WILSON'S PATENT

Single Slide Binder.

No. 1
4to size

"C" Quality

Patent No. 217501/23.
Patent Application No. 32614/5

BRITISH MANUFACTURE.

W. H. H. & Co., Ltd., R.
VIII. DEPOSITION AND PARAGENESIS.

The broad scale variation in the composition of the vein-fillings has been discussed at some length and it is now necessary to turn to the structure and arrangement of the minerals as seen in typical vein-sections. By this means, some light may be thrown on the mode and conditions of deposition of the minerals.

The problems of vein-structure have received scant attention from workers in the area. Leithart (1838) briefly referred to the subject, and Finlayson (1910A) described and figured several veins, but considered that the structures showed a great lack of regularity. For this reason, he suggests that groundwaters have re-distributed the vein material, producing the complex structures now seen.

Banding is a phenomenon common to the majority of vein-deposits. It is found in its best development in veins belonging to the epi-thermal (high temperature) stage of ore deposition; and also occurs in mesothermal and hydrothermal deposits, according to Bastin et aliter (1931). Structurally, most of the North Pennine veins exhibit composite banding, in which a single mineral-species may appear several times in the sequence. In view of the widespread nature of this phenomenon among all classes of ore-deposits, Finlayson's argument in favour of redistribution is hardly justified. Moreover, it is much more difficult to account for the crustification on his hypothesis than on a theory of primary origin.
Vein-sections, Sedling Mine

Figure 57

Figure 58

Figure 59

F Massive amethyst fluor spar; G galena; Z blende; Q quartz.
Figure 60: Vein-section, No. 3 level West, Boltsburn Mine
October 1930

Figure 61: Vein-section, North lead, West level mine,
October 1931
Figure 62: Ideal Section of the White Vein, Hunstanworth

Figure 63: Relation of fluor spar and silica in material from Whiteheaps mine.
Figure 64: Association of chalcedony, fluorspar and galena in material from banded vein, Groversake mine.

Figure 65: Vein-section, Force Burn vein, exposed at the surface in Upper Teesdale.
A few veins in the present area fail to show banding and these will be described after the banded types have received some attention.

**Banded Veins.**

The diagrams on pages 160 - 164 are selected from measured sections taken during the investigation, and represent the best examples of banding examined.

Banded relations, parallel to the vein walls are to be found between all the principal minerals; but it must be made clear that the bands do not exhibit a simple sequence of minerals, since each mineral may be repeated several times. In the majority of veins, moreover, while some of the bands—especially those of the matrix—are continuous in the section visible, it very frequently happens that the sulphides occur as a series of apparently isolated masses within the gangue. Inspection reveals that these are almost invariably aligned parallel to the banding (see figs 58, 64, 65); further, a discontinuity in the deposition of the matrix occurs along the surface joining them up. This was proved in the case of a small scale example from Lunehead Mine. In the hand specimen, an apparently continuous band of sulphide-material about .5mm thick occurred with barytes on either side. Polished surfaces (P 86, 87) under the microscope revealed that the band was really a string of crystals of chalcopyrite. A thin section (T 35) showed clearly that a definite cessation of crystallisation of barytes took place at the surface by which the chalcopyrite crystals are joined, and that subsequent crystallisation of barytes started again from the same surface.
or from the outer margins of the chalcopyrite. (Fig. 66)

Figure 66. Photomicrograph of thin section of veinstuff from Lunehead, between crossed nicols. Black spots with well-defined margins are chalcopyrite; these are joined by a surface which marks a discontinuity in the crystallisation of the barytes, which makes up the rest of the field. ×30

Crystallisation proceeded from left to right; the surface joining the sulphide crystals was roughly parallel with the wall-rock of the vein.
The surface joining the sulphides is conspicuous in this case because later groundwaters have travelled along it, partly replacing the chalcopyrite with limonite and malachite, and depositing a tiny string of limonite on the portions of the surface which are without chalcopyrite crystals. A composite photograph accompanying the present work shows the line of sulphide crystals joined up by the tiny string of limonite. Two sets of events, separated by a long interval of time, have taken place in this case -

i. Cessation of deposition of barytes; deposition of chalcopyrite on barytes surface in isolated masses; deposition of further barytes on chalcopyrite or on the surface. These events belong to the main mineralisation-period.

ii. Penetration of groundwaters along the surface (which would form an easy path for them to traverse). Replacement of chalcopyrite by limonite and malachite. These events are of recent occurrence, and took place within the oxidation-zone.

The inference from this example is that the isolated strings of sulphide crystals are to be regarded as part of the banded structure since they represent a break in the deposition of the matrix in the same way as does a continuous band of sulphide-materials. Surfaces joining up the members of large-scale examples such as those at Sedling, Force Burn, Dubbysike and many other localities were readily detected. As this structure has not, as far as I know, been previously recorded from any
between disperse phases in colloidal solution is invoked -

"... mutual reaction between ferric hydroxide and silica particles in colloidal solution resulted in those two substances being deposited together and the ferric oxide having, presumably, a higher surface tension, took the inside position of the aggregates which may have been added to subsequently by deposition of more silica. The external surface of the latter would be negatively charged against the water of the solution in contact with it and hence would attract, neutralise and hold, ferric oxide particles that came within its range of action. In this way, an external layer formed round the silica. In its turn the outer surface of this ferric hydroxide layer was positively charged and able to attract negatively charged particles that came within its range. In this manner, partly by mutual reaction, and partly by mere deposition, an alternating deposit of haematite - silica - haematite - stannic oxide was formed."

(1927 pp 68, 69)

The author stresses the fact that mutual reaction will not take place unless the disperse phases are present in certain definite proportions. A number of other cases are quoted, together with some simple examples of the operation of this mode of deposition, such as the precipitation of ferric hydroxide on silica in baths etc., as well as in sandstones.

It is possible that deposition from colloidal solutions due to reaction between disperse phases and the wall rock has taken place in the banded veins of the present area.
It is notable that colloform chalcedony is found in a great many veins, as at Groverake, Hunstanworth, Blanchland and Metalband. The view that the solutions were colloidal is not therefore entirely untenable. The process would follow some such course as this - Suppose that the first solution to arrive contained chiefly silica and fluorspar as the disperse phases. The limestone surface would be positively charged with respect to the waters of the solution, and would attract the negatively charged silica particles, neutralising their charge, and remaining the silica. The outer surface of the quartz or chalcedony layer so formed would be negatively charged with respect to the fluorspar particles, which would now be attracted until in its turn, the silica surface was covered; more silica would then be deposited on the fluorspar. It must be admitted, however, that this is not a complete explanation, since it does not account for the accumulation of thick bands. Fluorspar at Sedling, for example, continued to be deposited long after the quartz surface was covered. The reason for this behaviour may well be found in the fact, mentioned by Boydell, that a suitable concentration is necessary to enable reaction to take place. Assuming a continuous supply of solutions to the vein, precipitation of a new phase would not take place until a suitable concentration was reached. As Boydell recognises, banding is produced "partly by mutual reaction and partly by mere deposition". It is the latter part of the process which presents the main difficulty, for it involves the deposition of positively-charged particles on a positive surface, unless the whole body of a wide band was precipitated (or coagulated).
simultaneously. This discussion cannot be carried further with advantage until laboratory investigation of multi-phase colloids has been carried out.

