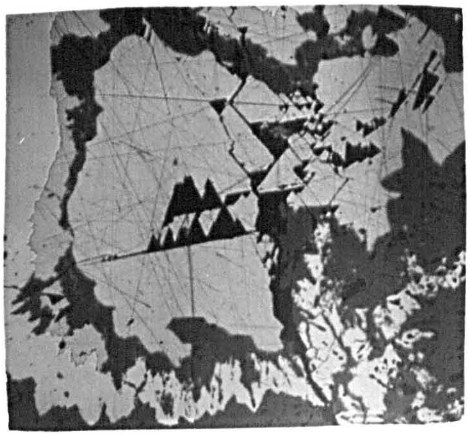
f. Massive intergrowth of galena, (white), and sphalerite, (light grey). The relationship between the two minerals is indicated in the upper left hand corner of the field by the narrow veinlet of galena cutting the sphalerite.
Glencrieff Mine, Wanlockhead, x30.
Polished section 147.



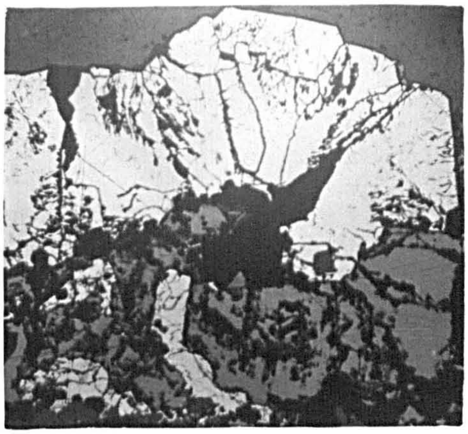
a.



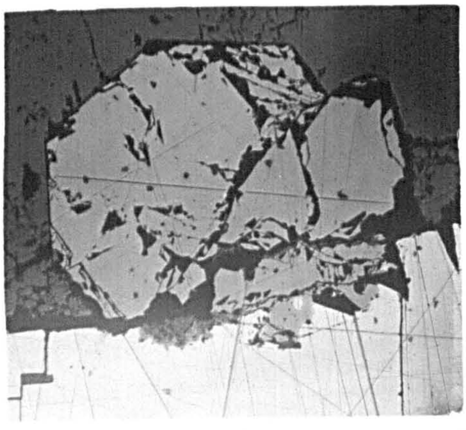
b.



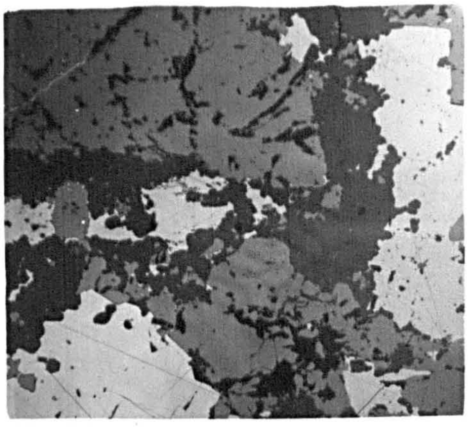
c.



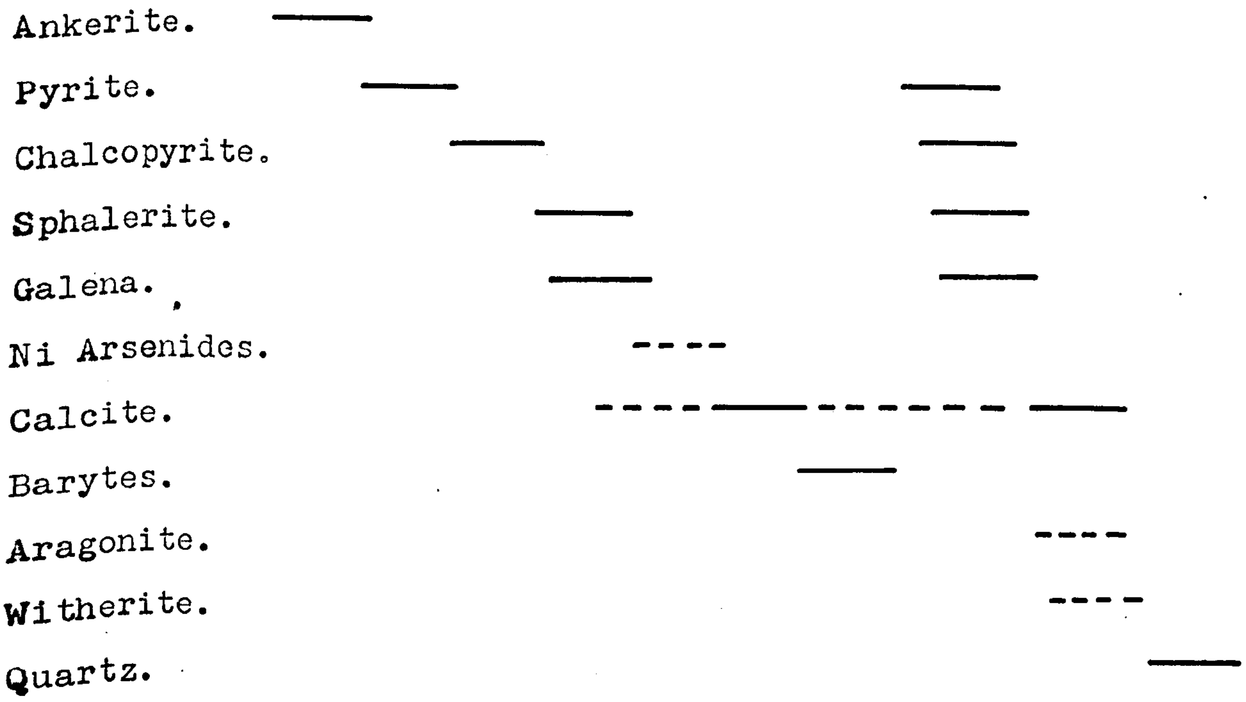
d.



e.



f.



It must be emphasised that whilst this paragenesis represents the relationships of the bulk of the minerals, minor discrepancies of small abundance, for example. calcite, barytes, and chalcopyrite later than quartz (described above), have been disregarded.

The uncertainties indicated in the diagram are due to lack of specimens of the minerals concerned, namely, the Ni arsenides, aragonite, and witherite, all of which are relatively rare minerals in the district. The sphalerite-galena relationship is depicted as overlapping, but as galena is generally replacing sphalerite in the massive intergrowths, the sphalerite was probably formed at a slightly earlier date than the galena.

A striking feature of the paragenesis is the occurrence of two generations of sulphide minerals. The relative amounts of the generations of each mineral could not be ascertained with any exactitude, but from the evidence on the dumps it appears that chalcopyrite, sphalerite and galena are in approximately equal quantities in both generations, whilst the first generation of pyrite preponderates over the second generation. Because of the inaccessibility of the veins in depth, the vertical distribution of the two sulphide generations could not be observed. However, a pointer is given by most of the material on the large dump at the Glencrieff Mine, which probably originated from the deeper parts of the mine, being of first generation sulphide, whilst in the veins near the surface, galena and chalcopyrite were later than the calcite filling of the vein, that is, of second generation.

The formation of the two generations of sulphide could be accounted for by assuming repeated mineralisation, but Edwards (1947, p.118) has shown that such an interpretation should not be invoked unless the weight of evidence renders a simpler explanation impossible, In the Leadhills-Wanlockhead area there is no weight of evidence to suggest repeated mineralisation, as not a single case of the second generation sulphide in contact with the first generation of the same mineral was observed. Thus an alternative interpretation is required, and is provided by Edwards (1952), who remarks (p.39), that "The paragenesis may be further complicated by the phenomena of replacement." The process envisaged is one where the elements of the replaced minerals were redissolved, and crystallised in a later second generation of the early formed mineral.

Evidence for extensive replacement in the primary minerals of the district is abundant, and has been indicated in the preceding diagrams (figs.11-19). Unless precipitated in an open space, each mineral has replaced earlier formed minerals, and the greatest replacement has been effected by the last mineral of the paragenetic sequence, quartz. The late introduction of quartz is considered to have been the main factor in the formation of the second generation sulphides.

The paragenesis of the vein minerals may therefore be suggested to have taken place in the following manner. Firstly, the formation of ankerite, followed by the sulphide minerals, calcite, and barytes, in paragenetical order. These minerals were followed by quartz, which, slowly moving upwards, effected replacement of all the minerals. The elements of the replaced minerals can be visualised as being mobilised and moving upwards with a greater velocity than the quartz, and on reaching a sufficiently high concentration being precipitated as a second generation of the original mineral. The slowly rising quartz, on reaching the site of the second generation mineral, would be later than that mineral. This mechanism would account for the observed relations of the second sulphide generation to quartz.

The introduction of the quartz may have taken place at a slightly later date than the earlier minerals, but the behaviour of the quartz makes it likely that all the minerals originated simultaneously from a common source, and that the quartz had a slower rate of mobility than the other minerals. If this interpretation is correct it can be predicted that the quantity of quartz may increase with depth, and furthermore that with increasing proximity to the source, the position of quartz in the paragenesis would move progressively nearer the commencement of the mineralisation. Thus specimens of massive pyrite and marcasite replacing ankerite, from the Glencrieff Mine, are infiltrated by quartz, the relationships suggesting that the quarts followed the iron sulphide in close continuity.

A partial analogy can be drawn with the Climax molybdenum deposit (Butler and Vanderwilt, 1933), where potash has been leached from a highly silicified core, and moved upwards, the zones of potash addition grading inward and downward to the highly silicified core (Schmedeman, 1938).

A comparison of the primary paragenesis with examples described in the extensive literature reveals certain similarities. Thus Edwards (1947, p.114) presented a summary of paragenesis in ore deposits, in which the sulphide minerals which occur in the Leadhills district were in the order, pyrite, Co and Ni arsenides, chalcopyrite, sphalerite, and galena. A discrepancy in the position of the Ni arsenide is apparent, as in the Leadhills despoit niccolite is later than galena. However, Ni arsenide is stated by Niggli (1929, p.15), to occur after sphalerite and galena, and has been noted in that position in the paragenesis of the Upper Mississippi Valley district (Behre, etc. 1950).

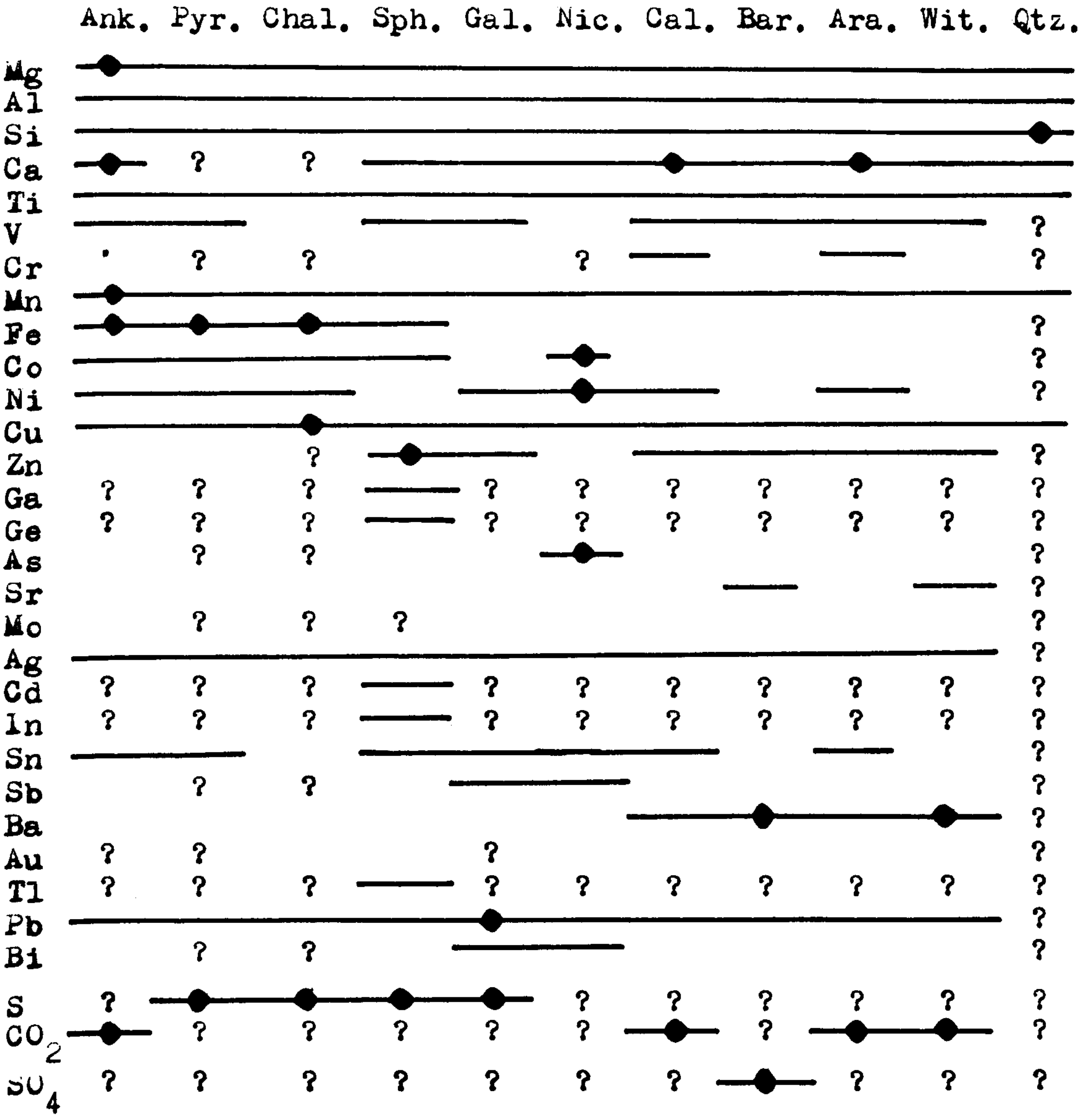
The sequence of the gangue minerals summarised by Edwards (1947, p.114) was "siderite (often manganiferous), fluorite, calcite, barytes". This also corresponds to the paragenesis of the Leadhills district, ankerite representing the manganiferous siderite, and fluorite being absent. Quartz was recorded as the first mineral, and this is anomalous with the Leadhills paragenesis. However, Lindgren (1933, p.544) stated that quartz appears early in the vein filling, but that the deposition may continue long.

j. The distribution of elements.

The distribution of elements through the paragenesis is tabulated below. The second generation of sulphides has been disregarded.

The distribution of the elements in the minerals of the deposit is largely governed by the laws of crystal chemistry. However, the fact of the actual presence of the elements recorded must be controlled either by the character of the source of the mineralising solution, or by the effect of contamination by the country rocks. Elements from the two sources cannot be distinguished with any certainty, although certain speculation can be advanced. Thus the presence in trace amounts in every mineral of Al and Ti may be due to contamination by the country rocks.

The position of Ca and CO_2 in the paragenesis requires comment as both are concentrated in two distinct phases of the primary mineralisation, namely as ankerite and calcite. No analyses of country rock can be quoted from the district, but all the fresh greywackes effervesce freely with acid, and a greywacke from Newmains, Dumfriesshire (Kennedy and Read, 1936, p.122), The distribution of elements in the primary minerals.



?	Element not determined.
—	Element present.
—●—	Concentration of the element.
Gap	Element either absent, or below the limit of spectral sensitivity.

Ank.	Ankerite	Nic.	Ni-arsenides
Pyr.	Fe sulphide	Cal.	Calcite
Chal.	Chalcopyrite	Bar.	Barytes
Sph.	Sphalerite	Ara.	Aragonite
Gal.	Galena	Wit.	Witherite

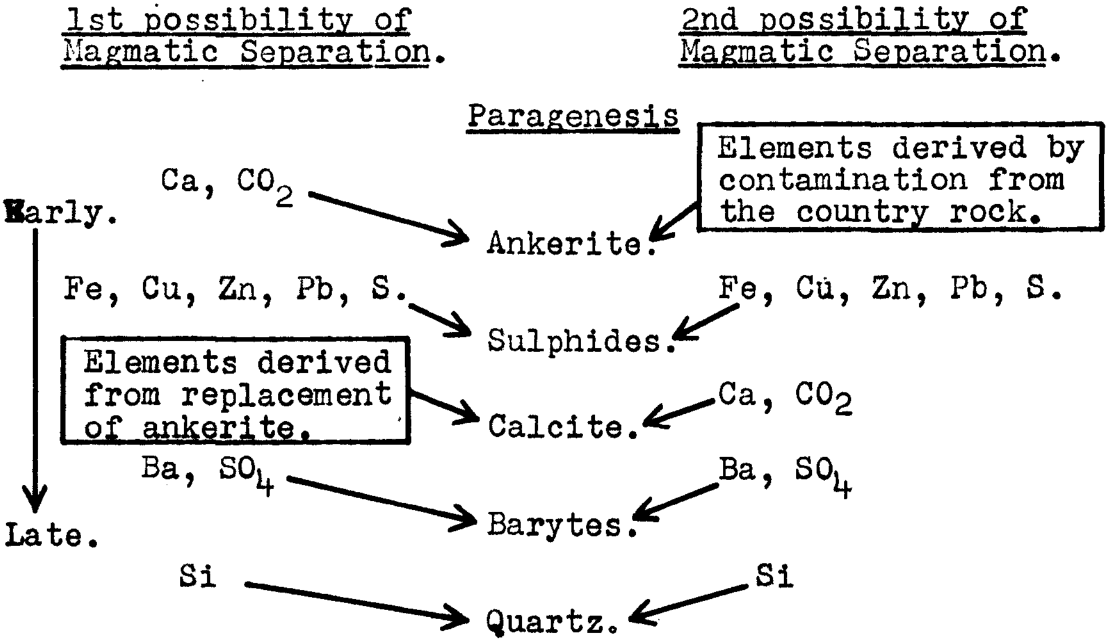
Qtz. Quartz

contained 9.80% CaO, and 6.60% CO_2. This concentration of Ca and CO_2, combined with the presence of Mg, Fe, and Mn, would allow the derivation of the constituents of ankerite from the greywacke. Wager (1929, p.105), Smythe and Dunham (1947, p.72), have ascribed the ankerite of the N. Pennine orefield to the contamination by the rocks formed by the metasomatic effect of the Whin Sill, and the uniformity in composition of the ankerite over a wide area of similar rock type in the Southern Uplands is suggestive of a control on the ankerite formation by the composition of the country rock. However, in the absence of quantitative data, the role of the country rock cannot be fully ascertained, whether it merely contaminated solutions consisting of magmatic Ca, Mg, and CO_2, or whether all the ankerite originated from the country rocks in response to the stimulus of the conditions preceding the introduction of the sulphide minerals.

Likewise doubt exists on the origin of the main generation of calcite, the modes of formation envisaged being either an introduction of magmatic Ca and CO_2, or the re-precipitation of $CaCO_3$ derived from the replacement of ankerite by the ore minerals and quartz, or a combination of both factors. The true interpretation is dependent on the quantitative relationships between ankerite and calcite, which are not available.

As the mineralisation is visualised as having originated from a magmatic source, the elements concentrated would, given favourable conditions, separate from that source in a definite order. On this basis, and disregarding contamination

Possibilities for the position of Magmatic Ca and CO_2 in the Paragenesis.



effects, the concentration of Co and CO_2 in two major positions in the paragenesis, namely as ankerite and calcite, is anomalous, as in such a magmatic separation Ca and CO_2 would be expected to occur in one position only. Two possibilities of a magmatic separation, and the distribution of the elements in the paragenesis are indicated opposite.

This view of the magmatic separation necessitates the derivation of one, or both, concentrations of Ca and CO_2 from a source other than the magmatic source. Both ankerite and calcite may well have been entirely derived from the country rock, but if some Ca and CO_2 did originate from a magmatic source, then no definite evidence can be invoked to substantiate the claim of either ankerite or calcite. Thus ankerite may be regarded as partly of magmatic origin because of the variety of elements incorporated in the mineral, whilst calcite may be similarly regarded because of the definite cross-cutting relationships of calcite to ankerite in material presumably from the deepest parts of the Glencrieff Mine, and because of the provision of an ordered sequence of separation from the magmatic source of sulphide, carbonate, and sulphate.

The small quantity of second generation calcite and aragonite are considered to have formed by reprecitation of the Ca and CO_2 derived from the replacement of the main calcite, in a manner analogous to that envisaged for the ore minerals.

From this discussion it is apparent that no definite distinction can be made between the elements of magmatic origin, and those incorporated by contamination. For this reason the geochemical character of the mineralisation can best be judged on the elements which are not present, rather than on the elements which are present in the minerals.

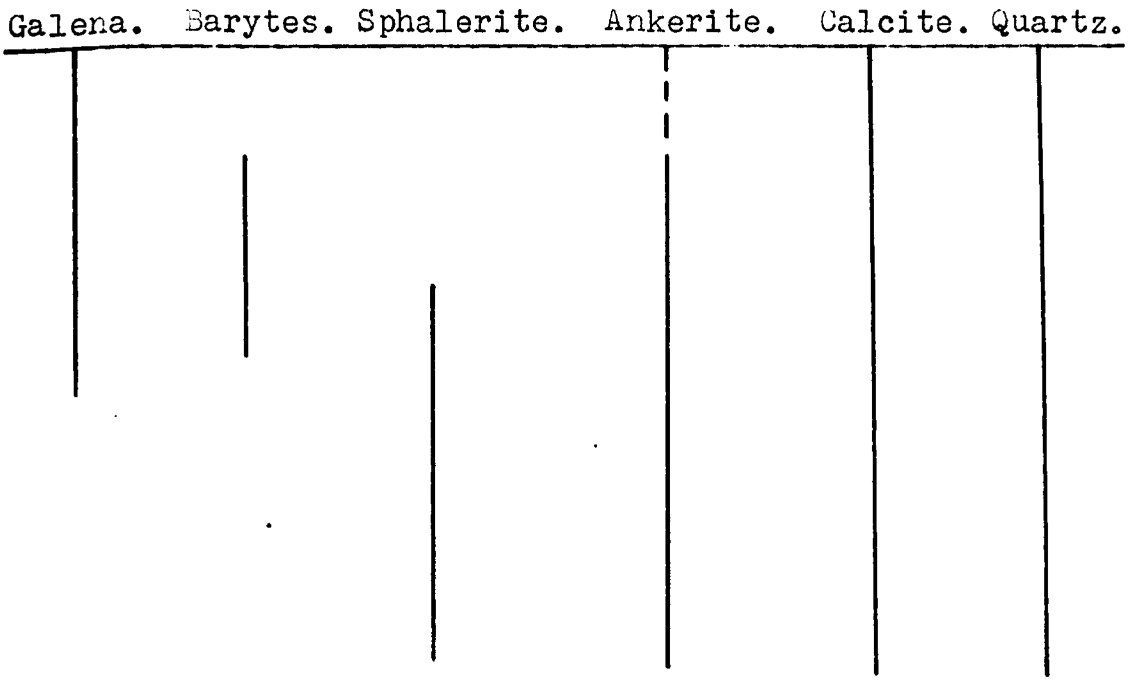
k. Zoning of the primary minerals.

Conclusive evidence of the presence, and distribution of mineral zones in the district has not been obtainable, owing to the mines not being opened in depth.

However, certain suggestions of a vertical zoning can be obtained from the limited literature on the deposits. Thus Brown (1918, p.132), in describing the New Glencrieff Vein, states that "... the finding of specimens from adit level to the 240 level has almost been continuous, but the varieties found have gradually changed as the mine gets deeper". He further points out (p.133), that the upper workings of the New Glencrieff Vein were rich in barytes, but in the lower workings the mineral is "seldom if ever, seen". Wilson (1921, p.23) described a further vertical change in the New Glencrieff Vein, at the south end of the vein the top levels were rich in galena, whilst from the 120 fathom level downwards the galena gradually gave out, until at the 200 fathom level the vein consisted almost entirely of sphalerite. A similar zonal sequence is present in Brow Vein (p.31), the ores at the high levels consisting mainly of galena, whilst at the 187 fathom level an intergrowth of galena and sphalerite occurred.

The only indication of lateral zoning given in the literature is by Wilson (1921, p.23), who stated, in the description of the New Glencrieff Vein, at the 120 fathom level, that "... a peculiar fact in connection with the blende is that it is restricted to the south end of the vein, and ends abruptly to the north, though quite recently specimens of blende have been obtained in the 240 fathom level at the N.W. end of the New Glencrieff Vein". Evidence of a lateral zoning is given by a comparison of the mineral contents of the old dumps to the east of a line connecting the foot of Glen Franka, to the confluence of Risping Cleuch and Elvan Water, and further continued to the confluence of Bellgill Burn with Glengonnar Water. The dumps are both old shaft and adit workings, generally of small extent, and it is considered that the minerals on the dumps can be taken as representative of the parts of the veins worked. All the dumps to the east of the line mentioned above, are characterised by the absence of sphalerite and barytes, the principal minerals being galena, calcite, and quartz. Immediately to the west, the Straight Brae, Risping Cleuch, Broad Law, and Wool Gill Veins all bear barytes.

If the lateral and vertical zones are regarded as having equivalence, as has been demonstrated in the case of the North Pennine orefield (Dunham, 1934, p.703), then, from the foregoing evidence, the mineral zones depicted below can be recognised in the Leadhills-Wanlockhead area.



The zonal distribution of ores was first publicly recognised early in the 20th century by various well-known authorities such as Spurr, Emmons, and Lindgren, and has been discussed since that time by many geologists, both in general, and as applied to specific districts or mines. Emmons (1924), summarised the whole zonal sequence, and the Leadhills-Wanlockhead minerals fall into his zone seven, viz., galena veins, sphalerite increasing with depth. The uppermost gangue zone of barytes conforms with the zoning described from the North Pennine orefield (Duhham, 1934, p.705).

1. Relationship of the mineral zones to the paragenesis.

Falling temperature is generally accepted as the prime cause of zonal distribution (cf. Dunham, 1934, p.705). On this concept the primary minerals would be precipitated within appropriate temperature ranges in the paragenetical order described namely, ankerite, pyrite, chalcopyrite, sphalerite, galena, calcite, and barytes. Thus the first stage in the mineralisation would result in the formation of zones according to theoretical principles. However, the later phenomena of replacement, mainly due to the introduction of quartz, was accompanied by the formation of second generation minerals. If either a rise or fall in temperature accompanied the introduction of quartz, the zonal sequence would tend to be partly obliterated, each mineral retaining either the upper or lower limit of precipitation, but the opposite limit moving either upwards in response to increased temperature, or downwards in response to a decrease in temperature. As has been emphasised, the zonal relationships could not be determined accurately, but the fact that some zonal sequence is recognizable would indicate that the late introduction of quartz took place at a similar temperature to that of the first stage of the mineralisation.

m. Stress conditions during the main mineralisation.

The structural evolution of the veins prior to the emplacement of the minerals has been discussed in earlier sections and may be briefly summarised as the delineation of the veins, and formation of open spaces, during the Caledonian Orogeny, followed by further deformation, including the offsetting of the veins along rejuvenated strike faults. During the evolution of the veins system, quartz of the early-stage mineralisation suffered deformation, as evidence by slickensiding and brecciation.

Some conception of the stress conditions at the commencement of the main mineralisation may be ascertained by a study of one specimen (plate 14), from the Glencrieff Mine, Wanlockhead. This specimen illustrates admirably the metasomatic effects of the mineralising solutions, the rock becoming progressively "bleached" with increasing proximity to the vein. The gradations of the bleached rock are controlled by small veinlets, parallel to the main vein, filled with ankerite and quartz. These veinlets originated by tension at an angle to the vein, as in one case a detrital plagioclase was broken through. A striking confirmation of the tension, and complementary pressure parallel to the vein, is provided by the abundant pyrite crystals developed in the altered rock. Every pyrite crystal is orientated with a long diagonal axis at right angles to the vein, and furthermore, elongation of this axis by distortion of the crystal has been instigated (plate 15), together with the formation of pressure fringes (cf. Hills, 1953, p.169), filled by later chlorite ankerite, and quartz.

The demonstration of tension at an angle to the vein in one specimen, does not, unfortunately, allow the postulation of tension throughout the district, but it does indicate that some force was being exerted on the rocks at the commencement of the main mineralisation.

Evidence of deformation during the course of the main mineralisation is very slender. Small cracks occur in pyrite, sphalerite, and niccolite, filled by later minerals, and the calcite filling of the Belton Grain Vein is cut by lenticles of barytes. In the minerals the opposite walls of the cracks are

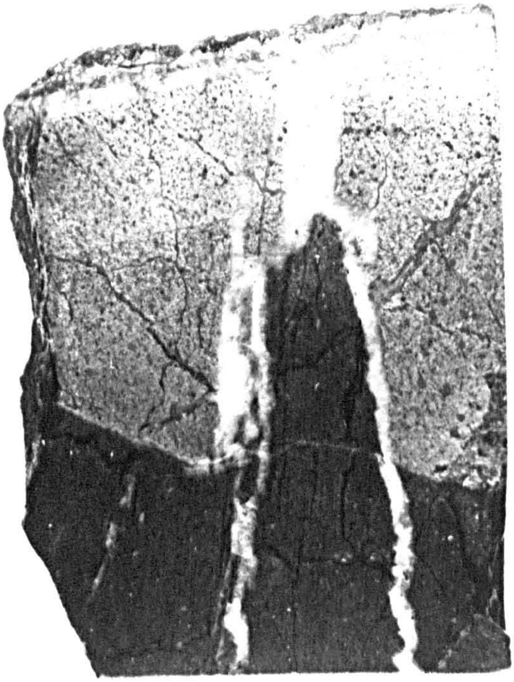


Plate XIV.

Specimen showing the metasomatic effects in proximity to a mineral vein, Glencrieff Mine, Wanlockhead, x1.

The cross cutting relationships of the ankerite vein, (top of the specimen), to the quartz veins, (white), clearly demonstrate the earlier formation of the latter.

In proximity to the ankerite vein the greywacke is bleached to a grey colour, due to a large development of pyrite, (black), and ankerite. Away from the vein the colour becomes increasingly darker, with decreasing pyrite and ankerite. The boundaries of the colour changes are small quartz veins, which slightly displace the large quartz veins. A detrital plagioclase was broken in the formation of the small quartz veins.

The above facts, taken in conjunction with the deformation of the pyrite crystals, (plate XV), allow the interpretation that the ankerite vein was formed by strong tension, approximately normal to the vein, before the introduction of the mineralising solutions.

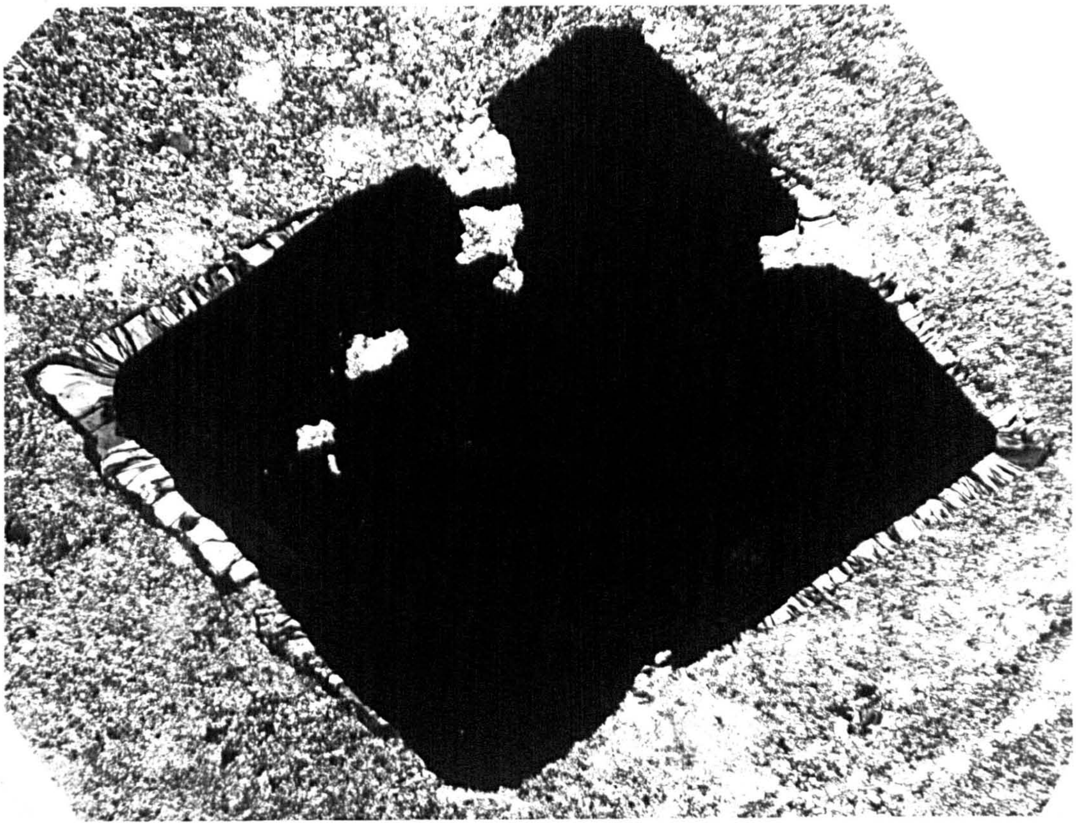


Plate XV.