An opportunity for testing the possibilities of the hypothesis outlined above was afforded at Sedling. A microscopic investigation of the silica associated with the fluor spar (which is detrimental to the economic value of that mineral) was undertaken at the request of the Weardale Lead Company (1931). The thin sections revealed that the fluor spar contained inclusions of quartz which thus represented the first-deposited mineral in the vein; these defied removal in the dressing process owing to their intimate association with the spar. The workings at that time were at the horizon of the Great limestone, and the dressed spar assayed up to 16% silica. It was suggested (working on the basis of the hypothesis outlined above) that the silica might be less troublesome at a sandstone horizon, where if the theory of mutual reaction holds, fluor spar should be the first mineral deposited. Specimens were accordingly obtained from an old rise into the Coal Sills sandstone. Assays showed that these contained an average of 2 - 2.5% silica. This test seems to lend weight to the theory.

It should be pointed out, however, that quartz is sometimes the first mineral to be deposited in sandstones, as at Yew Tree and Whiteheaps. In both these cases, the sandstones were highly ferruginous; this fact may possibly account for the prior deposition of silica.
A further test of the hypothesis proved disappointing. The cavities in the Bolteburn flats exhibit beautiful primary crustification. It was considered that if it could be shown that an electro-negative mineral is always succeeded by an electro-positive one and vice versa, the hypothesis would receive strong support. The results of the examination of a number of sequences are included in table XI on page 172. They show that no such regularity in deposition exists. There is, however, the possibility of undetected discontinuous banding in these sequences, which would upset the order; so that the results are inconclusive in one direction or the other.

The only alternative to the hypothesis of mutual reaction is to assume that the solutions were oversaturated with respect to one primary mineral at a time. In this case the difficulty is to account for the frequent repetitions in the banded structures, and if this hypothesis is to be upheld, it is necessary to postulate repeated pulses of solutions containing single minerals in ordinary solution, as opposed to colloidal solution.
Table XI: Order of Deposition of Minerals in Cavities

Boltsburn Flats.

<table>
<thead>
<tr>
<th>No.</th>
<th>Altered lst.</th>
<th>Purple</th>
<th>Green</th>
<th>Colourless</th>
<th>Galena</th>
<th>Blende</th>
<th>Quartz</th>
<th>Molybdenum</th>
<th>Pyrite</th>
<th>Dolomite</th>
<th>Siderite</th>
<th>Caloite</th>
</tr>
</thead>
<tbody>
<tr>
<td>E4</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>E21</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>E5</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>E10</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>E11</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>E12</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>E19</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>E20</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
</tbody>
</table>

Fluorspar
The Bearing of Banded Structure on Paragenesis.

The order of deposition of minerals, if deduced solely from vein-sections showing banding would reveal most minerals repeated several times. It is, however, evident that there exists a range under which a given mineral may be deposited if local conditions in the vein are favourable. Emphasis must be laid upon this point, since the paragenetic sequence deduced from microscopic evidence appears to contradict itself if this is not borne in mind. For example, some specimens show fluorspar preceding galena, others fluorspar following galena. The results of the microscopic investigation will therefore be interpreted in the light of the banded structure. It should be noticed that the deposition of minerals within a limited range, which is so evident from a study of the banded veins, is also in accordance with the view already expressed in Chapter VI.

Before turning to the microscopic evidence, the extent of the paragenetic range of each major primary mineral, as inferred from field evidence, will be summarised.

Chalcopyrite

At Barbary, chalcopyrite is found in veinlets traversing the Copper Hazles sandstone at the margin of the main vein. It occurs sometimes in the first sulphide-band of the main vein (assuming that deposition started at the walls of the vein) in association with galena. Later sulphide bands in the same vein contain galena, blende and pyrite, but never chalcopyrite; yet the conditions during the formation of these bands
were presumably favourable to the deposition of that mineral, had it been present in the solutions. The limited range of the mineral is therefore obvious. At Sedling the primary copper ore, chalcopyrite, is confined, in all accessible workings to the immediate vicinity of the wall-rock.

M a s c a s i t e.

This mineral occupies an early place both at Rodderup Fell and at Sedling. In the latter case, it has been deposited in the first sulphide band only, with blende.

Z i n c B l e n d e.

Blende occupies various positions. At Barbary it is later than the first galena band, but precedes several later bands of that mineral. At Boltsburn (See fig.60) it is earlier than most of the galena. In a great many cases, it is intimately associated with galena, as at Handsome Mea, Willyhole and Green-hurth.

G a l e n a.

The range of galena is considerable. Repeated bands occur from those carrying chalcopyrite, through those with blende to those in which it is the sole sulphide. No single vein-section or even mine represents the whole range. It shows, however, signs of dying out when the wide barytes veins are reached, and at Force Burn (Fig.65) and Lunehead, the galena is confined to narrow discontinuous bands near, though not against, the wall rock. The central part of the vein in these cases is wholly occupied by barytes. In these cases, it seems that local conditions have been unfavourable for the deposition of galena.
as the first mineral, though it has followed as soon as the wall rock was well covered with barytes.

Pyrite.

It may be said with truth that pyrite is ubiquitous, but it is noteworthy that its greatest development occurs in association with blende.

Fluorspar and Barytes.

In the Scordale veins and flats, there is strong evidence that fluorspar invariably preceded barytes in order of deposition, since in the cavities examined, fluorspar in every case occurs in contact with the country rock or with galena, whereas barytes occurs encrusting the fluorspar. Further, in every case the fluorspar crystals exhibit idiomorphic faces against the barytes; the inverse relation has never been observed. Similar evidence is forthcoming at Highfield, Flushiemea, and Snaigill, and indeed in every case where these two minerals can be seen in contact. No single exception to this rule has been found in upwards of 1000 specimens examined. The best established fact, therefore, in the paragenetic sequence is that fluorspar precedes barytes.

Coloured varieties of fluorspar.

At Sedling and Groverake, the relative positions of green and purple fluorspar in the sequence can be established. The purple variety precedes the green variety in both these cases. (Figs. 58, 59). The relation of the purple and amber varieties as seen at Rodderup Fell, has already been described.
Dolomite.

Dolomite when it occurs is an early mineral. Veins and strings at Handsome Mea frequently show dolomite against the walls and galena and/or blende in the centre, sometimes with quartz. (P. 170) Veins of blende cut dolomite veins in a specimen from the old Tees mine (Fig. 67), near Moor House.

Figure 57. Paragenetic relations of Dolomite and Blende, Tees Mine.

Siderite.

The position of siderite is more difficult to assess. At Boltsburn, Barbary and West level, it is one of the earliest mineral; but veins of siderite have cut the consolidated vein-stuff. (page

Quartz and Chalcedony.

Quartz and chalcedony occur in all stages of the fluor spar-bearing veins; but are absent from barytes veins, or confined to the proximity of the wall-rock as at Nentsbury.
Calcite is the last mineral to crystallise in almost all veins in which it occurs. This is the case at Boltsburn, Stanhopeburn, Rodderup Fell, Nesbury, Esp's and Scordale; the only exception seen was at Tynebottom, where the walls of some small strings were lined with the mineral, the interior being occupied by galena; and in one of the veins in the Little Whin quarry at Stanhope, where similar conditions held. In flat-deposits in which replacement of type II has taken place, it increases in amount towards the outermost edges, until it is the sole cavity-filling before the deposit dies out (Dunham, 1932).

Granular Veins.