Pyrite crystal elongated and showing well developed pressure fringes, filled with quartz, x90.

The example is taken from the hand specimen, plate XIV, and is orientated in that specimen so that the long diagonal of the pyrite is normal to the ankerite vein.

generally coincident, which, together with the form of the barytes lenticles in the Belton Grain Vein, would suggest a tensional force, acting approximately at right angles to the veins.

These small cracks and veins are indicative of a very slight stress, most probably tension, during the actual mineralisation, but no evidence of any movement after the completion of the mineralisation exists. Thus of all the specimens examined in the field and museum, only one (45.77), of queried locality Leadhills, was observed which showed slickensides, and slickensides in galena can easily be produced by the breaking during mining operations.

From the foregoing flimsy evidence it may be tentatively deduced that the commencement of the mineralisation was attended by fairly strong tension, which decreased through the mineralisation to become almost negligible, and that no evidence of a further recurrence of deformation is present.

C. PARAGENESIS OF THE SECONDARY MINERALS.

The secondary minerals in the veins are products of the oxidation of the primary minerals, and can generally be related to the primary source mineral. The most common secondary minerals are derivatives of the sulphide minerals, and will be described under the metal of the primary mineral, namely lead, copper, and zinc.

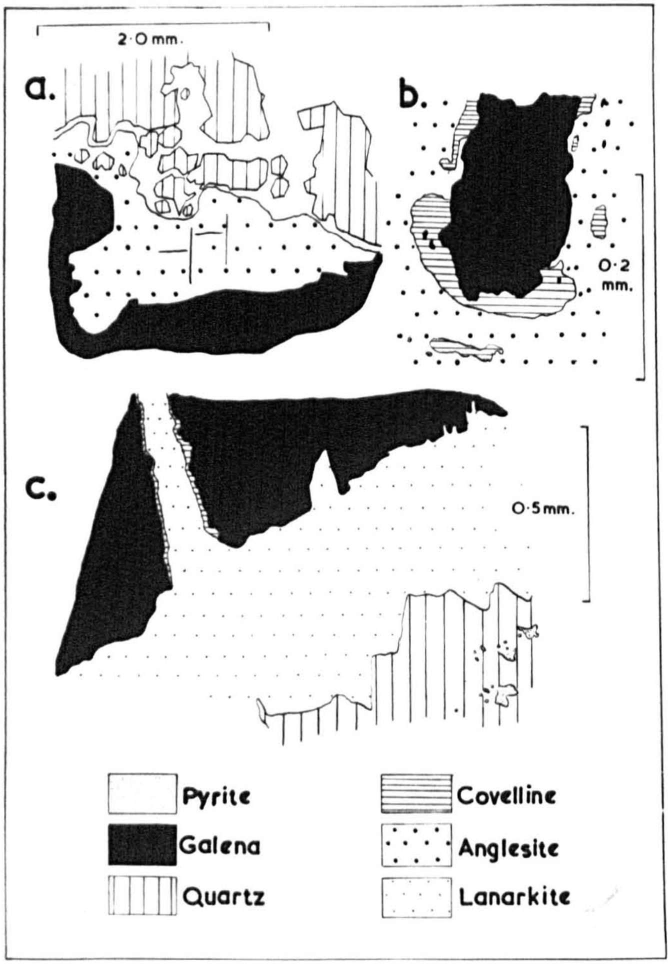


Figure 20. Oxidation products of galena.

a. Galena replaced by anglesite.
Big Wool Gill, (P.S. 112).
b. Galena replaced by covelline, followed by anglesite.
High Pirn Mine, (P.S. 131).
c. Galena replaced by covelline, followed by lanarkite.
Whytes Cleuch, (P.S. 101).

The relationships of the secondary minerals were chiefly determined in hand specimen, the main criterion used being that of encrustation. This study was supplemented by polished sections.

Although no rigid paragenesis is present, owing to variations in the composition of the solutions, several general sequences have widespread occurrence in the district.

a. The Lead secondary minerals.

The only primary lead mineral in the veins is galena, PbS, and previous writers (Anderson, A.L., 1930; Lindgren, 1933, p.854; Swartzlow, 1933), on the oxidation of galena concluded that the general sequence is the formation of anglesite, $PbSO_4$, followed by cerussite, $PbCO_3$. This sequence was confirmed in the galena ores of the Leadhills-Wanlockhead district. However, in ores where the galena is associated with chalcopyrite, $CuFeS_2$, the first formed mineral was generally covellite, CuS, pseudomorphs of covellite after galena having been recorded (e.g., 1001.218).

The covellite is followed by sulphate, thus reverting to the normal sequence. The sulphate is largely anglesite (fig. 20a, b), though one case of lanarkite, $Pb_2(SO_4)O$, replacing galena from Whytes Cleuch, was noted (fig.20c). Anglesite occurs as a pseudomorphous rim to the oxidised galena, replacing it along the cleavages, and may be black in colour due to disseminated galena, with a gradation outwards to a white colour. Recrystallisation of the anglesite gives the beautiful crystals common on specimens from the Susanna Vein.

In chalcopyrite bearing galena ores, such as the Cove, and East Stayvoyage, anglesite may be encrusted upon by caledonite, $Pb_5Cu_2(SO_4)_3(CO_3)(OH)_6$, and linarite, $PbCu(SO_4)(OH)_2$. Pseudomorphs of both these minerals after anglesite occur.

Cerussite, $PbCO_3$, replaces the anglesite round cores of oxidised galena, all gradations of replacement existing. The carbonate may occasionally replace galena without any intermediate sulphate stage, and in a specimen from Glencrieff Mine, hydrocerussite, $Pb_3(OH)(CO_3)_2$, has replaced galena along its cleavages. The massive carbonate resulting from the replacement is often black in colour, analogous to anglesite.

Cerussite is the starting point of many of the further mineral sequences present in the district. In the exclusively lead ores, the most common replacement of cerussite is by members of the pyromorphite group, $Pb_5(PO_4)_3Cl$, which occur both in a massive form pseudomorphous after cerussite, or as hexagonal crystals. In one specimen from Whytes Cleuch, the intermediate replacement of cerussite by apatite, $Ca_5(PO_4)_3Cl$, was followed by pyromorphite. Hydrocerussite may replace cerussite and pyromorphite (270.609). Vanadinite, $Pb_5(VO_4)_3Cl$, with the descloizite group, $(Cu\text{-}Zn)Pb(VO_4)(OH)$, occasionally represent the end stages of this paragenesis.

The second sequence after cerussite in exclusively lead ores is rather uncommon in the district, and consists of leadhillite, $Pb_4(OH)_2(SO_4)(CO_3)_2$, and lanarkite, $Pb_2(SO_4)O$. Leadhillite is only genetically associated with massive, as opposed to crystals of, cerussite, as on Mine Hill. Material from the

Susanna Vein and Cove Vein illustrated the relationship between leadhillite and lanarkite, the lanarkite invariably resting upon the leadhillite. Leadhillite and lanarkite formed on pyromorphite in the Hopeful Vein.

When the copper ion was present in appreciable quantities, the mineral sequence after cerussite becomes more complicated, and shows little uniformity. Several of the parageneses include, cerussite-malachite-linarite, cerussite-linarite and caledonite-anglesite, cerussite-leadhillite-caledonite, and cerussite-hydrocerussite-malachite.

The rare minerals of the district, crocoite, $PbCrO_4$, and phoenicochroite, $Pb_3O(CrO_4)_2$, from the Hopeful Vein, are both embedded in massive white cerussite. The chromium bearing pyromorphite has similar paragenetical relationships to the other pyromorphite.

It must be emphasized that the relationships described above do not include all the sequences present in the area, which show considerable variation, as indicated in the mixed lead-copper minerals. This variation can be expected from solutions of varying composition. However, a certain definite paragenesis is widespread over the district, namely, anglesite-cerussite, followed either by pyromorphite, or by leadhillite-lanarkite.

The formation of anglesite has been ascribed to the direct oxidation of galena (references quoted above), and if carbonic acid were present, cerussite, which is less soluble than anglesite, would replace that mineral. The formation of pyro-

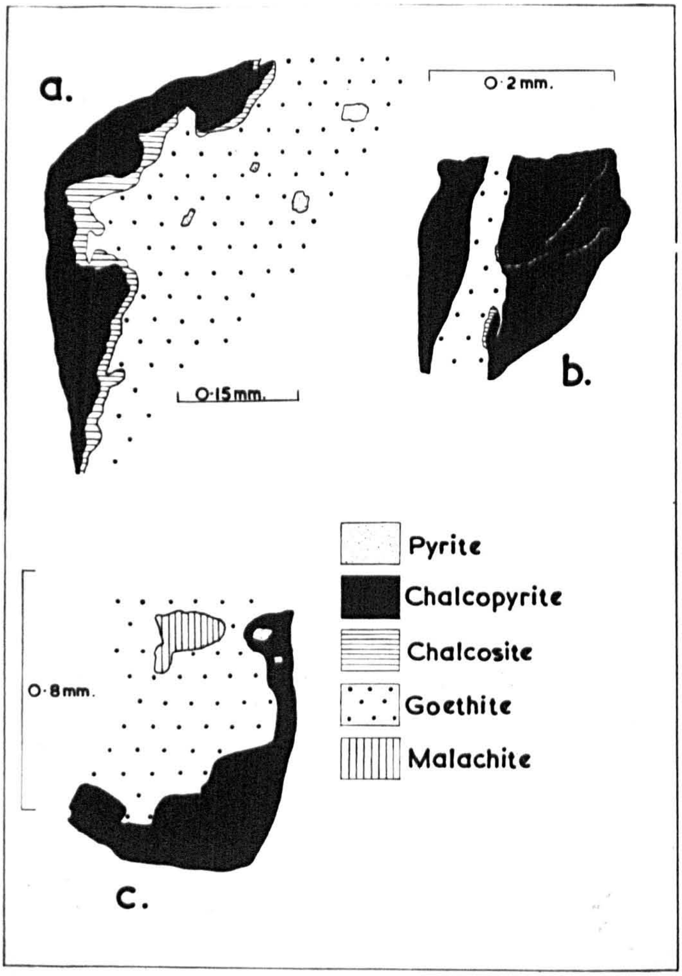


Figure 21. Oxidation products of chalcopyrite.

a. Chalcopyrite oxidised to chalcosite and goethite. Note that original inclusions of pyrite in the chalcopyrite appear unaffected by the oxidation.
Glencrieff Mine, (P.S. 111).

b. Chalcosite replacing chalcopyrite along cracks. Goethite is later than the chalcosite.
Glencrieff Mine, (P.S. 111).

c. Malachite formed in the goethite.
Susanna Vein, (P.S. 118).

morphite can be tentatively attributed to the action of orthophosphoric acid, whilst the leadhillite and lanarkite may be regarded as due to a progressive change in the solutions from carbonic to sulphuric. Similar changes in both anion and cation can be invoked to explain the other sequences mentioned.

b. The secondary minerals of Copper.

The oxidation of copper ores has been extensively described in the literature on ore deposits. A general study was made by Schwartz (1934), who arrived at a paragenesis of sulphide, followed by cuprite, and malachite, whilst Lindgren (1933, p.832), describes the formation and occurrence of the secondary sulphides of copper.

The only primary copper mineral in the Leadhills-Wanlockhead district is chalcopyrite, $CuFeS_2$. The secondary alteration of the mineral is well illustrated on material from the dumps by the side of the road near Glencrieff Mine, where massive chalcopyrite is replaced along cracks by chalcocite, Cu_2S, and goethite, $FeOOH$, as depicted in Fig.21. It is noticeable that the chalcopyrite is replaced with greater rapidity than inclusions of pyrite, confirming experimental work of Koch and Grassely (1951). Malachite, $Cu_2CO_3(OH)_2$, crystallised after the goethite, as radiating crystal aggregates, followed by numerous small crystals of brochantite, $Cu_4(OH)_6(SO_4)$, which in turn were followed by small amounts of linarite, $PbCu(SO_4)(OH)_2$, and white platy cerussite, $PbCO_3$.

Explanations have been advanced for the formation of chalcocite by the action of sulphuric solutions on chalcopyrite, and of goethite by oxidation of ferric sulphate (e.g. Lindgren, 1933, p.829). The formation of malachite indicates the presence of carbonic acid in the solutions, and the succeeding minerals suggest a compositional change in the solutions through sulphuric to carbonic, together with a progressive increase of lead.

The majority of the remaining copper mineral parageneses have been covered in the preceding section, and are complex, showing little uniformity. It is of interest, however, to note that brochantite, $Cu_4(OH)_6(SO_4)$, and caledonite, $Pb_5Cu_2(SO_4)_3(CO_3)(OH)_6$, do not occur together in the district. Brochantite occurs in oxidised copper ores, whilst both caledonite and brochantite are present in oxidised lead-copper ores, both associated with linarite, $PbCu(SO_4)(OH)_2$, and both often pseudomorphous after galena. Because of this relationship, and the chemical composition of the minerals, it would appear that linarite and caledonite are formed from solutions in which lead predominates over copper, but, of the two minerals, only linarite is formed from solutions in which copper exceeds lead. Brochantite is formed under the latter conditions, and is the only mineral formed from solutions deficient in lead. The exact ratio of Pb:Cu to give the requisite conditions is not known. Thus in the sulphates a sequence is present, depending on increase of copper with respect to lead, through anglesite, caledonite, linarite to brochantite, the conditions allowing the formation of caledonite ting the formation of brochantite, and vice versa.

c. The secondary minerals of Zinc.

The only specimen carrying all the zinc secondary minerals was an unnumbered specimen from the Grant Institute. The locality was merely "Leadhills". The paragenesis of the minerals is straightforward, each successive mineral encrusting upon the preceding one, and comprises hemimorphite, $Zn_4(OH)_2(Si_2O_7)H_2O$, followed by aurichalcite $(ZnCu)_5(OH)_3(CO_3)_2$, and hydrozincite, $Zn_5(OH)_3(CO_3)_2$.

Other secondary minerals present in the district include barytes, $BaSO_4$, and gypsum, $CaSO_4.2H_2O$. The latter mineral can be accounted for by the interaction of sulphuric with calcium bearing solutions, given the correct concentration conditions. Barytes occurs in thin, colourless, hexagonal plates, encrusting upon malachite. It has been suggested (Palmqvist, 1939), that as barium sulphate is only slightly soluble, barium is transported as $BaH_2(CO_3)_2$, which is more soluble that $CaH_2(CO_3)_2$. Precipitation of barytes from such a solution would be facilitated by interaction with a sulphuric solution.

d. The depth of oxidation.

No observations of the depth of the oxidation zone in the district could be made. However, Wilson (1921, p.19) noted the presence of hemimorphite between the 80 and 100 fathom levels in the south end of the New Glencrieff Vein, and stated (p.20), that the base of the oxidised zone in that part of the vein was 200 fathoms below the surface. Brown (1918, p.132), described the occurrence of hemimorphite, cerussite, hydrocerussite, and pyromorphite, from between the 80 and 120 fathom levels in the New Glencrieff Vein. The minerals occur either in vugs or in the mass of the vein, and in the latter case were pseudomorphous after the primary minerals, fine pseudomorphs of hemimorphite after calcite being recorded.

The occurrence of such a deep oxidation zone is not characteristic of the whole district, as Mr. J. Blackwood of Leadhills pointed out that the veins of the Leadhills Dod, i.e. Brow, Sarrowcole, Hopeful, Marchbank, Scar, and East Stayvoyage, had an oxidation zone 60 fathoms in depth (oral communication).

According to Wilson (1921, p.20), at the south end of the New Glencrieff Vein, the 120 fathom level was driven through a wide, open, well watered fissure, and he suggested that water was finding its way into the south of the vein, and was flowing northwards, the flow of water presumably effecting the deep oxidation.

As the present day conditions of the water table are only little known, and nothing is known about the flow of the water through the veins, no constructive criticism of Wilson's suppositions will be offered.

IV. GENERAL DISCUSSION OF THE MINERALISATION.

THE CLASSIFICATION OF THE ORE DEPOSIT.

The majority of the lead-zinc veins are regarded as having been deposited from solutions of deep-seated origin, (cf. Dunham, 1950, p.13), and, according to Niggli (1941), a genetic classification should take into account the temperature of the mineralisation, the place of separation of the ore bearing solutions, the physico-chemical state of the solutions, and the distance from the source, and from the surface of the earth.

The approximate temperature of the mineralising solutions is generally indicated by the mineral assemblage, and on this basis, the absence of high temperature silicates and of textures such as the solid solution of chalcopyrite and sphalerite, point to the temperature not being high. This deduction is supported by the character of the minor elements incorporated in the sphalerite, and by the application of the work of Kullerud (1953), by which the actual temperatures of the mineralisation can be ascertained. The maximum and minimum temperatures calculated were 281°C and 143°C. As the specimens on which the determinations were made cannot be localised accurately, the figures given cannot be regarded as the true maxima and minima of the deposition, but serve to indicate the order of the temperature.

The place of separation of the ore bearing solutions will be commented upon more fully in a later section, but, adhering to the terminology of Niggli, the deposits may be classified as plutonic. The physico-chemical state of the solutions may, by analogy with other deposits, be regarded as hydrothermal. From the marcasite-pyrite relationship the solutions may tentatively be considered to have been acid in the early stages of the mineralisation, changing fairly rapidly to alkaline, and therefore supporting the conclusions of Schmedeman (1938).

A quantitative approach to the problem of the depth of formation of the deposits can be made. Thus if a gradual upwards decrease in temperature took place in the mineralisation, as is suggested by mineral zones, then an approximate figure for the depth of the deposition can be calculated from the determined temperatures to represent the conditions at the top and bottom of the range of workings in the veins. By this method, the surface height above sea level was approximately 3000', and the minerals deposited between 1800' and 3600' below the surface. As will be appreciated, owing to the absence of localised specimens these figures can be claimed only to give the order of the depth of deposition. An alternative method of calculating the height of the area in the post Carboniferous period is provided by the outlier of Permian rocks to the north of Leadhills. These rocks dip to the north with an average inclination of 15°, and in the absence of faulted margins, and assuming no regional tilting, this dip can be considered depositional. By further assuming a constant slope upwards to the Leadhills area, the height of that area was approximately 4000', a figure of similar order of magnitude to that derived from the temperature.

The Leadhills-Wanlockhead mineralisation can therefore be summarised as of a low to intermediate temperature, without direct evidence of igneous affiliation, hydrothermal, probably deposited at less than 5000' below the surface, and with a vertical component of at least 1800'.

The deposits are of a similar mineral assemblage to the Mesothermal group of Lindgren (1933), though the temperature and depth are rather smaller than the ranges given (p.529). However, in the Lindgren-Graton classification adopted by Dunham (1950, p.14), the deposits form an admirable example of the deep mesothermal veins and replacements.

THE AGE OF THE DEPOSIT.

a. Local Evidence.

The mineralisation of the Southern Uplands was assigned, by Finlayson (1910), to the Hercynian Orogeny, chiefly on comparison with other areas, and the fact that the mineral veins strike transversely across the Caledonian fold axes. However, from a study of the structural relations it has been shown that the main vein directions in the Leadhills-Wanlockhead area could have originated under late Caledonian stress, and so invalidates the structural argument of Finlayson.

A statistical analysis of the structural trends of the Leadhills-Wanlockhead veins (fig.4), reveals the presence of a minority of veins trending N.W. to W.N.W., including Brow, Susanna, and Glen Eas Veins. This trend is predominant in the remainder of the Southern Uplands (fig.4, encl.2). The formation of W.N.W. veins of considerable length such as the Brow Vein, cannot be easily accounted for by the stress conditions of the Caledonian Orogeny, and it is of significance that the trend of these veins is parallel to both Permian and Tertiary dykes in the Southern Uplands. Evidence of a relationship between the W.N.W. veins and the dyke intrusion is provided by the Black Craig Vein, near Newton Stewart (Wilson, 1921, p.50), where the minerals occur in lenticular shaped spaces between the vein walls and the margins of a dyke of sinuous course. The dyke was classified "basalt" by Wilson (p.51), though dykes similarly classified at Strontian (p.84), proved to be monchiquites (oral communication by Professor Kennedy).

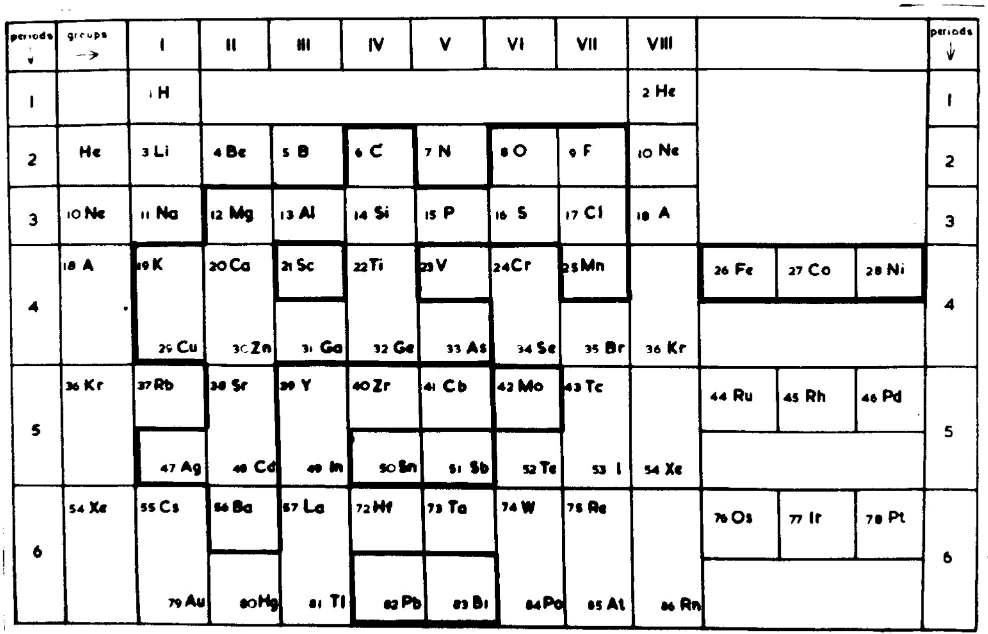
It would appear, therefore, that the W.N.W. veins can be regarded as post Caledonian. As the mineral veins over the whole of the Southern Uplands have great geochemical and areal similarities they are most probably of a similar age and origin, and the vein to dyke relationship in the Black Craig Vein suggests that the mineralisation was post monchiquite dyke phase, and therefore probably post-Permian in age.

Some measure of support is given to this conclusion by the fact that negligible post mineralisation movement was evidenced in the Leadhills-Wanlockhead district, though such support must be treated with caution, particularly as direct observation of the veins below the zone of oxidation could not be made.

B. Regional Evidence.

Finlayson (1910) advanced the view that all the lead-zinc deposits in the British Isles were of an Hercynian age, and since that communication opinion has been divided, the general tendency being to regard the deposits in the Lower Palaeozoic rocks as genetically connected to the Caledonian, rather than to the Hercynian Orogeny (cf. Jones, 1922, p.179).

If all the lead-zinc deposits were regarded as of a similar age and origin, it would be expected that all would show similarities in geochemical assemblage, within the limits imposed by the character of the country rock. A comparison between the elements recorded from a definite post Carboniferous deposit, the N. Pennine orefield (Dunham, 1948), listed below, and the elements detected in the Leadhills-Wanlockhead district, reveals the presence of fluorine, in fluorite, CaF_2, in the N. Pennine



periods ↓	groups →	I	II	III	IV	V	VI	VII	VIII		periods ↓
1		1 H							2 He		1
2	He	3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	10 Ne		2
3	10 Ne	11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl	18 A		3
4	18 A	19 K 29 Cu	20 Ca 30 Zn	21 Sc 31 Ga	22 Ti 32 Ge	23 V 33 As	24 Cr 34 Se	25 Mn 35 Br	36 Kr	26 Fe 27 Co 28 Ni	4
5	36 Kr	37 Rb 47 Ag	38 Sr 48 Cd	39 Y 49 In	40 Zr 50 Sn	41 Cb 51 Sb	42 Mo 52 Te	43 Tc 53 I	54 Xe	44 Ru 45 Rh 46 Pd	5
6	54 Xe	55 Cs 79 Au	56 Ba 80 Hg	57 La 81 Tl	72 Hf 82 Pb	73 Ta 83 Bi	74 W 84 Po	75 Re 85 At	86 Rn	76 Os 77 Ir 78 Pt	6

Elements recorded from the N. Pennine Orefield.

orefield, whilst no quantity of fluorite has been recorded from the Leadhills area. As this was the only discrepancy in the elements present in both deposits, a review of the distribution of fluorite was made, and the startling fact revealed that, not only in the British Isles, but over the whole world, fluorite, although present in small amounts in other rocks, is concentrated in limestones. Examples of this concentration include the N. Pennine orefield (cf. the Lake District); Derbyshire; N. Wales (cf. Central Wales); Kentucky-Southern Illinois; E. Tennessee; Park City, Utah; Coso, California; Mexico, etc. (cf. Dunham, 1950, pp.24-35). Such concentrations of fluorite cannot be merely fortuitous, and could be due to either an absence of fluorine in the source of the lead-zinc deposits in rocks other than limestone, to derivation of the fluorine from the limestone, or, finally, to concentration of the introduced fluorine by some characteristic of the limestone.

As the validity of the first of these factors in under question, the possibilities of the remaining suggestions will be discussed. Figures for the abundance of fluorine in sediments include 250 g/ton in Ordovician limestone, 510 g/ton in Ordovician and Cambrian shales (Rankama and Sahama, 1950, p.764), and 210-550 g/ton in limestone (Goldschmidt, 1954, p.579). Whether the concentration is sufficient to account for the fluorite deposits in limestone is not germane to this speculation, as if the distribution of fluorine was controlled solely by the amount of the element in the country rock, the equally high fluorine content of other sediments would allow the formation of fluorite in rock types other than limestone. Although no experimental evidence can be quoted, the fixation of fluorine in such a highly co-ordinated structure as fluorite, at low to intermediate temperatures probably demands a special environment, and the abundance of fluorite in limestones suggests that a high concentration of Ca is required. The fact that calcite is not an abundant mineral in the N. Pennine orefield (Dunham, 1948, p.93), would indicate that much of the calcium combined with fluorine, and would explain the quantity of witherite, $BaCO_3$, dependent on carbonic acid liberated from limestone during the reaction with fluorine, and a high concentration of Ba.

From this discussion it may be concluded that although the fluorite rich lead-zinc deposits in limestone are probably derived from a magmatic source in which fluorine was present, the absence of fluorite in deposits in other rock types does not necessarily indicate that fluorine was not present in the magmatic source of such deposits, but that any flourine was not fixed. The disappearance of fluorine from such deposits cannot be related to the incorporation of the element in other vein minerals, as flourine was not detected in any of the Leadhills-Wanlockhead vein minerals. The disappearance may possibly be related to the hydrofluoric acid present in natural water and fumaroles.

The remaining marked geochemical similarities between all the British lead-zinc deposits in Carboniferous and pre-Carboniferous rocks, together with the fact that no definite Caledonian date could be assigned to any of the latter deposits, suggests the strong possibility that all originated from a similar source in post Carboniferous times. The age of the N. Pennine mineralisation was considered to be post Lower Permian (Dunham, 1948, p.119), and a Tertiary age was not discounted. Support for a post Permian dyke phase age is given in the Strontian district, where the mineralisation was effected along shattered monchiquite dykes (oral communication by Professor Kennedy).

THE GENESIS OF THE ORE DEPOSIT.

The majority of lead-zinc deposits are regarded as having been deposited from solutions of deep-seated origin, and the geochemical assemblage, large scale replacement, and mineral zoning, serve to indicate such an origin for the Leadhills-Wanlockhead deposit. The fundamental problem of the genesis is, then, the source of the vein solutions.

The two main sourced of the mineralising solutions can be regarded as having been either acidic or basic, and the problem of the origin of the solutions can be attacked from two angles, namely the character, and the igneous associations of the mineralisation. Of these, the former is provided by a comparison of the geochemical character of the deposit with the geochemical character of the magma types, and the latter from the character of the igneous activity during the periods in which the mineralisation could have taken place.

d. The geochemical character of the deposit.

The distribution of elements tabulated below was compiled from Rankama and Sahama (1950). The rock types selected, granite, gabbro, and peridotite, are regarded as

Abuddance of some elements in Igneous rocks.

Element.	Granite.	Gabbro.	Peridotite.
F	500	300	
Mg		Enriched	
Ti		Enriched	
V	30	320	
Cr	2	340	3400
Mn	0.05%	0.15%	
Fe	2.48%	8.84%	
Co	8	79	237
Ni	2.4	158	3160
Cu	16	149	
Zn	150	90	
Ge	3	2	
Sr	120	140	
Mo	12	3	
Ag	Enriched		
Sn	80	8	0
Ba	430	60	3
W	83	24	
Pt		Enriched	
Au	Enriched		
Pb	9-27	9	
Bi	Enriched		

Unless otherwise stated, figures in g/ton.

providing a general indication of the distribution of elements in the acid, basic, and ultrabasic magmas. Of the elements detected in the Leadhills-Wanlockhead district, Ti, V, Cr, Co, Ni, and Cu, are enriched in basic and ultrabasic magmas, whilst Ba, Ag, Sn, Sb, Au, and Bi, are enriched in acidic rocks. It has previously remarked that great difficulty is experienced in distinguishing between elements introduced from a magmatic source, and elements introduced by contamination during the upward passage of the solutions. Evidence from the elements present must, therefore, be treated with caution. However, for the present purpose, if all the elements are regarded as originating from a magmatic source, the only conclusion to be drawn is that elements of both basic and acidic magmas are present. Significant elements not detected in the deposit include Mo and W, and as both are highly typical of granitic rocks and of ore deposits associated with granitic rocks, their absence would favour derivation from a basic source. Some measure of support is given to this suggestion by the absence of Au, although the element is widespread in the district associated with the early stage mineralisation. Gold is enriched in granitic rocks, from which it may be tentatively deduced that the early stage mineralisation was genetically associated with the Caledonian granites, whilst the absence of Au in the lead-zinc mineralisation can be attributed either to a lack of Au in the granitic crust due to depletion in the Caledonian Orogeny, or to derivation of the lead-zinc minerals from a basic source. It should be noted that the typical basic element platinum is not present in the deposit.

Niggli (1929) identified ore deposits with processes of igneous differentiation, and concluded that Fe, Mn, Pt, Pd, Cr, Ti, Ni, Co, P, Cu,(Ag, Pb, Zn, and Bi), can be enriched in connection with basic igneous rocks, whilst missing from the deposits where differentiation has not advanced beyond the opening stages are Sn, Ge, Mo, W, and Au. Of these elements, Pb, Zn, and Cu, are stated to be of frequent connection with the differentiation leading to granitic and granodioritic magmas, and only the Pt metals, Cr, Ni, and Co, are, as a rule, separated so early that they do not reappear in the later stages of the differentiation process. On this basis, lead-zinc deposits of the Mississippi Valley type, which include the N. Pennine orefield and the Leadhills deposit, were regarded as being derivatives of a little differentiated basic magma, principally due to the presence of Ni, Co, Cu, and absence of Au, Ag, Sn, Mo, and W.

b. <u>The association with igneous activity</u>.

The conception of igneous activity and the derivation of magmas employed in the following discussion is that of Kennedy (1938). Thus the igneous rocks are divided into Plutonic and Volcanic Associations, the former derived from a granitic crustal layer and characterised by granodiorites and granites emplaced in orogenic regions, and the latter derived from the intermediate layer, subdivided into an upper Tholeiitic layer, which gives rise to the calc-alkaline suite, and a lower Olivine-basalt layer, which gives rise to the alkaline suite.

The derivation of ore deposits from the three crustal layers was discussed by Kennedy (1948). The general absence of metallic ores in true alkaline provinces was pointed out, together with the predominant relationship of ore deposits to rocks of the plutonic association, and it was concluded that the ultimate source of the metallic ores lies in the granitic layer, and possibly in the immediately underlying Tholeiitic layer.

With this association in mind, the igneous activity during the probable time of the mineralisation will be discussed. As it has been shown that the age of the mineralisation is post-Caledonian, the Caledonian igneous activity, of a predominantly plutonic nature, will be disregarded.