There are a few examples of veins in which crystallisation has started from a number of nuclei within the vein rather than from the wall-rock. The veinstone here has a granular sometimes almost granitic aspect. The general condition for occurrences of this sort seems to be the presence of large numbers of shale fragments, which have acted as nuclei - as at Raine's working at Coldberry mine, and in some of the material from Smallcleugh. Simultaneous deposition of minerals also produces a similar texture; but few if any veins are completely filled by this process. Individual bands in banded veins frequently consist of a granular aggregate of several minerals; this is frequently the case with the sulphides. Intergrowths are common under these conditions. An intergrowth of siderite and barytes occurs in a small vein east of the Stanhope burn. (P177)
Microscopic Evidence of Paragenesis.

The slight age-diversity in the ore-minerals was investigated by means of thin sections and polished surfaces; by this means it was possible to supplement the field-evidence. In carrying out this part of the work, a recent paper by Bastin et aliter (1931) summarising the criteria of paragenesis and replacement has been of the utmost value, as have the articles of Colony on mineral-sequence, and Newhouse on the microscopic criteria of replacement in a recent book on the investigation of ores, edited by Fairbanks (1928).

In the tabular summary which follows, the type of evidence relied on in each case is indicated. Only one particular type calls for mention here, that of idiomorphism. It is frequently the case in banded structures that the older band exhibits idiomorphic crystals against the next younger band. This is particularly the case with fluor spar and quartz (see figs. 63, 64), and occasionally applies to galena. In these cases there is no doubt about the relative ages of the bands, and the idiomorphism simply confirms the interpretation. In the case of the invariable idiomorphism of fluor spar against barytes, however, it was considered possible that this might be due to the greater "crystallising-power" of the fluor spar. Microscopic investigation revealed that this is probably not the case. The fluor spar does not show idiomorphism against the mineral or rock immediately preceding it, nor is it ever found as isolated crystals within the barytes, or growing on barytes. The idiomorphism therefore proves the earlier age of the fluor spar.
<table>
<thead>
<tr>
<th>Locality</th>
<th>Order</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rodderup Fell</td>
<td>1. Chalcopyrite</td>
<td>Replaces 1st.</td>
</tr>
<tr>
<td>P.81</td>
<td>2. Galena</td>
<td>Encrusting 1st.</td>
</tr>
<tr>
<td>P.84</td>
<td>3. Chalcedony</td>
<td>Encrusting galena.</td>
</tr>
<tr>
<td>Sedling</td>
<td>1. Chalcopyrite</td>
<td>Irregular remanie</td>
</tr>
<tr>
<td>P.59</td>
<td>2. Galena</td>
<td>masses of chalcopyrite in galena.</td>
</tr>
<tr>
<td>P.60</td>
<td>3. Pyrite</td>
<td></td>
</tr>
<tr>
<td>P.71</td>
<td>4. Blende</td>
<td></td>
</tr>
<tr>
<td>Mentebury</td>
<td>1. Chalcopyrite</td>
<td>Replacing 1st.</td>
</tr>
<tr>
<td>P.73</td>
<td>2. Galena and Blende</td>
<td>Replacing galena.</td>
</tr>
<tr>
<td>P.77</td>
<td>3. Quartz</td>
<td>Replacing pyrite.</td>
</tr>
<tr>
<td>Handsome Mea</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P.167</td>
<td>1. Chalcopyrite</td>
<td>Replacing and enclosing (1)</td>
</tr>
<tr>
<td></td>
<td>2. Blende</td>
<td>Veining all sulphides.</td>
</tr>
<tr>
<td></td>
<td>3. Galena</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Galena and Blende</td>
<td>&quot;mutual boundaries&quot;;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>but galena contains</td>
</tr>
<tr>
<td></td>
<td></td>
<td>chalcopyrite inclusions;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>blende does not.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Encloses (1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Idiomorphism and replacement.</td>
</tr>
<tr>
<td>Location</td>
<td>1.</td>
<td>2.</td>
</tr>
<tr>
<td>---------------</td>
<td>---------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>Handsome Mea</td>
<td>Dolomitisation of 1st.</td>
<td>Dolomite</td>
</tr>
<tr>
<td>P.117</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P.168</td>
<td>Dolomite</td>
<td>Chalcopyrite &amp; Blende</td>
</tr>
<tr>
<td>P.108</td>
<td>Granular</td>
<td>Veinstuff with</td>
</tr>
<tr>
<td></td>
<td></td>
<td>shale-inclusions</td>
</tr>
<tr>
<td>109</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nentsbury</td>
<td>Dolomite</td>
<td>Pyrite</td>
</tr>
<tr>
<td>P.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sedling</td>
<td>Galena</td>
<td>Pyrite</td>
</tr>
<tr>
<td>P.61</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P.165</td>
<td>Marcasite &amp; Quartz</td>
<td>Chalcopyrite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rodderup Fell</td>
<td>Marcasite &amp; Quartz</td>
<td>Galena</td>
</tr>
<tr>
<td>P.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scordale</td>
<td>Fluorspar</td>
<td>Barytes</td>
</tr>
<tr>
<td>T.24.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Explanation of Figures

Photomicrographs.

No.

68. Thin section, showing relation of Fluorspar and barytes.  x15

69. Another field in the same section, showing a cavity lined with fluorspar, and filled with later barytes

Scordale (T.24)  x15

70. Polished surface showing chalcopyrite replacing blende which is encrusted with galena and later chalcedony

Rodderup Fell (P.81)  x25

71. Polished surface showing replacement veins of galena (white) penetrating blende (grey).

Handsome Mea (P.167)  x66
Specimens containing mixed sulphides were rarely to be obtained, and for this reason, the microscopic evidence carries much less weight than the field evidence, and is chiefly valuable because it confirms the general sequence deduced from field-evidence. Many more polished surfaces were prepared than are recorded in Table XII; only those which afford reasonably certain evidence have been included. The early appearance of chalcopyrite and marcasite is confirmed by this part of the investigation; the relations between blende and galena are shown to be variable, as might be expected under the circumstances.

The thin sections of metasomatized limestone supply additional data for the paragenetic sequence. At Boltsburn and Handsome Mea, the first change is the replacement of the limestone by carbonate-rhombs. In the former mine, these occur in two generations; the first of tiny but well formed crystals and the second of large, less well formed rhombs, enclosing the first. Fluorspar, galena and quartz replace both these types, though in some cases the enclosure of the smaller type alone suggests that galena may have been contemporaneous with the larger type. The first change in the Rodderup Fell material, in contrast with the above, was the replacement of the limestone by quartz and fluor spar. The quantity of carbonate-minerals (apart from calcite) is surprisingly low in this deposit, while the iron seems to have been precipitated as marcasite or pyrite in preference to siderite.
Explanation of Figure 72.

Photomicrograph of polished surface of veins of stuff from Nentsbury. White areas, barites; black areas, witherite (removed by etching with HCl). Strong black lines, pyrite and blende. \( \times 40 \)
The relation of primary barytes and witherite has not previously received any attention. Polished surfaces of veinstuff from New Brancepeth and Nentsbury were investigated by etching out the witherite with 50% HCl; the barytes remained unchanged. In all specimens examined, an intimate intergrowth of the two minerals was displayed. (P 138, 139, 140, New Brancepeth; P 173, 174, 175 Nentsbury). In two specimens from Nentsbury in which barytes greatly predominates, the form of the intergrowth appears to be tabular, resembling pure barytes, the crystals being outlined by blende and pyrite (P 173, 174) (Fig. 73).

When witherite was predominant, this characteristic was not shown. A thin section also revealed the intergrowth between the two minerals. (T 22)
Paragenesis: Summary.

The fact that barium minerals always follow fluor spar makes a convenient and valid basis for correlating the paragenetic evidence, and by this means the diagram below was devised. This summarises the results of the investigation.