The Hercynian igneous activity in Britain is divisible into the Plutonic association of the orogenic area in the south west of the country, Devon and Cornwall, with which are associated mineral deposits bearing typical granitic elements such as Sn, W, and Mo, and the Volcanic associations of the non-orogenic remainder of the country. The members of the Volcanic association represented are both alkaline, e.g. monchiquites, and calc alkaline, e.g. quartz dolerites, and by the process of formation envisaged by Kennedy, namely the rise of the geo-isotherms in response to orogeny, would, given suitable structural conditions, theoretically allow the intrusion of rocks of the alkaline suite followed by rocks of the calc alkaline suite. Continued rise of the geoisotherms would effect the melting of the base of the granitic crust, and although no acid dykes are observable, a derivation of the minerals from such a position is a possibility.

At this point the field relationships of the mineral veins to igneous activity can be remarked upon. In Scotland the mineralisation is later than the alkaline monchiquite suite, and in the north of England is later than the typically tholeiitic Whin Sill. The relationships to the Tertiary intrusives are not so well defined. In the Leadhills district the effect of the

Tertiary tholeiite cannot be ascertained, but in the N. Pennine orefield (Dunham, 1948, p.119), no lead-zinc minerals were introduced along the walls of the Tertiary dykes, which favours a pre-Tertiary dyke age for the mineralisation. The sericitisation of a member of the Cleveland dyke echelon in Coldberry Gutter was stated to be possibly formed by injection into carbonaceous strata. The deposits can therefore be regarded as having been emplaced between the Permian and Tertiary igneous activity. Any suggestion of the origin of the mineralisation must account for the paucity of mineral deposits connected with the Tertiary igneous centres.

If the deposits are regarded as genetically connected to the Hercynian Orogeny the sequence of intrusion in response to rising geoisotherms would have been, alkaline suite, calc-alkaline suite, and mineralisation, in which case the deposits would necessarily have been derived either from a high level in the tholeiitic layer, or from the granitic crust. The geochemical assemblage support a derivation from both sources, i.e. the top of the tholeiitic and the base of the granitic layers. However, if the deposits are regarded as genetically connected to the Tertiary Orogeny, then the introduction of the tholeite dykes after the mineralisation would mean that the minerals were derived from either the base of, or below, the tholeiitic layer. These views are summarised in the Table below.

	Hercynian	Tertiary	↑ Rising Geoisotherms
Granitic	(3) Minerals		
Tholeiitic	(2) Calc-alk.	(2) Calc-alk.	
Olivine basalt	(1) Alkaline	(1) Minerals	

Now, as ore deposits are generally absent in alkaline provinces, it may be concluded that a theoretical approach to the origin of the deposits favours a genetic connection with the Hercynian Orogeny, which necessitates derivation from the top of the tholeiitic and base of the granitic crustal layers. Support is given to this conclusion by the fact that such a geochemical assemblage did exist in Hercynian times, as evidenced by the mineralisation of south west England in the Hercynian Plutonic Association. Furthermore, this assumption of the genesis of the minerals provides as explanation of the lack of deposits genetically associated with the Tertiary igneous centres of the country, as the crust had been devoided of metallic elements during the Hercynian Orogeny, and therefore no elements remained to be mobilised by the Tertiary igneous activity.

On carrying these speculations a step further, it will be apparent that if the deposits were derived from the melting of a certain crustal layer in response to the rise of geoisotherms initiated by the Hercynian Orogeny, then, as the focus of the orogeny was in the south west of the country, the rise in the geoisotherms would, in the non-orogenic area, take place later moving away from the orogenic region. The logical conclusions of this mechanism is that the actual age of the mineralisation in the country may be expected to become progressively younger with increasing distance from the Hercynian Orogenic region.

c. Localisation of the deposits.

All the evidence available on the lead-zinc deposits of the country would indicate that the deposits originated from magmatic centres, giving rise to both lateral and vertical zoning, so well illustrated in the N. Pennine orefield. Although the concentration of the deposits appears random, some order can be introduced. Thus in the Southern Uplands a concentration is apparent round the Cairnsmore of Fleet Granite, near the Criffel Granite, in the Hare Hill Granite, and, further north, round the Strontian Granite. Trotter (1944) pointed out that both the Lake district and the Alston Block are up domed areas, and all the localities mentioned are probably domed up areas of the granitic crust. It may be argued that other deposits, such as the Leadhills-Wanlockhead example, do not occur in up domed areas, and that the whole argument falls down, but only geophysical evidence can prove the configuration of the crust in such districts

The minerals are therefore visualised as having been concentrated in local up-domings of the granitic crust, and the passage to the surface effected by deep fissures, in some cases those employed by rocks of the volcanic association. In the Southern Uplands such fissures trend W.N.W. and examples are provided by the Brow Vein, and by Black Craig Vein. The distribution from these major channels of ore bearing solutions would be governed by the structural conditions of the country rock.

FUTURE ECONOMIC PROSPECTS OF THE DISTRICT.

In the light of the interpretation of the ore deposits presented in the foregoing pages, certain generalisations and inferences on the prospects of the Leadhills-Wanlockhead district can be put forward.

The ore deposits are visualised as having been introduced along channels striking north north west in the area and therefore such veins should be rich in ore. From these channels the mineralising solutions would be introduced into favourable structural positions in the crust. It was shown, in the discussion of the geology of the district, that north-south stress acting on the intersecting joint system of the district would effect the formation of open spaces on the more north westerly trending portions of the veins. On this conception, therefore, ore may be expected to be generally concentrated in such north westerly trending structures.

The precipitation of the minerals from solutions of a deep-seated origin would be controlled by temperature, the control effecting the formation of mineral zones in which every mineral should theoretically be limited to a certain depth range, dependent on the precipitation conditions of that mineral. The limits of the mineral zones can often be determined in mining operations, but in the absence of accurate data from that source, only general speculations are permitted. Thus the indication of decrease of galena at depth in both the Brow and Glencrieff Veins would suggest that in these workings the base of the galena zone of deposition was reached, and consequently that with further depth sphalerite may be dominant, and according to classical theory, should give place at greater depth to a dominantly pyritic assemblage.

From the lateral variations of the mineral zones, in which it was pointed out that the east of the district lies in the uppermost zones recorded, it may be deduced that this area is a potential high producer of both lead and zinc, as in depth the lower mineral zones would theoretically be tapped.

The paragenetical relationships of the minerals indicates that the last stage in the mineralisation was the introduction of quartz, which, having a considerable zonal range elsewhere, may be expected to increase in depth.

The future of the district appears, therefore, to lie not in greater depth than that attained in the New Glencrieff Vein, but in working the other known veins down to a corresponding level, and in developing the area to the east of Leadhills in depth.

Specific occurrences of minerals which may warrant further examination include the vein of galena discovered by the Marr brothers on the north slopes of Glen Ea's Hill, a probable continuation of the Bulmer Vein, the occurrence of brecciated greywacke and calcite in Glen Ea's Burn, and the occurrence of small quantities of galena along the joints of the microdiorite dykes outcropping in the Shortcleuch Water, and in Melli Grain.

APPENDIX I.

DESCRIPTION OF THE LEADHILLS AND WANLOCKHEAD VEINS.

The mineral veins of the Leadhills-Wanlockhead area were described by Wilson (1921), and the following descriptions are intended largely to supplement that work.

The veins are arranged alphabetically.

Bay Vein.

The vein was worked from the Bay Shaft. From the evidence of material on the dumps the vein was rich in sphalerite.

Belton Grain Vein.

The vein has been extensively worked from the surface and the position of outcrop is marked by the old workings, particularly over, and to the north of, Wanlock Dod. The chief sulphide minerals are galena and chalcopyrite, and the vein is rich in supergene minerals. The general strike is 25° W. of N., and the vein hades to the east.

The top level of the vein was worked from Taits Adit in Whytes Cleuch, and where Taits Adit cuts the Belton Grain Vein, the vein is 4' wide, consisting mainly of brecciated greywacke in a matrix of calcite, with pods of barytes, quartz replacing both minerals. 25' to the south the vein widens to 7' and carries a persistent 3" veinlet of galena and chalcopyrite in the centre of the vein. In the stope above Taits Adit the vein dies out to the north, and is reduced to a 4" zone of crushed rock with a ¼" barytes veinlet on the foot wall, whilst 30' to the south the vein is 2'6" wide and carries 9" Barytes on the foot wall and 1"-1½" galena and chalcopyrite on the hanging wall. The pinching out of the vein is probably due to the effect of the shear zone which strikes along Whytes Cleuch.

Broad Law Vein.

The Broad Law Vein was worked from levels and old shafts on the S.W. flanks of the Broad Law and near Big Wool Gill. All the old working dumps are rich in galena, the lowest dump (Loc.149) also carrying zinc minerals. Barytes is a common gangue mineral, with subsidiary quartz, calcite, and ankerite.

The vein continues to the north as the Wool Gill Vein, both veins having a similar mineral content, and both hading to the S.W. Southwards the vein has its continuation as Haddingtons Vein.

Brow Vein.

The Brown Vein was the principal vein worked at Leadhills. The position of outcrop is indicated by a line of old workings extending from south-east of Glengonnar Shaft over to Snar Head, the vein trending 50° W. of N., and hading to the south-west. In 1929 the Marr brothers of Leadhills exposed the outcrop of what was probably the Brow Vein in the south bank of the gully west of Wet Bush. The vein appeared 18" thick and was mainly quartz, with pockets of goethite. It dipped S.W. at approximately 60° (MacGregor, 1929).

The vein was worked principally from Lady Anne Shaft (Loc.106), and Glengonnar Shaft. The latter was closed in

February 1929, "owing to failure of ore in veins wrought" (MacGregor, 1929). The last workings on the vein included stoping on levels down to the 232 fathom level.

The sulphide minerals of the vein are galena and sphalerite, with chalcopyrite, calcite, barytes, and aragonite.

Brown's Vein.

Brown's Vein was one of the principal veins worked at Leadhills, mainly from Wilsons Shaft (Loc.51), and Glengonnar Shaft. The vein was worked down to 160 fathoms.

The position of outcrop of the vein can be followed only with difficulty, and is indicated by several grassed over workings.

Bulmer Vein.

The vein runs from the S.E. slopes of Wellgrain Dod, where it was worked by a shaft and two levels, due south across Bulmer Moss, swinging approximately 12° E. of S. before reaching the shaft on Bulmer Moss.(fig.22). This part of the vein is cut by the dolerite dyke on Bulmer Moss and was worked by a level driven along the side of the dyke from Wellgrain, the approximate length of the drive, calculated from the dump dimen$ions, was 4000'. North of the dyke the vein appears to have been almost barren, dying out south-east of Wellgrain Dod, where numerous trials have failed to locate the vein. South of the dolerite dyke the vein was quite rich in lead, both dumps 202 and 38 carrying appreciable amounts of galena.

To the south of the shaft on Bulmer Moss the vein swings south, parallel to the jointing in Overcleuch, and was worked by a shaft and a small level near the head of Overcleuch. Both dumps carry abundant gangue, particularly calcite. Galena is present in very small quantity.

In the late 1920s, J. and R. W. Marr discovered a new vein on the north slopes of Glen Ea's Hill (MacGregor, 1929). The vein was worked from a small shaft and carried galena and pyromorphite. The strike is aligned with Bulmer Vein, and the vein is probably a southward continuation of Bulmer Vein.

Carses Vein.

A line of old grassed over workings marks the position of the vein. No mineral specimens were obtained from the vein. Carses Vein probably continues southward as Portoto Vein.

Claystring Vein.

The vein trends 35° E. of N., parallel to the strike of the country rock, and, as is suggested by its name, is probably a barren strike fault. However, the evidence of a small shaft on the vein indicates the presence of gangue minerals, quartz, ankerite, and barytes, together with small quantities of galena and chalcopyrite.

The Sarrowcole Vein appears from the published maps to end on the Claystring Vein, which suggests that the Claystring has acted as a local structural control, the minerals being concentrated on the foot wall wide of the "claystring".

Cog Burn Veins.

Several potential veins outcrop in Cog Burn and its tributaries. The most powerful of these outcrops is in Cog Burn 40 yards east of the junction with Glenlosk Burn. This vein consists of a band of brecciated rock in a matrix of calcite, with a clay gouge on the foot wall, and trends 40° W. of N., hading to the east. The other veins in Cog Burn are all bands of brecciated greywacke cemented by calcite.

In the east tributary of Glenlosk Burn, the vein marked by Wilson outcrops as a narrow zone of brecciated greywacke in a barytes matrix.

Cove Vein.

The Cove Vein was mainly worked at the north end. Two large shaft dumps in Whytes Cleuch, and a grassed over level north of Wanlockhead school are the only surface indications of the vein.

In Taits Level the vein is wide and diffuse, with no well defined foot or hanging walls. The vein filling is brecciated country rock with quartz and calcite, barytes occurring near the foot wall. The whole vein is stained with hematite and chrysocolla.

Crawfurds Vein.

The vein was worked by a shaft near the head of Whytes Cleuch and its course cannot be traced at the surface. It is probably the vein cut by Taits Adit 90 yards to the west of Belton Grain Vein, where a small stope has been driven along a 1'6" vein of calcite with stringers of barytes.

From the material on the shaft dump the vein carried galena and chalcopyrite. Secondary minerals are abundant.

East Stayvoyage Vein.

The outcrop of the vein is marked by a line of workings extending from the side of the road on the county boundary, northwards over the north flank of Wanlock Dod. The workings are all old shafts, two of which were of large dimensions. The material is mostly from the gossan zone, and is hematite stained and carries a wealth of secondary minerals. Primary minerals include quartz, ankerite, calcite, and barytes, with galena, chalcopyrite, and pyrite.

A small vein runs at a slight angle to the East Stayvoyage Vein, crossing it near Loc.156. This vein was worked from the surface by two small shafts, and was known as Stay the Voyage Vein.

Georges Roust Vein.

The vein trends 56° W. of N., and hades to the S.W. It can be traced on the surface by a line of grassed over dumps. A large shaft dump (173) shows the vein to have carried galena, chalcopyrite, pyrite and marcasite, with a gangue of quartz, ankerite, calcite, barytes, and aragonite.

To the north west the vein joins with Sarrowcole Vein and continues as the Laverock Hall Vein, whilst to the south east it terminates against Browns Vein.

Glasgow Vein.

The vein was cut by an eastward drive from Borlase Shaft. It carried sphalerite and galena.

Glen Ea's Vein.

The vein trends 55° W. of N., and hades to the south west. It was worked by a series of levels driven on the north west flanks of Glen Ea's Hill. A cross cut was driven from the north east. All the dumps carry abundant galena.

Glennery Scar Vein.

The vein was worked from Gripps Level, and from the evidence of the three surface dumps was made up of a quartz-calcite gangue, with a small quantity of galena.

The vein strikes as a continuation of Labour in Vain Vein, though Labour in Vain hades south west, whereas Glennery Scar hades to the east. Wilson attributed the abrupt change in direction at the north end of the vein from N.N.W. to slightly E. of N., to the joining with the continuation of the Laverock Hall Vein.

Goldscaurs Vein.

This vein is in Dumfriesshire and is the southward continuation of New Vein, the line of outcrop following Camsheugh. A line of trials was made in Camsheugh and the absence of any minerals on the dumps indicates that the Goldscaurs Vein was of small dimensions.

Gordons Vein.

The position of the vein is marked by three old shafts and a level on the north side of Lamb Knowes. The vein carried sphalerite and galena, with a gangue of quartz, ankerite, calcite, and barytes. Wilson suggested that this vein was the continuation of Brow Vein, as it is aligned in strike with Brow Vein, and has a similar mineral content. If this is so, the part of the vein between Gordons and Brow has not been worked, the last visible workings on the Brow Vein being at the head of Snar Water.

Gordons Vein appears to terminate to the north against a chert anticline.

Haddingtons and Road Vein.

The name Haddingtons Vein was only applied to the vein south of the junction with Broad Law Vein. This portion of the vein was worked from several small shafts along the course of the vein on the north side of Shiel Gair Rig. The minerals on the dumps show the vein to have carried galena and barytes, with some calcite and ankerite. In contrast to Haddingtons Vein, the north end, or Road Vein, from the evidence of the two dumps, did not carry barytes, although galena was plentiful.

As barytes is a characteristic mineral of the Broad Law Vein, occurring on all the dumps, Haddingtons Vein, on mineral content evidence, could be regarded as the southward continuation of the Broad Law Vein, whilst Road Vein is a subsidiary branch of the Broad Law-Haddingtons Vein.

Hopeful Vein.

The vein trends 44° W. of N. and hades to the south west, showing a similarity with Brow Vein which it crosses near Lady Anne Shaft (Loc.106). Apart from Lady Anne, which was worked mainly on the Brow Vein, the Hopeful Vein was worked from two small shafts. The minerals on these dumps show the vein content to include galena, chalcopyrite, quartz, calcite, barytes, and ankerite. Secondary chromium minerals have been recorded from locality 45.