![Diagram showing paragenetic sequence of minerals]

**Figure 74: Paragenetic Ranges of Primary Minerals.**

I have endeavoured in carrying out this part of the work to be unbiased by the regional distribution of minerals; indeed, much of the investigation of paragenesis was done before the zonal arrangement became clear. It is, however, quite evident that the order to deposition of the minerals conforms with the zonal sequence, and must be regarded as strong confirmatory evidence.
of the theory deduced from the sequence. The discussion of the actual mode of deposition of the minerals in the veins has introduced a new factor into the general theory, namely the rhythmic precipitation of almost pure materials, giving rise to banded structure. This is superimposed upon the general sequence of paragenetic ranges (controlled by the same factors as those which have controlled the regional zonal sequence), and is probably due to more local conditions in the veins.

**Continuity of Deposition.**

It remains finally to direct attention to one special implication of the vein-structure. The granular type of vein structure implies simultaneous deposition of material; the banded type implies continuous deposition. It follows that the primary minerals all belong to a single period of mineralisation.

The truth of this statement is challenged by only one vein in the Pennines - the Great Sulphur vein. A complete chapter will be devoted to this unique vein, for it does not conform in any respects with the normal veins. So far as the great bulk of the deposits is concerned, the above statement may be taken to be entirely true. A few cases of veinlets which cut across the banded structure - such as the quartz-veinlets at Sedling (Fig. 58) and the quartz which has distorted the cleavage of Boltsburn galena (Fig. 77) - are purely local, even in the deposits concerned, and no doubt represent the expiring local phase of the mineralisation.
Explanation of Figures.

Photomicrographs.

75  Marcasite veined by galena: polished surface
    Rodderup Fell (P 82)  \( \times 30 \)

76  Cube of galena in marcasite; may represent an
    inclusion or replacement of marcasite by galena.
    Sedling (P 61)  \( \times 25 \)

77  Mechanical distortion of galena owing to the
    introduction and crystallisation of quartz.
    The cleavage after following a straight line
    across the specimen (not shown on the photomicrograph) bends beside the later quartz crystal.
    Boltsburn (P 52)  \( \times 25 \)
The problem of the composition of ore-forming solutions, and more particularly, of the state of combination of the elements making up the geochemical assemblage, is of much more than local interest, and indeed applies to deposits of the type described here in all parts of the world. Unfortunately, little can be added towards the solution of the general problem from the geological evidence assembled during the present investigation. For completeness, however, and for the sake of future work, certain aspects of the geochemical problem will here receive consideration.

All possible modes of formation— including deposition from magma, gas, hot aqueous solution and cold aqueous solution—have been proposed at one time or another for the Pennine Ore deposits. It has been tacitly assumed throughout the present work that the minerals were deposited from aqueous solution, and there is ample justification for this view, since there is no sign whatever of thermal alteration of the country rock, such as would be occasioned my magmas or hot gases, both of which could exist only at temperatures of the order of 1000°C if they contained an assemblage of elements such as that found here. The contrast between the "Saccharoidal limestone", a pure white marble produced by the recrystallisation of limestone during the intrusion of the Whin sill, and the limestone metasomatically altered by the vein-solutions, is most convincing in this respect.
Composition of the Solutions.

As seen at present, the elements introduced by the solutions occur combined as follows in the primary minerals -

(Rare minerals in brackets)

- Sulphides: Cu, Zn, Pb, Fe (Co, Ni, As, Sb)
- Fluoride: Ca
- Carbonates: Ca, Ba, (Sr), Fe, Mg.
- Sulphate: Ba
- Oxide: Si

The solutions, besides containing these substances, were rich in carbon dioxide, a fact which is clearly demonstrated by the work of Finlayson (1910B), Wager (1929A) and Smythe (1930) on the "white whin" and by the extensive limestone replacements. From the evidence afforded by analyses of unaltered and white whin rock, Wager has deduced that the solutions contained silica, iron and sodium, by comparing the analyses on a basis of constancy of alumina. Since alumina is usually determined by difference, this result must be viewed with some caution. However, Smythe has shown that whatever reasonable basis of comparison is used, there is a definite increase in alkali - potassium in this case - in the Force Burn white whin. Some increase in sodium is also probable. Since the increase in alkalis in the altered dolerite cannot be accounted for by residual concentration, it must be concluded that they were present in the solutions.

In addition, it is not unreasonable to assume that hydrogen sulphide was an important constituent of the solutions,
since a vast amount of sulphide minerals were precipitated from them.

**Temperature of the Solutions**

That the solutions were at some temperature greater than that of groundwaters at the depth at which the ores were deposited may be inferred from the existence of a zonal distribution of minerals, corresponding to falling temperature.

Allen, Crenshaw, Johnston and Larsen (1912) have shown that the upper limit for the formation of marcasite is 450°C. Since this mineral is one of the earliest to appear in the Pennine deposits, this temperature represents an upper limit for the solutions under consideration. It is probable, however, that their maximum temperature was considerably less than 450°C. Included fragments of coal were obtained from veins at Boltaburn (Fluor spar zone), New Brancepeth, Blagill and Fallowfield (Barytes zone). In none of these cases was there any sign of coking in the coal. As this change is initiated at about 300-350°C, it may be taken that when they reached the coal, the vein-solutions were below this temperature. The absence of alteration of the limestone beds by heat supports this view.

The lower limit of temperature is very difficult to fix, and it is probable that in the outermost zone, the temperature had reached that of the groundwaters. Barytes is well known to be deposited at ordinary temperatures (Lindgren, 1919 p.376). Fluorspar, on the other hand, is seldom if ever found in deposits from springs at ordinary temperatures, but is known to be deposited from hot springs in volcanic
regions (Lindgren op. cit. p. 108). Aragonite has been shown to be formed by hot solutions at or about the boiling-point of water (Linck 1903.). At the same time, this mineral can also be formed at ordinary temperatures, since it occurs in the valves of mollusca and on coral islands.

Nature of the Solutions.

The relative merits of true and colloidal solutions, and the state of combination of the various elements and compounds in them may conveniently be considered together. The chemical aspects of the deposition of minerals from solution also fall logically into this section.

The possibility that some or all of the substances did not travel in the solutions combined as they are now found is supported only by the limited occurrence of calcite where extensive limestone-metasomatism has taken place, the calcium being apparently used up in fluorspar. On the other hand, fluorspar is in no way restricted to the limestone beds or their proximity. If the calcium was derived from the decomposition of limestone, it is possible that some such compound as the halanhydride silicon tetrafluoride existed in the solutions; the invariable association of a certain amount of silica with fluorspar in the present area is perhaps noteworthy, though it should also be mentioned that in the southern Pennine area (Derbyshire district), large bodies of fluorspar without appreciable amounts of silica. The evidence, therefore, is contradictory, and no great reliance can be placed upon it,
It seems far more probable that most of the elements were present in the solution combined as now found.

The case for true solutions will be taken first.

Table Xlll below, shows the solubilities of the various primary minerals (from Seidell, 1919)-

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Solubility in water at MTP grs/litre</th>
<th>Solubility in water with CO$_2$ grs/litre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chalcopyrite</td>
<td>.00069</td>
<td></td>
</tr>
<tr>
<td>Zinc blende</td>
<td>.00086</td>
<td></td>
</tr>
<tr>
<td>Galena</td>
<td>.0149</td>
<td></td>
</tr>
<tr>
<td>Fluorspar</td>
<td>.0027</td>
<td></td>
</tr>
<tr>
<td>Barytes</td>
<td>.022</td>
<td>1.10</td>
</tr>
<tr>
<td>Witherite</td>
<td>.070</td>
<td>1.175</td>
</tr>
<tr>
<td>Siderite</td>
<td></td>
<td>6.191</td>
</tr>
<tr>
<td>Calcite</td>
<td>.43</td>
<td></td>
</tr>
</tbody>
</table>

Table Xlll: Solubilities of Primary Minerals.