Horners, Jeffreys, or Portoto Vein.

This vein is a continuation of Carses Vein, Portoto or Jeffreys Vein running south eastwards from Browns Vein to Raik Vein, whilst the continuation to Moffats Shaft is known as Horners Vein.

The vein was worked from Gripps Level, Horners Vein from Moffats Shaft and a shaft between Moffats and the Raik Vein. The chief sulphide mineral on the dumps is sphalerite, with subordinate galena and chalcopyrite, and the main gangue is calcite, with quartz, ankerite, and barytes.

From the evidence of a line of old workings, Horners Vein continues south eastwards from Moffats Shaft, though there is no evidence of it reaching Shortcleuch Water.

Highlandmans Vein.

The vein is only indicated on the surface by a grassed over level north of the Wanlockhead Church.

Katystaklin Vein.

Katystaklin Vein is a small vein which trends 25° W. of N., and hades east. The outcrop is marked by a line of old grassed over dumps. A small level dump on Shortcleuch Water shows the vein to have carried chalcopyrite, barytes, quartz, and calcite. The north end of the vein was worked by a level from Moffats Shaft.

The vein was classified by Wilson as belonging to the Copper veins of Scotland (Wilson, 1921), on the evidence of the Shortcleuch dump, though he states (p.38) that the probable northward continuation of the Katystaklin Vein has yielded galena between the Katystaklin and Poutshiel Levels.

Labour in Vain Vein.

The vein was worked by two shafts (145 and 175), and from Gripps Level. It trends 35° W. of N., and hades to the south west. The vein content is ankerite, calcite, quartz, and barytes, with small amounts of galena, chalcopyrite, and sphalerite.

Lammingtons Vein.

Slightly to the north of the junction with Carses Vein, Raik Vein splits into a S.S.E. and a south trending branch. The former is known as the continuation of Raik Vein, whilst the latter is known as Lammingtons Vein. The vein is similar to Raik Vein in that it carries sphalerite, and was found to carry good zinc blende where it was cut in the 154 fathom level in the workings on Brow Vein (Wilson, 1921).

A small vein connecting Raik and Lammingtons Veins is known as Wester Vein. There is no distinct surface evidence of this vein.

Laverock Hall Vein.

The vein trends in a northward direction, and hades to the east. It was worked from three shafts on Laverock Hall, the mineral content of the vein including galena, chalcopyrite, and pyrite, with a gangue of quartz, ankerite, calcite, barytes and aragonite.

Wilson suggested that the vein continued northwards to join Glennery Scar Vein, and caused the latter to make an abrupt change in direction. There is no surface evidence to support this suggestion.

To the south the vein splits into the Sarrowcole and Georges Roust Veins, the latter having a similar mineral association to that of the Laverock Hall Vein.

Lees Vein.

The position of Lees Vein is marked by a small shaft (188) to the north of the railway cutting between Leadhills and Wanlockhead, and two shafts and a level south of Peter's Sike. Galena was not recorded from any of the workings; quartz and calcite are the only gangue minerals, with occasional pyrite and chalcopyrite. Hematite is common.

Lochnell Vein.

The vein is probably a continuation of Wilsons Vein, and is marked at the surface by two dumps high on the side of Wanlock Dod, and further down in Wanlockhead by the Dod Adit (Loc.196), and Williamsons Adit (Loc.208). To the south of Wanlock Water the vein joins Straitstep Vein.

Williamsons Adit was driven north along the vein following the foot wall, mostly a thin clay band, the vein occasionally widening out into impersistent lenses of brecciated greywacke in a matrix of quartz or calcite, with a thin vein of galena on the foot wall. A sharp bend in a north westerly direction alters the character of the vein, a persistent 1" veinlet of galena appearing on the footwall of the 2'6" wide vein, which is largely filled with brecciated greywacke cemented by calcite. Occasional lenses of barytes are to be observed. The foot and hanging walls are well defined, both marked by a thin clay band.

Mr. Borthwick, the Company Geologist, recognized a westerly loop on Lochnell Vein, the wall between the loop and the main vein being brecciated. A small strike fault with a maximum displacement of 10' cuts the north end of the loop before it rejoins Lochnell. The shatter belt of the fault is veined with barytes.

The foot wall of the Lochnell Vein shows well marked mullion structure dipping 30° north.

The ore from Williamsons Adit is a mixed galena-sphalerite ore. Galena is predominant in the vein above the adit.

Long Cleuch Vein.

The vein trends 33° W. of N. and was worked from three small shafts, which were drained by two levels. The only sulphide mineral is chalcopyrite, with a gangue of quartz, calcite, and ankerite.

March Vein.

The surface evidence for this vein is slender, and consists of two small levels and two small shaft dumps, the minerals on the dumps are small quantities of quartz and calcite with hematite staining. No galena or lead secondary minerals were observed. The vein probably passes through the head of Moss Burn where there is an outcrop of hematite stained brecciated greywacke. To the north the vein was suggested by Wilson to split into the East and West Stayvoyage Veins.

Marchbank Vein.

The vein was worked from small opencast workings. The gangue minerals included quartz, calcite, and barytes, with galena as the principal sulphide mineral. The vein is noteworthy for the abundant secondary minerals, particularly those of copper.

Meadowhead Vein.

The vein trends 35° W. of N., hading to the south west, and was reached by a cross cut from Borlase Shaft in 1928 (MacGregor, 1929). From the evidence of the two surface shafts (128, 144), the main sulphide minerals were galena, and chalcopyrite, with subordinate amounts of sphalerite. The gangue was quartz, calcite, ankerite, and barytes.

A shaft near the foot of Susanna scar has a similar mineral assemblage to the two dumps on Meadowhead and suggests a continuation of Meadowhead as the vein marked by Wilson parallel to the Portobello Vein.

Middle Grain Veins.

The Middle Grain Veins are two veins which have been worked along their courses by small shafts, particularly at the head of Middle Grain. The dumps carry abundant galena, and the chief gangue is calcite.

In Middle Grain both veins occupy faults which displace a N.E. striking microdiorite dyke. The fault lines have been eroded and make distinct features in the small gully as this area is one of the better exposed parts of the mining field.

Both veins swing westwards through Middle Grain, the eastern vein then swinging in a northerly direction on crossing the Middle Grain gully. A small shaft, barren of ore minerals, was sunk on to the vein. The vein probably dies out slightly to the north of Well Grain, a level and numerous trials on the S.W. flanks of Well Grain Dod having failed to locate the vein.

The Middle Grain Veins were also worked from Lithams Shaft, on Bulmer Moss, the dumps carrying abundant galena and lead secondary minerals.

Mill Vein.

A small shaft on Mill Vein shows the vein to have been rich in blende. The vein was chiefly worked from Borlase Shaft.

New Vein.

This vein was described by Brown (1918) as a stringer that intersects the Belton Grain Vein at the head of Camsheugh. The vein was further described as being rich in vanadinite, a description fully confirmed by the finding of numerous vanadinite specimens on the dumps.

New Cove Vein.

The position of the vein cannot be traced from the workings in Whytes Cleuch. The vein was worked from the surface by a shaft and a level. In Taits Adit a drive was made along the vein, which is only a clay stringer, with a tendency to swing round towards the Cove Vein.

New Glencrieff Vein.

The New Glencrieff Vein is reputed to be the richest vein in the area. It was mainly worked from the Glencrieff Mine and the large dumps show a profusion of mineral specimens. The south end of the vein was worked from the Glencrieff Horse Level.

To the north the vein splits into two branches, the East and the West Branches. The Glencrieff Shaft was sunk on to the West Glencrieff Vein, which, at the adit level varies in width from 3' to 6', the bulk of the vein being brecciated greywacke in clay, veined with calcite, and bearing vugs filled with calcite and galena. The foot and hanging walls are well marked, both coated with clay, and carrying galena associated with barytes on the foot wall, and galena alone, or with calcite, on the hanging wall. Replacement of both gangue and ore minerals by quartz is extensive.

In the Glencrieff Horse Level the walls show slickensiding dipping to the north, and the vein varies from a $\frac{1}{2}$" clay band to a 4'-5' wide mass of brecciated rock in clay, with calcite veining. Galena and barytes occur as impersistent lenticles on the hanging wall.

A microdiorite dyke is displaced 70' in a sinistral direction in the Glencrieff Horse Level.

To the north both branches pinch out against the northward dipping shatter belt in which the Glencrieff Shaft was sunk, and which strikes along Whytes Cleuch.

Old Glencrieff Vein.

The vein is to the east of the New Glencrieff Vein. It was worked from levels, and judging by the dumps the vein content was poor.

By the side of the road to the east of the Glencrieff Shaft are several dumps extremely rich in copper secondary minerals (loc.210). These were probably worked from the north end of the Old Glencrieff Vein.

Raik Vein.

The Raik Vein can be traced by old shaft workings from slightly north of the Leadhills Reservoir to the Dead Burn. Wilson continued the vein to join the Broad Law Vein, but whereas the rest of the Raik can be followed by old workings, there are no old surface workings between the Dead Burn and the Broad Law Vein.

The predominant minerals are sphalerite and galena with quartz, calcite, barytes, and ankerite. Hemimorphite is a common secondary mineral on the dumps.

Reids Vein.

Reids Vein trends parallel to the Broad Law Vein, and was worked from two shafts south of Big Wool Gill and a level driven from the centre of the plantation on the Abington Road.

As in the case of the Broad Law and Wool Gill Veins, the shaft workings on the higher levels carry galena only, whilst the lower level workings have both galena and sphalerite, with hemimorphite, on the dumps.

Risping Cleuch Vein.

The vein trends 43° W. of N., and is marked by a line of shafts running along the east bank of Risping Cleuch. A small level was driven at the south end of the vein, and is the present source of the stream. The only minerals on the dumps are galena, with pyromorphite and cerussite, and quartz.

Roanburn Vein.

The vein can be traced on the surface by a line of old shaft workings from Moffats Shaft (Loc.24) to the Deadburn. A level was driven northwards along the vein from Moffats Shaft, the vein following a "brecciated felsite dyke" (Wilson, 1921, p.38) The minerals on the small dumps are mainly gangue, quartz, calcite, and ankerite, with minor amounts of galena and chalcopyrite.

Sarrowcole Vein.

The outcrop position of the vein can be easily traced from the line of small shallow pits which were worked in the gossan zone. The predominating minerals are quartz, pyromorphite and cerussite. An indication of the character of the primary minerals is given by the assemblage of a shaft dump at the south end of the vein, the minerals including quartz, ankerite, calcite and barytes, together with galena and chalcopyrite.

The Sarrowcole Vein joins with Georges Roust Vein at Locality 52, and is probably continued as a small vein to the west of the Laverock Hall Vein, marked by a line of small pit workings in which quartz, ankerite, calcite and barytes were unearthed, with minor amounts of galena and chalcopyrite.

Scar Vein.

The position of the outcrop of the vein is marked by a series of small barren shaft dumps, to the west of Glengonnar Shaft.

The vein was postulated by Wilson to continue south east across the railway and the presence of two small levels aligned with the strike of the Scar Vein supports that contention.

Shieling Burn Vein.

Two levels were driven on to the north end of the vein in Glenglass. The material on the dumps is largely crushed black shales veined with calcite, suggesting that both levels were driven on to the shatter belt which striked through the Glencrieff Mine and along Whytes Cleuch. Further to the south two small levels were driven on the spur between Glencrieff and Glenglass.

Near the head of Glenlach Burn a vein of brecciated greywacke in barytes outcrops, whilst to the south a level has been driven through a quartz porphry dyke, the dump indicating a vein rich in barytes and hematite. These two vein occurrences have tentatively been linked as the southward continuation of the Shieling Burn Vein.

Shortcleuch Vein.

The vein trends approximately 45° W. of N., and was worked from two levels. The vein carried galena with subsidiary chalcopyrite, in a gangue of quartz, ankerite, and calcite.

Straight Brae Vein.

The vein was worked in Risping Cleuch from three shafts, the mineral content including galena, barytes, calcite and quartz. A level was driven from the foot of the viaduct to drain the workings, the level mouth giving rise to a powerful spring. Wilson (1921, p.41) states that the vein is visible in Risping Cleuch and "consists mainly of greywacke breccia strung with quartz and a thin seam of yellowish brown clay". This is not at present exposed, as the valley floor is covered with grass.

Straitstep Vein.

The vein has a general N.N.W. trend and hades to the east. In the southern part of its course the vein is joined by Lochnell Vein, and worked by shafts, the mineral content of the dumps indicating the vein to be rich in sphalerite.

The north end of the vein was worked from the Bay Shaft and from a level slightly north west of the Wanlockhead Church. Both localities support the concept of a high zinc content of the vein.

Susanna Vein.

The vein trends 73° W. of N., and hades to the north. It is marked by a large open cast working to the north of Leadhills village.

The dominant sulphide minerals are galena, sphalerite and chalcopyrite, whilst the vein is famous for the abundant secondary minerals formerly obtained from the open cast workings.

In 1928 the Marr brothers of Leadhills drove a level at the top of Lady Manners Scar on the north side of the small central ridge, and after driving in 30' struck the Susanna Vein. This signifies that the outcrop on the published Survey maps should be moved south about 60' (MacGregor, 1929).

The vein can be traced towards Glenkip Head by the old surface workings, but there is no evidence of it reaching Glenkip Head. Several small hematite occurrences were recorded on the scars of Glenkip Head, but could not be linked with certainty to the Susanna Vein. Furthermore, three trial levels were driven to the east of the Glenkip Head scars, all failing to cut the vein, which suggests the possibility that the vein failed against a chert anticlinal somewhere to the east of the Glenkip Head scars.

West Stayvoyage Vein.

The only surface evidence for this vein is a small level on the north side of Wanlock Dod. The level is grassed over, and the minerals present are quartz, calcite and galena, with secondaries. The dump is hematite stained.

Wilsons Vein.

Wilsons Vein is the possible northward continuation of Lochnell Vein. There is no surface indication of the outcrop, and the vein was only worked from one shaft in Whytes Cleuch.

The vein was cut in Taits Adit, and a drive was made along the vein. A compass survey along the drive from Taits Adit to the winze (fig.5) shows the vein to deviate in direction. A small lense of galena occurs on the foot wall 69' from Taits Adit, but for most of the drive the vein is brecciated greywacke in calcite, with clay on both the hanging and foot walls. Barytes predominates on the foot wall and occasionally occurs on the hanging wall, or veining the vein filling, either parallel to the vein, or at an acute angle across the vein parallel to the strike of the greywacke. At the winze the vein bears galena, and increases in thickness towards the south, from 18" to 38" in the space of 14', with the galena, associated with barytes and quartz, widening from a ¾" veinlet to a 2"-4" veinlet. The bulk of the vein is brecciated greywacke in calcite.

Wool Gill Vein.

The vein is probably a northward continuation of the Broad Law Vein and was worked by a level in Big Wool Gill and two shafts to the south. As in the case of the Broad Law and Reids Veins, the upper shaft dumps carry galena only, whilst the lower level dumps have abundant sphalerite and hemimorphite with galena.

The presence of two barren trial levels on the west slopes of Wool Law suggests that the vein dies out slightly to the north of Big Wool Gill. The pinching out would coincide with the first outcrop of the chert belt to the north of Leadhills.

LOCALITIES TO THE NORTH OF THE LEADHILLS-WANLOCKHEAD AREA.

The Drake Law Workings.

Veins of lead were said to have been discovered on the lands of Gilkerscleuch, Glendouran, and Glendorch (Wilson, 1921, p.43). The latter two localities could not be recognised. The former is situated on the east side of Drake Law, 4½ miles N.N.E. of Leadhills.

The workings consist of several old levels and shafts, with evidence of a N.N.W. trending vein. Barytes and quartz are the only vein minerals on the dumps, and the country rock is greywacke, with the exception of a level on a dolerite dyke, on which the rock is mainly dolerite but includes some chert.

Craighead Quarry.

Craighead Quarry is situated to the north west of Abington. Formerly the quarry was worked for Essexite, but in latter years the greywacke to the north end of the Essexite has been quarried, chiefly for roadstone.

Galena occurs in the greywacke in small pockets along the two main joint directions, 15° W. of N., and 65° W. of N. The galena is not worked because of the small extent of the bearing areas, though the galena may attain a veinlet 1"-2" in width. The gangue is barytes and is commonly associated either with the galena, or occurs in mono mineralic joint fillings. Calcite and pseudomorphs of goethite after ankerite are present. A small amount of chalcopyrite is associated with the calcite veinlets.