The common vein minerals are thus only very slightly soluble in pure water, and the amount of water which would be necessary to produce the concentrations of ores found would far outrun the bounds of possibility were no other solvents present in the solutions. However, the solubility is greatly increased in the presence of dissolved carbon.
dioxide; and a hot solution of hydrogen sulphide
is known to dissolve galena (Mellor, 1927) and may also act
as a solvent for the other sulphides as suggested by Boydell
(1927). In addition, the probable occurrence of alkalis
in the solutions is of great interest, since these are known
to dissolve both sulphides and silica, and have been postulated
by a great number of authors as solvents in ore solutions.
The difficulty is to account for the complete absence of
compounds of potassium and sodium among the vein minerals;
however, they may well have passed away with the water from the
ore solutions as soluble carbonates or sulphates, being
disseminated and ultimately removed by groundwaters. While
actually in the vein solutions, the alkalis might be combined
as carbonates, sulphides or sulphates.

Deposition from true solutions would be brought about
by fall of temperature, causing successive saturation of
the solutions with respect to various constituents. Boydell
points out that the principal objection to ore deposition from
true solutions is the necessity for the maintenance of a slight
dergee of supersaturation. The present area is a case in point.
The evidence implies that the saturation of the solutions
coincided with a convenient set of openings in the country rock.
This may have been due, of course, to a comparatively sudden
change of pressure; but the role of pressure in actual examples
of ore deposition is very difficult to assess. Further, the
banded structure of the veins presents many difficulties
if true solutions are advocated, since it implies an alternating
supply of different pure substances in solution, exactly
supersaturated at the required place.

Turning now to colloidal solutions, Boydell (1925, 1927) has brought forward string arguments in favour of the possibility that some sulphide-ore-bearing solutions are of this type, protected by hydrogen sulphide. The presence of carbon dioxide does not affect the protection of the sulphides. The following minerals have been prepared in colloidal solution in the laboratory -

Galena, barytes, fluor spar, silica. (Hellow, 1927)

The occurrence of colloform silica in the Pennine deposits has already been mentioned; the intimate association of galena and blende with this material (at Groversake and Shildon, for example) suggests that these may also have coagulated from colloidal solution. The bearing of the banding of the veins on the nature of the solutions has already been fully discussed.

Precipitation from colloidal solution can be brought about by a number of different factors. Paterno, Masevichelli and D.Vita have shown that colloidal solutions of fluor spar are stable in the presence of copper sulphide, and sulphuric acid, but are less stable when calcium carbonate, zinc sulphide or barium sulphate are present ($\text{Cu}_2\text{S}$, $\text{CO}_2$). This seems to apply directly to the present problem. If it be assumed that the first solutions to arrive contained the copper sulphides and fluor spar in colloidal suspension, the copper minerals might well be deposited first, the fluor spar remaining in solution. Fluorspar would, however, be coagulated by limestones, or by the arrival of slightly later solutions with zinc blende, or barytes. The work of these authors thus
supplies a possible clue to the mechanism of deposition in the present area. Boydell (1927) has advocated the deposition of lead and zinc sulphides from colloidal solution by electrolytic action during a limestone-replacement process at Santa-Fulalia, Mexico. Similar reasoning applies to the Pennine limestone replacements.

So far, it has been shown that colloidal solutions possess certain advantages over true solutions as the medium in which the North Pennine minerals were introduced. The final test lies in the answer to the question "Will deposition from colloidal solution account for the regional zonal sequence which is the central fact of Pennine ore-deposition?"

Tolman and Clark (1914) believe that progressive escape of the peptising agent (H₂S) would be sufficient to produce a zonal sequence; but this remains unproved. Unfortunately, little is known about the effect of temperature and pressure on colloidal solutions: the question cannot therefore be answered in the affirmative.

Thus it is impossible to decide definitely between true and colloidal solutions, and until the laboratory investigation of the latter type of solution has advanced much further, this question must remain open.

**Pyrite and Marcasite.**

The restriction of marcasite to the fluor spar area, and the occurrence of pyrite in both that and the barytes zone has already been mentioned. Near the junction of the two zones, epimorphs of marcasite have been found at three localities -
Nentsbury, Esp's and Grasshill. In specimens from the first of these, the epimorphs have been partly filled with pyrite (Fig 78). In each of these cases, marcasite occurred as an early mineral, replacing limestone, or intergrown with siderite or dolomite. The barytes appeared later in the paragenesis, and it is suggested that contemporaneous with its deposition, the marcasite was reabsorbed by the solutions and converted into pyrite (or siderite) which was deposited either in situ, or in some other part of the vein. The reabsorption of the marcasite is definitely a primary effect, for the epimorphs occur far below the oxidation-zone, and show no evidence of the oxidation of marcasite in the presence of limonite or sulphur.

The work of Allen, Crenshaw, Johnston and Larsen (1912-1914) on the iron sulphides has shown that marcasite,
the unstable form, is deposited from acid solutions only; while pyrite is formed from neutral and alkaline solutions. In the localities where the epimorphs are found there thus seems to have been a change from acid to alkaline; the coincidence of this change with the oncoming of barytes is too striking to be dismissed without some mention, though the significance of the phenomenon is not yet understood.

The quantity of marcasite is not such that the generalisation that the solutions in the fluor spar zone were acid is justified; the deposition of marcasite more probably depended upon local peculiarities in the character of the solutions. At the same time, the change from the fluor spar zone to the barytes zone is so marked that it was probably accompanied by some profound change in the nature of the solution. The appearance of the second generation of chalcopyrite also indicates that a change in the solutions took place at the barytes fluor spar boundary.
X. FACTORS CONTROLLING ORE-DEPOSITION.

1. In Veins.

In the study of ore-genesis, the importance of tectonics is seldom sufficiently stressed; yet in the fissure-vein type of deposit, the formation of openings in the rocks by earth-movements is clearly fundamental to the formation of the ore-body. A chapter of the present work has already been devoted to the regional tectonics; the veins, however, present certain special tectonic features which merit separate consideration. First place will be given to these in this chapter, in which it is intended to evaluate the relative importance of the various factors which have controlled the nature and extent of individual vein deposits.

Tectonic Features of the Fissure-Veins.

Attention has already been directed to the twofold distinction between the fissure-veins and the regional joint-system:—

(i) The vein-fissures are normal faults with a small throw in most cases; the joints have no throw and are probably shear-fractures.

(ii) The vein-fissures have only a slight hade in hard beds but hade steeply in the shales; the joints stand vertically in all beds.

A reason for the difference in character of the two types of fracture has already been suggested; the joints are correlated with a regional compressive force, the vein-fissures with
differential regional uplift, of later date.

In the earlier movements, the effect of the stress has been to produce vertical shearing fractures; during the later uplift the resulting tension has made possible the production of small normal faults. The response of the various types of rock to the tension has not been the same; the soft shale beds have fractures along planes inclined from 5°-45° from the vertical; the hard beds have fractured at only a few degrees from the vertical.