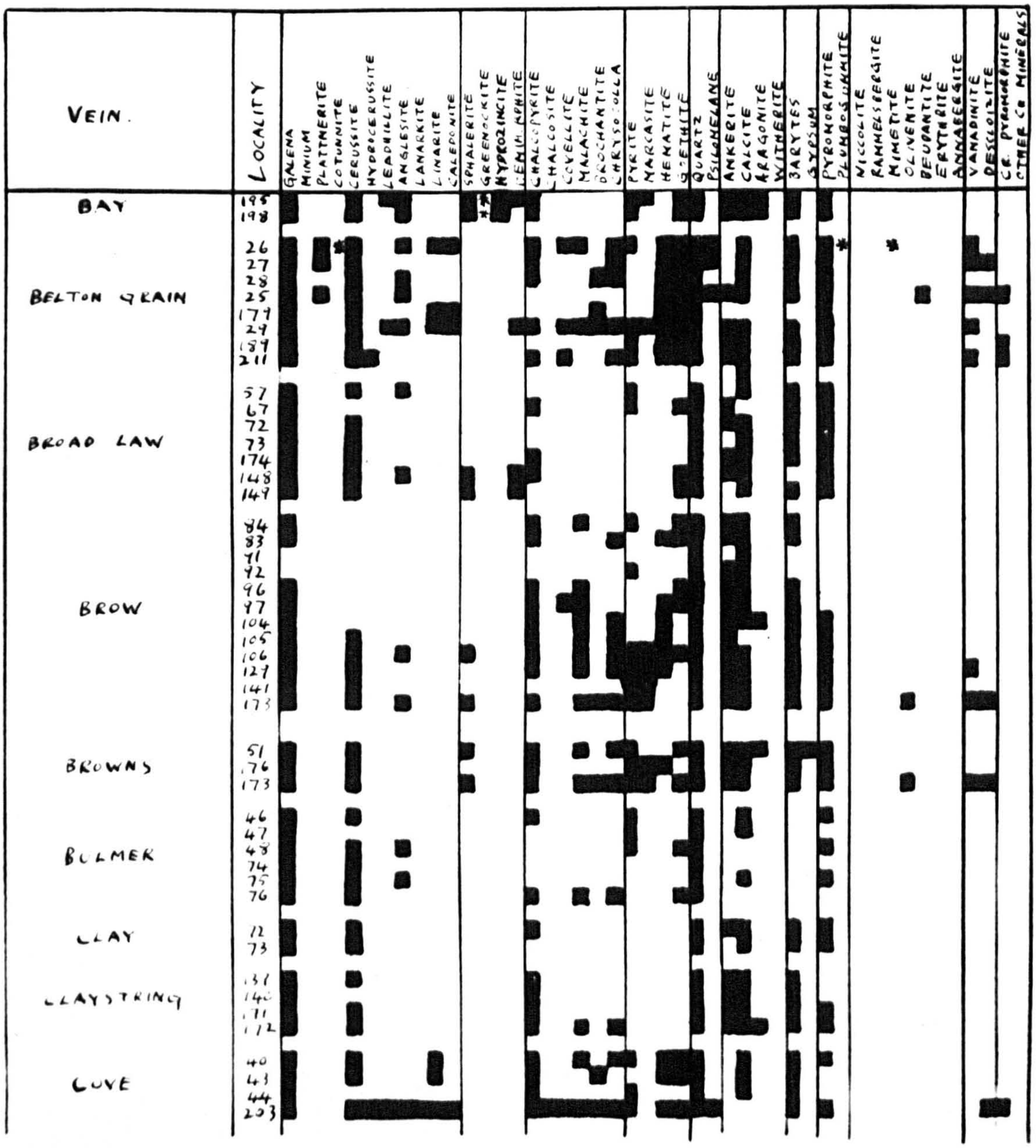
Other minor occurrences of chalcopyrite and calcite were observed along the joints of greywacke at Redscar Heugh on the Spango Water, one mile to the south east of the Spango "Granite", and in the Southern Upland Fault on the north side of the Spango "Granite".

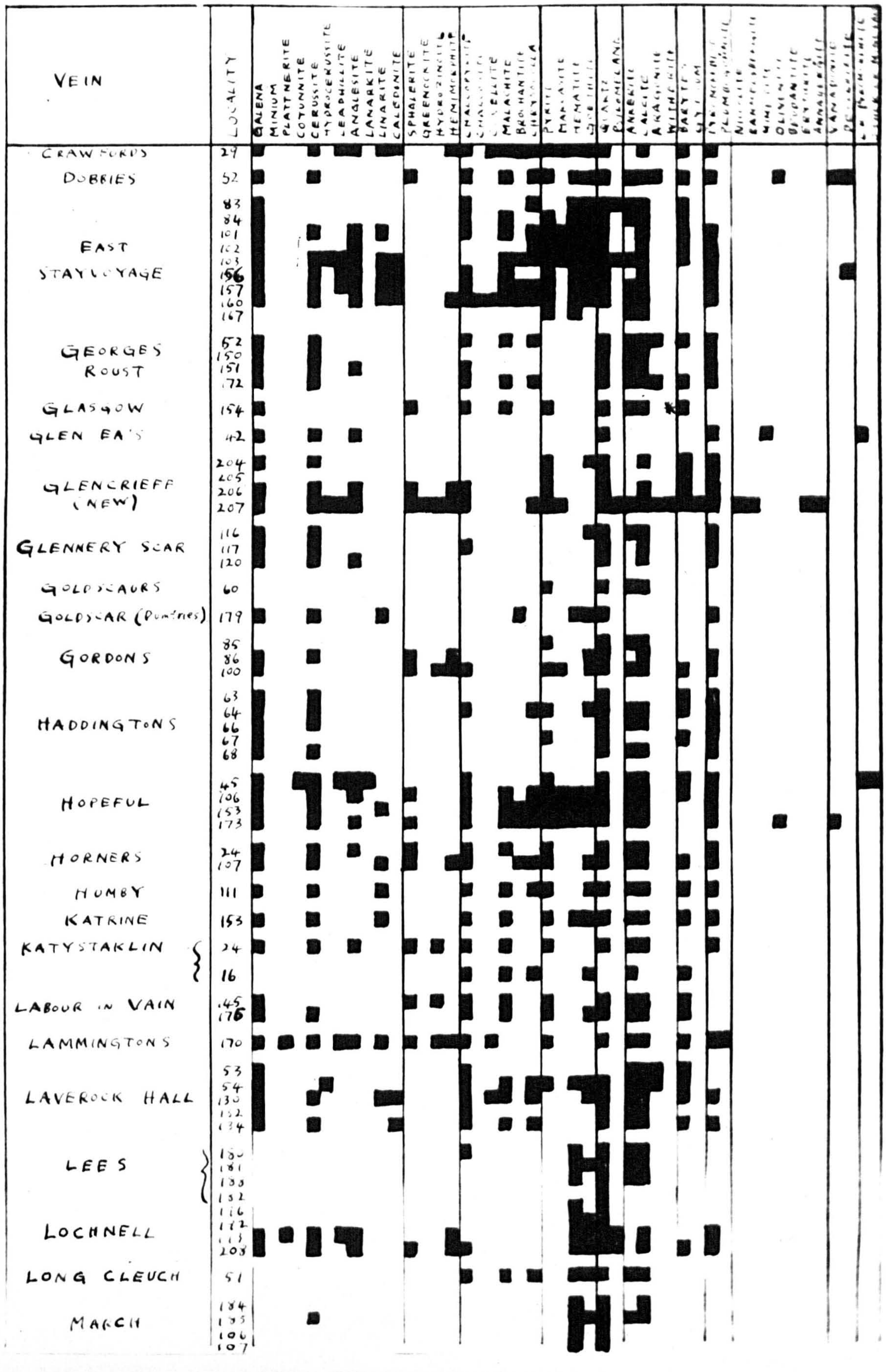
APPENDIX II.

THE DISTRIBUTION OF MINERALS IN THE DISTRICT.

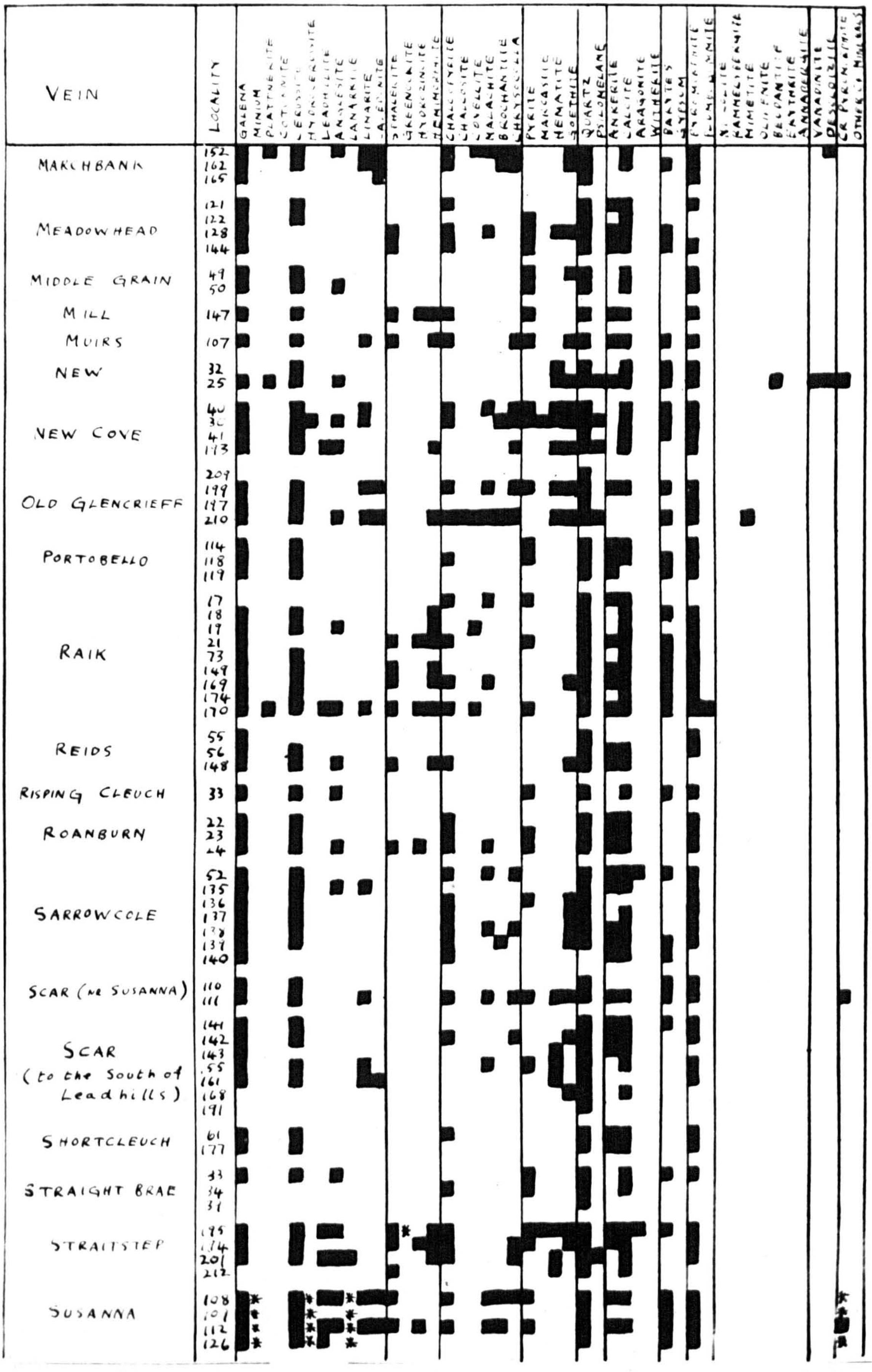
In the following list the minerals are arranged in the same order as in the descriptions in Section II. The mineral localities are given on the map, (Encl. 1).

Minerals collected from specific localities are indicated by the appropriate blackened square, whilst minerals recorded in museum collections only are indicated by an asterisk.





VEIN	LOCALITY
CRAWFORDS	29
DOBBIES	52
EAST STAYLOYAGE	83 84 101 102 103 156 157 160 167
GEORGES ROUST	52 150 151 172
GLASGOW	154
GLEN EA'S	42
GLENCRIEFF (NEW)	204 205 206 207
GLENNERY SCAR	116 117 120
GOLDSCAURS	60
GOLDSCAR (Dumfries)	179
GORDONS	85 86 100
HADDINGTONS	63 64 66 67 68
HOPEFUL	45 106 153 173
HORNERS	24 107
HUMBY	111
KATRINE	153
KATYSTAKLIN	24 16
LABOUR IN VAIN	45 176
LAMMINGTONS	170
LAVEROCK HALL	53 54 130 132 134
LEES	180 181 183 182
LOCHNELL	116 112 113 208
LONG CLEUCH	51
MARCH	184 185 106 107


VEIN
LOCALITY
GALENA
MINIUM
PLATTNERITE
COTUNNITE
CERUSSITE
HYDROCERUSSITE
LEADHILLITE
ANGLESITE
LANARKITE
LINARITE
CALEDONITE
SPHALERITE
GREENOCKITE
HYDROZINCITE
HEMIMORPHITE
CHALCOPYRITE
CHALCOSITE
COVELLITE
MALACHITE
BROCHANTITE
CHRYSOCOLLA
PYRITE
MARCASITE
HEMATITE
GOETHITE
QUARTZ
PSILOMELANE
ANKERITE
CALCITE
ARAGONITE
WITHERITE
BARYTES
GYPSUM
PYROMORPHITE
PLUMBOGUMMITE
NICCOLITE
RAMMELSBERGITE
MIMETITE
OLIVENITE
BEUDANTITE
ERYTHRITE
ANNABERGITE
VANADINITE
DESCLOIZITE
CR PYROMORPHITE
OTHER MINERALS
MARCHBANK
152
162
165
MEADOWHEAD
121
122
128
144
MIDDLE GRAIN
49
50
MILL
147
MUIRS
107
NEW
32
25
NEW COVE
40
30
41
193
OLD GLENCRIEFF
209
199
197
210
PORTOBELLO
114
118
119
RAIK
17
18
19
21
73
149
169
174
170
REIDS
55
56
148
RISPING CLEUCH
33
ROANBURN
22
23
24
SARROWCOLE
52
135
136
137
138
139
140
SCAR (nr SUSANNA)
110
111
SCAR (to the South of Leadhills)
141
142
143
155
161
168
191
SHORTCLEUCH
61
177
STRAIGHT BRAE
33
34
31
STRAITSTEP
195
194
201
212
SUSANNA
108
109
112
126
*

VEIN	LOCALITY	GALENA	MINIUM	PLATTNERITE	COTUNNITE	CERUSSITE	HYDROCERUSSITE	LEADHILLITE	ANGLESITE	LANARKITE	LINARITE	CALEDONITE
WEST STAYVOYAGE	97	■				■			■			
WILSONS (Leadhills)	56	■				■						
	148	■				■			■			
WILSONS	30	■				■	■		■		■	
WOOL GILL	58	■				■						

VEIN	LOCALITY	SPHALERITE	GREENOCKITE	HYDROZINCITE	HEMIMORPHITE	CHALCOPYRITE	CHALCOSITE	COVELLITE	MALACHITE	BROCHANTITE	CHRYSOCOLLA
WEST STAYVOYAGE	97										
WILSONS (Leadhills)	56										
	148	■			■	■					
WILSONS	30					■			■	■	■
WOOL GILL	58	■		■	■	■					

VEIN	LOCALITY	PYRITE	MARCASITE	HEMATITE	GOETHITE	QUARTZ	PSILOMELANE	ANKERITE	CALCITE	ARAGONITE	WITHERITE	BARYTES	GYPSUM	PYROMORPHITE	PLUMBOGUMMITE
WEST STAYVOYAGE	97			■		■			■					■	
WILSONS (Leadhills)	56					■		■	■					■	
	148				■	■		■	■					■	
WILSONS	30	■	■	■	■	■	■		■			■		■	
WOOL GILL	58	■				■			■			■		■	

VEIN	LOCALITY	NICCOLITE	RAMMELSBERGITE	MIMETITE	OLIVENITE	BEUDANTITE	ERYTHRITE	ANNABERGITE	VANADINITE	DESCLOIZITE	CR PYROMORPHITE	OTHER CR MINERALS
WEST STAYVOYAGE	97											
WILSONS (Leadhills)	56											
	148											
WILSONS	30											
WOOL GILL	58											

References.

Ahrens, L.H. 1950. Spectrochemical Analysis.

Allen, E.T., Crenshaw, J.L., Johnston, J., Larsen, E.S. 1912. The Mineral Sulphides ofIron. Am. J. Sci. Vol.33, p.169.