The changing hade of the veins is mentioned by Forster (1809) but the credit of realising the significance of the relation between this phenomenon and the width of the vein is due to Leithart (1838). A modified form of his diagram appears on the next page. The diagram is self-explanatory; it emphasises a fact which is of general application in the area, namely that veins having only a small throw are wide in the hard beds, and narrow or pinched out in the soft beds. Carruthers (1923) gives a reproduction of an old section of Wolfcleugh vein which shows this feature. A section of Burtree Pasture vein, the original of which is at the Allenheads Estate Office, and a section of the East Cross Fell vein, now in the possession of the Rev. W. Walton of Alston, both show the same feature particularly well. Care has been taken to verify this characteristic of the veins in the field; and there is no doubt about the reality of its existence. In no case was a mineralised vein having a throw of less than 15' seen other than having steeply in thick shale beds; the amount
of mineral material was always small. On the other hand, when both "cheeks" of the vein consisted of sandstone or limestone, the vein stood almost vertical. The following were the best examples of steep hade in shale observed –

In Stony Hill shaft, West level mine, the Boltsburn vein pinches out and hade steeply to the south in the shale beds above and below the Little limestone.

The Esp's vein hade steeply in the Black bed (here 6' thick) near the top of the Great limestone.

Several steeply bading veins can be seen in the shale below the Fell Top limestone in the lower adit level of the Burnhead Trial, Hunstanworth, and in the Whiteheaps horse level.

The Lodgefield vein hade steeply in the shale above the Scar limestone at Barbary.

This feature can also be observed at the surface, as at Raven beck, where a barytes vein is almost vertical in the Whin sill, but hade at about 45° in the shale underlying the sill.

These facts emphasise the dependence of ore-deposition upon the physical properties of the country rock and their varying response to regional tectonics. The variation in productivity of the veins with the country rock is well attested by mining operations. The great productivity of the veins at the Great limestone horizon is to be referred in part of the fact that over most of the area, it is the thickest bed in the Yoredale series. The beds above that horizon have seldom yielded much ore, but two districts are exceptional in this respect. The mines at Hunstanworth,
Shildon, Reeding, and Beldon, near Blanchland, and those lying about Hudeshope, Great and Little Eggleshope and Sharberry, north of Teesdale have wrought wide and rich veins above the Great limestone. The fact is certainly related to the distribution of hard beds in the country rock. The accompanying sections (page 201) show that the shale beds which are present in Weardale, the Allendale and Alston Moor are replaced in the districts mentioned by thick sandstones.

The beds below the Great limestone are much more constant in character than those above that horizon, and do not call for special reference. Variations in the size of ore bodies in those beds are due to some cause other than
Figure 30

Sections to show beds above the Great limestone in various parts of the North Pennine area:

- Dowgang shaft, Menthed (S. Smith 1922 p.17)
- Allenheads general section (S. Smith 1923 p.53)
- Burtree Pasture mine (Weardale Lead Co. Ltd.)
- Sharnberry mine (R.G. Carruthers 1923 p.17)
- Boltsburn mine (Weardale Lead Co. Ltd.)
- Jeffrey's shaft (Hunstanworth mines Ltd.)
- Shildon shaft (S. Smith 1923 p.35)
variations in the thicknesses of hard strata.

The Whin sill, being a hard bed, fractures almost vertically; but only a few veins have been wide when traversing this intrusion. A list of veins known in the Sill is as follows:

<table>
<thead>
<tr>
<th>Name</th>
<th>Character of Vein in Whin sill</th>
<th>Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allensoleugh</td>
<td>Strings: poor</td>
<td>Q</td>
</tr>
<tr>
<td>Birkdale Hush</td>
<td>2&quot; wide</td>
<td>B</td>
</tr>
<tr>
<td>Burtree Pasture</td>
<td>Good in places</td>
<td>F</td>
</tr>
<tr>
<td>Cowgreen (bore)</td>
<td></td>
<td>G</td>
</tr>
<tr>
<td>Force Burn</td>
<td>3&quot; wide</td>
<td>B</td>
</tr>
<tr>
<td>Greenhurth</td>
<td>5-6&quot; wide; rich</td>
<td>Z, G, Q, B, S</td>
</tr>
<tr>
<td>Greenlaws East</td>
<td>Poor</td>
<td>F, G, Q, S</td>
</tr>
<tr>
<td>Hartside (Loo Gill)</td>
<td>2-3&quot; several veins</td>
<td>B</td>
</tr>
<tr>
<td>Dufton</td>
<td>Poor</td>
<td>B</td>
</tr>
<tr>
<td>Little Whin quarry</td>
<td>Poor</td>
<td>C, S, G</td>
</tr>
<tr>
<td>Maizebeck mines</td>
<td>Poor</td>
<td>B, G</td>
</tr>
<tr>
<td>Merrygill</td>
<td>Poor</td>
<td>B</td>
</tr>
<tr>
<td>Moss Shop</td>
<td>Very poor</td>
<td>B</td>
</tr>
<tr>
<td>Nursery Hook trial</td>
<td>Poor</td>
<td>F, Q, G</td>
</tr>
<tr>
<td>Ord &amp; Maddisons qy.</td>
<td>6&quot;</td>
<td>F, C, G</td>
</tr>
<tr>
<td>Park End quarry</td>
<td>2&quot;</td>
<td>B, G</td>
</tr>
<tr>
<td>Raven Beck</td>
<td>2-3&quot;</td>
<td>B</td>
</tr>
<tr>
<td>Rodderup Fell</td>
<td>6-10&quot; Rich</td>
<td>F, C, Q, C</td>
</tr>
<tr>
<td>Scordale</td>
<td>Poor</td>
<td>Q, C, G</td>
</tr>
<tr>
<td>Settlements</td>
<td>10-20&quot;</td>
<td>W, B</td>
</tr>
<tr>
<td>Silverband (Y)</td>
<td>Poor</td>
<td>B, G</td>
</tr>
<tr>
<td>Silverband (W)</td>
<td>Poor</td>
<td>B</td>
</tr>
<tr>
<td>Sir John's mine</td>
<td>Poor</td>
<td>G, C, F</td>
</tr>
<tr>
<td>Slitt</td>
<td>Poor</td>
<td>G, E</td>
</tr>
<tr>
<td>Tees mine</td>
<td>?</td>
<td>G, F, Z, S</td>
</tr>
<tr>
<td>Tynebottom</td>
<td>Poor</td>
<td>S, C</td>
</tr>
<tr>
<td>Winch bridge</td>
<td>Strings</td>
<td>S, Z, C</td>
</tr>
</tbody>
</table>


Table XLV: Veins known in the Whin Sill.

The explanation for the narrowness of so many veins when traversing the Whin sill lies in the fact that the sill lies at a relatively deep level, where as shown later, Leithart's mechanism fails to operate; and in the chemical properties of the rock (page 155).
Before passing on to discuss the limitations of the mechanism, however, certain theoretical deductions must be considered. The diagram on page 200 shows that while the "cheeks" of the fissure are in contact in shale beds, they stand apart in the harder strata. The vertical movement in the fissure thus produces slickenside striated parallel to the direction of greatest slope in the shale, which are frequently found, but not in the hard beds. The width of the openings in the hard beds, moreover, depend upon the amount of movement, and upon the hade of the vein in shale. Figure 81, opposite, explains the relations; providing that the hade of the vein approximates to 0° in the hard beds,

\[ w = t \cdot \tan a \]

where \( w \) is the width
\( a \) the hade in shale
\( t \) the throw of the vein.

The width is thus independent of the thickness of the hard bed.

It is clear that the dominant stress in causing this type of opening in the rocks was a horizontal tension at right angles to the direction of the vein. The available evidence shows that open spaces which were formed by this mechanism were speedily filled with mineral material and
rock fragments, and there is no good evidence that
the spaces remained unfilled for any length of time; on the
contrary they seem to have been formed and filled simultaneously.
Had this not been the case, the shale material between A and B
(Figure 81) would in time have collapsed; but the veins show
no evidence of this other than a few fragments, and these
usually occur near the top of the wide part of the vein,
and not in the lower part. There has been a definite limit
to the possible amount of stretching and the widest veins
do not exceed 30-40'; the vast majority are less than 10' wide.
Correspondingly, all the veins in which Leithart's mechanism
has operated have a small throw, never greater to my knowledge
than about 15', and often less than this.

All veins do not, however, display the features
described above and it is noteworthy that the exceptions
are generally those associated with a large displacement. In
these the dominant stress has been vertical and not horizontal
in direction. It is suggested that they represent a slightly
earlier event in the regional tectonic history than the
ordinary veins; it is possible that the doming was preceded
by normal faulting. The existence of two classes of
fissures was recognised by Forster, who calls those with
a uniform hade "Regular veins"; this term will be adopted
here for the veins in which Leithart's mechanism has not
operated- i.e. those due to vertical stress. With regard
to the mineral content of this type, the following extract
from Forster (1883 ed. p.125) is significant -
"There are a great many regular veins which carry no ore at all. There are others which carry a small rib, and are yet unprofitable. Others, again, carry small fragments here and there, which are too insignificant to make them worth working."
The reason for the poverty of this type of vein, which is a fact of general observation in all parts of the area, lies in its structure, and in the fact that the large displacement usually tends to bring hard beds opposite soft beds. The Cross veins of Nenthead and West Allendale exemplify the "regular" veins. None have carried over 2' of mineral material and few as much as that. It is true that important flat deposits are associated with the Smallcleugh and Carr's veins, but these represent a separate problem. The respective displacements of the Cross veins in question is as follows:-

<table>
<thead>
<tr>
<th>Vein</th>
<th>Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Ashgill</td>
<td>18 - 21' SW</td>
</tr>
<tr>
<td>Cowhill</td>
<td>12 - 18' SW</td>
</tr>
<tr>
<td>Carr's</td>
<td>44' NE at Longcleugh</td>
</tr>
<tr>
<td></td>
<td>165' NE at Nentsbury</td>
</tr>
<tr>
<td>Smallcleugh</td>
<td>20 - 30' NE</td>
</tr>
<tr>
<td>Great</td>
<td>96' NE</td>
</tr>
<tr>
<td>Coalcleugh W.</td>
<td>126' NE</td>
</tr>
<tr>
<td>Coalcleugh E.</td>
<td>112' SW</td>
</tr>
</tbody>
</table>

These form a miniature rift.

There are a few exceptions, such as the Browngill vein (60-84' N) near Carrigill, and the Lodge Sike vein of Teesdale. In the former case the vein became much richer as the throw decreased, both to east and west of the point of maximum displacement near Whitesike.
The vast majority of the productive veins thus belong to the "Non-Regular" class, as those due to horizontal tension will henceforth be called.

If Leithart's mechanism represented the whole truth about the "Non-regular" veins, it would be expected that all hard beds would carry ore-bodies of approximately equal width in a given vein. When the deposits had been exhausted at a given horizon, it would simply be necessary to sink to the next lower hard bed, where an equally valuable deposit would be found. Unfortunately the facts have proved quite otherwise. The history of the North Pennine mining is a history of disappointments due to the deterioration and dying-out of the veins in depth. The behaviour of the Escarpment veins in the Melmerby Scar limestone - the thickest hard bed in the Pennines testifies to the reality of the downward impoverishment of the veins. At Silverband and Dufton Fell, many of the veins can actually be traced downward through this bed, but all of them are practically devoid of ore; the minerals have been restricted to beds lying at much higher stratigraphical horizons; at Dufton to the Tynebottom limestone, and at Silverband, the Four Fathom and Great limestones. The most famous deep trial in the area was one made in the Rampgill vein by the Veille Montagne Zinc Co. This has been described by Smith (1923). A shaft sunk from the Great limestone horizon (which was particularly rich in this mine), was carried down to the lower Little limestone, only a short distance above the Melmerby Scar limestone. The vein was productive down to the Slaty Hazle sandstone, but gradually
narrowed, and below that horizon split up into narrow strings, all of which were barren of ore. Essentially then, this vein resembles a "gash" vein in narrowing downwards. A similar condition holds at Sedling, where at the west end of the mine, a shaft was carried down to the base of the Scar limestone. This was successively narrower at each succeeding hard bed. Further examples are quoted by Carruthers, who lays great stress on the rapid impoverishment of the veins when followed downwards. In the upper part of the Hudeshope Valley the veins have all been wrought high up on the valley sides; and beds in the bottom of the valley, including the Great limestone, were generally unproductive, although explored for long distances, as at Marlbeck Low level, Pikestone Brow and Coldberry Low level. Smith points out that the long exploration and drainage levels, the Blackett level in East Allendale, and the Kentforce level in the Kent Valley, were both driven below the productive horizon in most of the veins cut. The Slitt vein of Weardale, usually about 20' wide when seen in the Great limestone, gradually narrows downwards, and is less than 2' wide in the Whin sill at the bottom of Slitt shaft.

The following data was taken from the Mine Reports on the Allenheads mines, and refers to the Allenheads Old vein -
<table>
<thead>
<tr>
<th>Horizon</th>
<th>Width of Vein</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firestone Sill</td>
<td>6½'</td>
</tr>
<tr>
<td>Pattinson Sill</td>
<td>(Good ore; no width given)</td>
</tr>
<tr>
<td>Little limestone</td>
<td>3 - 4'</td>
</tr>
<tr>
<td>Great limestone</td>
<td>1 - 4'</td>
</tr>
<tr>
<td>Four Fathom limestone</td>
<td>1' approx.</td>
</tr>
<tr>
<td>Mattock Gill hazle</td>
<td>Pinched out; thin strings only</td>
</tr>
<tr>
<td>Six Fathoms hazle</td>
<td></td>
</tr>
</tbody>
</table>

Similar instances could be multiplied from all parts of the field. The most impressive cases are those in which the Great limestone has proved unproductive in veins which in higher beds have contained a considerable width of mineral. The mines at Hunstanworth provide the best instance. Here, the Jeffreys, Ramahaw and Whiteheaps veins have attained widths of 10 - 30' of fluor spar, quartz and galena in the Grit sills sandstone. (See section of Jeffreys shaft, page 201). Seven shafts have penetrated the Great limestone, but an examination of the mine records reveals that in no instance have the veins been productive in this stratum; this is confirmed by two reports on the Hunstanworth property, one by Bewick (1869) the other by Hetherington (1917). Similar impoverishment of the vein in the Great limestone took place at Shildon, where the veins were successfully worked in the Grit Sills and Hippie Sill. The veins of the Upper Hadeshope district, which have already been mentioned, pinch out above the
Great limestone.

There is therefore no doubt as to the reality of the downward impoverishment of the veins. The horizon at which the veins cease to carry workable ore-bodies varies considerably from place to place. It is proved impossible to relate it to present topography. In valleys like Hudeshope and Bollihope, the productive level lies considerably above the valley bottom; on the other hand there are many instances in which veins have shown wide sections far below river level, as at Smittergill, the Tees mine, Brandon Walls, Groverake and many others. It is not therefore possible to postulate secondary enrichment, which would of necessity be related to topography. Moreover, there is no evidence in the veins of the operation of this process.