Allen, E.T., Crenshaw, J.L., Merwin, H.E. 1914. The effect of temperature and acidity in the formation of marcasite, (FeS_2) and wurtzite, (ZnS); a contribution to the genesis of unstable forms. Am. J. Sci., Vol.38, p.393.

Anderson, A.L. 1930. The incipient alteration of galena. Econ. Geol., Vol.25, p.528.

Anderson, E.M. 1951. The dynamics of faulting.

Anderson, H.V., Chesely, K.G. 1933. X-ray study of the transformation of marcasite into pyrite. Am. J. Sci., Vol.25, p.315.

Bailey, E.B., Holtedahl, O. 1938. North western Europe Caledonides.

Bannister, F.A. 1933. The identity of mottramite and psittacinite with cupriferous descloizite. Min. Mag., Vol.23, p.376.

Beck, R. 1909. The nature of ore deposits.

Behre, C.H., Heyl, A.V., McKnight, E.T. 1950. Zinc and Lead Deposits of the Mississippi Valley. Internat. Geol. Congr., 1948, Part VII, p.51.

Blyth, F.G.H. 1949. The sheared porphyrite dykes of South Galloway. Q.J.G.S., Vol. CV, p.393.

Boldyrev, A.K., Mikheev, V.I., Dubinina, V.N. 1938. X-ray determinative tables for minerals. Part I. Annales de l'Institut des Mines a Leningrad, Vol.XI.

Borovick S.A., Propenko, N.M. 1938. Germanium in sulphide ores. Bull. Acad. Sci. U.R.S.S., Cl. Math. Nat. Ser. Geol., p.341.

Brakken H., Harang, L. 1928. Zur Kristallstruktur einiger rhombischer Verbindungen MK_2. Zeits Krist. 68, p.123.

Brown, J.S. 1936. Supergene sphalerite, galena, and willemite at Balmat, N.Y. Econ. Geol., Vol.31, p.331.

Brown R. 1918. The mines and minerals of Leadhills. Trans. Dumfries. and Galloway Nat. Hist. Soc., Vol.6, p.124.

Brown, R. 1925. More about the mines and minerals of Wanlockhead and Leadhills. Trans. Dumfries. and Galloway Nat. Hist. Soc., Vol.13, p.58.

Buerger, M.J. 1934. The pyrite-marcasite relation. Amer. Min., Vol.19, p.37.

Butler, B.S., Vanderwilt, J.W. 1933. The Climax Molybdenum Deposit. U.S.G.S. Bull. 846 C.

Chirva, E.F. 1935. Der pyromorphit aus der Erzgrube von Beresovsk in Ural. Trav. Inst. Lomonassov, Acad. Sci. U.R.S.S., No.5, p.86.

Collet, L.W. 1927. The structure of the Alps.

Collie, 1889. On some Leadhills minerals. J.Chem. Soc., Vol.55, p.90.

"Dana" 1944. System of Mineralogy, 7th.Edn. I.

"Dana" 1951. System of Mineralogy, 7th.Edn.II.

Deer, W.A. 1935. The Cairnsmore of Carsphairn Igneous Complex. Q.J.G.S.,Vol.XCI, p.47.

Dewey, H. 1925. The mineral zones of Cornwall. P.G.A., Vol.36, p.107.

Dunham, K.C. 1934. The Genesis of the North Pennine Ore Deposits.
Q.J.G.S., Vol.XC, p.689.

Dunham, K.C. 1950. The Geology, Paragenesis, and Reserves of Lead and Zinc.
Internat. Geol. Congr., 1948.

Dunham, K.C. 1948. The Geology of the North Pennine Orefield, Vol. I.
Mem. Geol. Survey.

Dunham, K.C. 1952. Fluorspar.
Mem. Geol. Survey, Mineral Resources, Vol.IV.

Edwards, A.B. 1947. Textures of the Ore Minerals.

Edwards, A.B. 1952. The ore minerals and their textures.
Jour. Roy. Soc. New South Wales, Vol. LXXXV, p.26.

Emmons, W.H. 1924. Primary downward changes in ore deposits.
Trans. Am. Inst. Min. Met. Eng., Vol. 70, p.29.

Evrard, P. 1945. Minor elements in sphalerites from Belgium.
Econ. Geol., Vol.40, p.568.

Finlayson, A.M. 1910. The metallogeny of the British Isles
Q.J.G.S., Vol. LXVI, p.281.

Gabrielson, O. 1945. Studies on the distribution of elements in Swedish sphalerites.
Sveriges Geol. Unders., Vol.39.

Gardiner, C.I.,
Reynolds, S.H. 1932. The Loch Doon Granite Area, Galloway.
Q.J.G.S., Vol. 88.

Gardiner, C.I.,
Reynolds, S.H. 1936. The Cairnsmore of Fleet granite, and its metamorphic aureole.
Q.J.G.S., Vol.XCII, p.360.

Goldschmidt, V.M. 1916. Geologisch-petrographische studien im hochgebirge des sudlichen Norwegens. IV, Ubersicht der Eroptivgesteine im Kaledonischen Gebirge zwischen Stavanger und Trondhjem. Vidensk. Selsk. Skrift. Kristiania, 2, p.75.

Goldschmidt, V.M. 1954. Geochemistry.

Gregg and Lettsom. 1858. Manual of Mineralogy of Great Britain and Ireland.

Harcourt, G.A. 1942. Tables for the identification of ore minerals by X-ray powder patterns. Amer. Min. Vol.27, p.63.

Heddle, M.F. 1923. The Mineralogy of Scotland, I.

Heddle, M.F. 1924. The Mineralogy of Scotland, II.

Hey, M.H. 1950. Chemical Index of Minerals.

Hills, E.S. 1953. Outlines of Structural Geology.

Jones, O.T. 1922. The mining district of North Cardiganshire and West Montgomeryshire. Mem. Geol. Survey, Mineral Resources, Vol.XX.

Kennedy, W.Q., Anderson, E.M. 1938. Crustal Layers and the origin of magmas. Bull. Volc. Serie II, T.III.p.23.

Kennedy, W.Q. 1948. Crustal Layers and the origin of ore deposits. Schweiz. Miner. Pt. Mitt., Vol. XXVIII.

Kennedy, W.Q., Read, H.H. 1936. The differentiated dyke of Newmains, Dumfriesshire, and its contact and contamination phenomena. Q.J.G.S., Vol.XCII, p.116.

King, B.C. 1937. The minor intrusives of Kirkcudbrightshire. P.G.A., Vol. XLVIII, p.282.

Koch, S., Grassely, Gy. 1951. Processe occuring at the decomposition of sulphide ores. Acta Universitatis Szegediensis, Acta Mineralogica, Petrographica, Tomus V, p.15.

Kullerud, G. 1953. The FeS-ZnS system. A geological thermometer. Norsk Geol. Tids., Bind 32, p.61.

Leedal, G.P. 1950. The Cluanie Igneous Intrusion, Inverness-shire and Ross-shire. Ph.D. Thesis, University of Leeds.

Leedal, G.P. 1952. The Cluanie Igneous Intrusion, Inverness-shire and Ross-shire. Q.J.G.S., vol.CVIII., p.35.

Lindgren, W.L. 1933. Mineral Deposits.

Lovering, T.S. 1935. Geology and Ore Deposits of the Montezuma Quadrangle, Colorado. U.S.G.S., Prof. Paper, 178.

MacGregor, A., MacGregor, A.G. 1948. The Midland Valley of Scotland. British Regional Geology.

MacGregor, A.G. 1930 The Geology of North Ayrshire. Mem. Geol. Survey of Scotland.

MacGregor, A.G. 1929. Report on the area around Lamb Knowes and Sowen Dod, with reference to the possibility of lead bearing veins.

MacGregor, M. 1937. The western part of the Criffel-Dalbeattie Igneous Complex. Q.J.G.S., Vol.XCIII, p.457.

McMurchy, R.C. 1934. The crystal structure of the chlorite minerals. Zeits Krist., 88, p.420.

Mikheev, V.I., Dubinina, V.N. 1939. X-ray determinative tables for minerals, Part II. Annales de l'Institut des Mines a Leningrad, Vol,XI.

Mitchell, J. 1919. The Wanlockhead Lead Mines. Mining Mag., Vol.21.

Moritz, H. 1933. Die Sulphidschen Erze der Tsumeb Mine, Neues Jahrb.f.Min., BB.67A,p.130.

Nevin, C.M. 1949. Structural Geology.

Newhouse, W.H. 1934. The source of V, Mo, W, and Cr, in oxidised lead deposits. Amer, Min., Vol. 19, p.209.

Niggli, P. 1929. Ore deposits of Magmatic Origin.

Niggli, P. 1941. Die Systematik der magmatischen Erzlagerstatten. Schw. Min. Pet. Mitt.,B.21,S.161.

Oftedahl, 1. 1940. Untersuchungen uber die Nebenbestandteile von Erzmineralien norwegischer zinkblendefuhrender Vorkammen. Skrift. Norske Vids., Akad.Oslo, I. Mat-naturv. Klasse, No.8.

Palmqvist, S. 1939. On the solubility relations of barium sulphate. Kungl. Fspiograf. Sollsk. Lund Forh., Vol.8, no.8, p.1.

Peach and Horne. 1899. The Silurian Rocks of Britain. Vol.I, Scotland. Mem. Geol. Survey, U.K.

Peacock, M.A., Dadson, A.S. 1940. On rammelsbergite and pararammelsbergite: distinct forms of nickel diarsenide. Amer. Min., Vol.25, p.561.

Pettijohn, F.J. 1949. Sedimentary Rocks.

Porteous, J.M. 1876. Gods Treasure House in Scotland.

Pringle, J. 1948. The South of Scotland.
British Regional Geology.

Rankama, K.,
Sahama, Th.G. 1950. Geochemistry.

Reynolds, D.L. 1931. The dykes of the Ards Peninsula, County Down.
Geol. Mag., Vol. LXVIII, p.97, 145.

Richey, J.E. 1939. The dykes of Scotland.
Trans. Edin. Geol. Soc., Vol.13,p
Part IV, p.393.

Schedeman, O.C. 1938. Notes on the chemistry of ore solutions.
Econ. Geol., Vol.33, p.785.

Schwartz, G.M. 1934. Paragenesis of the oxidised ores of copper.
Econ. Geol., Vol.29, p.55.

Schwellnus, C.M. 1946. Vanadium deposits in the Otavi Mountains, S.W.Africa.
Trans. Geol. Soc. S.Africa, Vol.48, p.49.

Short, M.N. 1940. Microscopic determination of the ore minerals.
U.S.G.S., Bull. 914.

Siegl, W. 1936. Uber Tarnowitzi und Plumbocalcit
von Tsumeb, Sudwestafrika.
Min. Petr. Mitt.,(Tschermack), Vol.48, p.286.

Skerl, A.C. 1934. Vanadium at the Rhodesia Broken Hill.
Mining Mag., Vol.50, p.280.

Smythe, J.A.,
Dunham, K.C. 1947. Ankerites and chalybites from the
north Pennine orefield, and the
north east coalfield.
Min. Mag., Vol.28, p.53.

Stoiber, R.E. 1940. Minor elements in sphalerite.
Econ. Geol., Vol.35, p.501.

Strunz, H. 1949. Mineralogische Tabellen.

Swartzlow, C. 1933. Note on the alteration of galena to anglesite, to cerussite. Amer. Min., Vol.18, p.174.

Sweet, J.M. 1931. Notes on British barytes. Min. Mag., Vol.22, p.259.

Trotter, F.M. 1944. The age of the ore deposits of the Lake District and the Alston Block. Geol. Mag., Vol.81, p.223.

Uytenbogaardt, W. 1951. Tables for microscopic identification of ore minerals.

Vokes, F.M. 1950. Ore paragenesis at New Consols Mine, Cornwall. M.Sc. Thesis, University of Leeds

Wager, L.R. 1929. Metasomatism in the Whin Sill of the north of England. Part I. Metasomatism by lead vein solutions. Geol. Mag., Vol.66, p.97.

Walker, F. 1925. A monchiquite dyke in Lauderdale. Trans. Edin. Geol. Soc., Vol.XI, p.390.

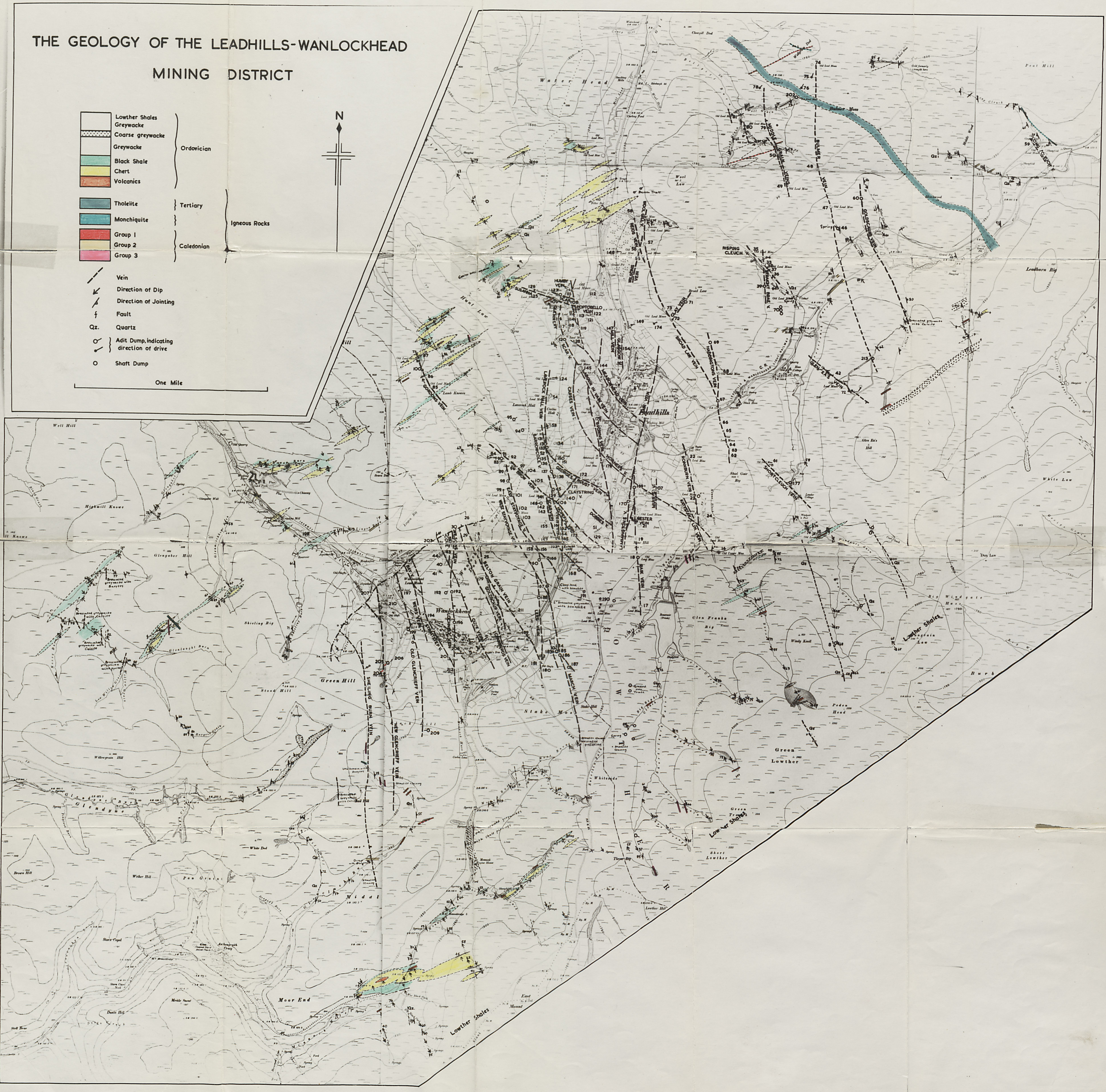
Warren, H.V., Thompson, R.M. 1945. Sphalerites from Western Canada. Econ. Geol., Vol.40, p.309.

Watson, J.A. 1937. Crawford Muir; its mining history and minerals. Trans. Edin. Geol. Soc., Vol. XIII, p. 98.

Wilson, G.V. 1921. The lead, zinc, copper, and nickel ores of Scotland. Mem. Geol. Survey, Mineral Resources, Vol. XVII.

THE GEOLOGY OF THE LEADHILLS-WANLOCKHEAD MINING DISTRICT

MINING DISTRICT



THE GEOLOGY OF THE SOUTHERN UPLANDS