The regional doming provides the clue to the downward narrowing of the veins; reference may now be made to the structure map on page 49. The areal structure implies that fissures having a "V" form should exist; correlation of the structure with the veins is thus an obvious step. It is therefore necessary to re-interpret Leithart's mechanism in terms of the downward narrowing of the veins. Figure 82 page 210 is an attempt to do this.

As has already been shown, the logical conclusion to be drawn from Leithart's mechanism is that there exists a definite quantitative relationship between the hade of the vein in shale, its width and its throw. Thus, the displacement remaining constant in a given vertical section of a vein, its decreasing width also implies decreasing hade in shale when followed
downwards; so that when open spaces cease to exist in the hard beds, the vein becomes a "Regular" vein. The diagram above emphasises these features. Direct field evidence of the changing hade in a succession of shales is very difficult to obtain, owing to the fact that at present no accessible mine operates over a sufficiently wide compass.
The "V" form applies to all veins; no vein is known to become wider when followed downwards apart from the variations due to shale beds, in the area covered by the dome. Moreover, there is good reason to suppose that all veins become very narrow before reaching the base of the Carboniferous system; many veins pinch out at upwards of 1000' above this level. Further, those which have been followed downwards to considerable depths tend to split up into several strings, so that below the limit of productivity in the veins, there exist many tiny veins. The formation of wide filled spaces in the veins was therefore confined to a region within 4000' of the surface at the time of mineralisation. Below this region, the tiny vein presumably extends down to a great depth, probably to several miles below the base of the Carboniferous. There is no reason to suppose that the doming affected only the Carboniferous rocks; the older rocks of the Pennine basement would also be involved, and hence it is necessary to find some explanation for the restriction of the "V" form in the veins to the uppermost part of the crust. This is to be sought in the different rates of ascension of the solutions under pressure in the tiny veins. The solutions which reached the near surface zone (which was already jointed) first would tend to open their fissures at the expense of those which had not yet been filled, thus causing lateral movements in that zone. These

1 The veins in the Coal measures lie in a basin and not in a dome.
could take place in the well-jointed Carboniferous rocks, whereas they could not take place in the much-cleaved Older Palaeozoic rocks. Proofs of this lateral movement will be brought forward shortly. The lateral stretching of the area in the near-surface zone is thus represented by a comparatively small number of wide veins; the stretching in the zone below, the limit of productivity is accounted for by a large number of tiny veins, the aggregate width of which is (on account of the doming) slightly less than the aggregate width of the near-surface veins. In many of the tiny veins in which the solutions were not successful in producing wide veins in some part of the Carboniferous series, there would be a tendency for the solutions to find a path to the successful veins. The splitting up of veins when followed downwards is accounted for in this way.

It must be made clear that it is not suggested that the vein solutions actually initiated the formation of open spaces in the Carboniferous rocks, much less caused the doming; these are held to be the results of regional earth-movements. It is suggested however that the extent of the spaces was modified by the solutions, which must have travelled under great pressure.

Apart from the few cases mentioned in which it lies above the Great limestone, the lower limit of productivity generally lies below that horizon. This limit at first sight appears to vary regionally, but one cannot dismiss entirely the possibility that this apparent tendency is due to local mining prejudice, and sometimes to the inaccessibility
(without incurring heavy pumping and sinking charges)
of the lower strata. There is strong evidence
of downward impoverishment for these considerations not
to invalidate the conclusions reached on that question; but
a hypothesis of regional variation of downward limit must
be approached with great caution. The following facts
seem to be well-established -

(i) The Hunstanworth district veins, and those of
    Lodgesike and Wiregill, are not productive
    in the Great limestone

(ii) The Nenthead and Allenheads veins do not carry
    far below the Four Fathom limestone

(iii) The Upper Tees and Upper South Tyne veins are
    productive in much lower beds

(iv) The Whin sill generally lies below the productive
    limit, but not always.

The ultimate explanations of such variations are these
most probably lies in the changing curvature of the beds in
the original dome; were the total number of veins
in the area, with their widths, and the curvature of the beds,
accurately known, it would be possible to test this hypothesis;
unfortunately, the data are much too incomplete for this to be
possible.

The table on page 214 presents the results of a
regional investigation of the productive horizons; it is the
aggregate of the observations recorded in the "Summary of Results"
and indicates that the lower limit of productivity most
frequently lie immediately below the Great limestone


<table>
<thead>
<tr>
<th>Horizon</th>
<th>Number of wide veins known</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Measures</td>
<td>9</td>
</tr>
<tr>
<td>Millstone Grit</td>
<td>10</td>
</tr>
<tr>
<td>Grindstone sill</td>
<td>18</td>
</tr>
<tr>
<td>Slate Sills (Grit sills)</td>
<td>38</td>
</tr>
<tr>
<td>Firestone sill</td>
<td>48</td>
</tr>
<tr>
<td>Little limestone and Coal sills</td>
<td>51</td>
</tr>
<tr>
<td>Great limestone</td>
<td>209</td>
</tr>
<tr>
<td>Four fathom limestone, Nattrass Gill hazle</td>
<td></td>
</tr>
<tr>
<td>Three yard and Five yard limestones and hazles</td>
<td>19</td>
</tr>
<tr>
<td>Scar limestone, Copper hazle</td>
<td>40</td>
</tr>
<tr>
<td>Tynebottom limestone</td>
<td>44</td>
</tr>
<tr>
<td>Whin sill</td>
<td>28</td>
</tr>
<tr>
<td>Lower beds</td>
<td>31</td>
</tr>
</tbody>
</table>

Table XV. Comparison of the numbers of productive veins known at various stratigraphical horizons.

The apparent upward impoverishment of the veins above the Great limestone suggested by this table is due to three factors –

(i). Over the western part of the area, the beds lying above the Little limestone have mostly been removed by denudation.

(ii) The thin nature of the hard beds of the Upper
Yoredales, except in very localised areas.
Only a very wide vein is worth working.

(iii). Genuine upward pinching-out, which will be considered under "Flat-deposits" for reasons which will appear hereafter.

It should be mentioned that the veins which penetrated the Coal measures are all associated with faulting of considerable magnitude - i.e. are "Regular" veins. The Coal Measures area, moreover, is structurally a basin. The veins should therefore become wider downward if the basin is really the counterpart of the Pennine dome as it appears to be. The witherite vein at Ushaw Moor shows some evidence of downward widening. At its outcrop near Standalone farm, it does not exceed 2' in width, at the horizon of the Low Main coal; whereas it is upwards of 10' wide in the mine, at the Harvey Coal seam horizon, 400' lower in the sequence.
**Influence of Intersecting Veins on Ore-Deposition.**

In the preceding pages, evidence of the tectonic control of ore-deposition has been adduced as an explanation of the vertical variations in the width of mineral-stuff exhibited by the veins. The lateral variations must now be considered.

Prime place here must be given to the influence of the direction of the veins. This has already been fully treated in Chapter III. Veins running NE-SW and E-W are productive, while those running NW-SE and N-S are unproductive as a general rule, except where they have been supplied with solutions from veins in the productive directions; and here they become unproductive away from the NE-SW or E-W veins. Nentsbury mine provides an example. The Sincay, Cox, Dupont and Liverick veins all become unproductive at distances varying from 600 to 1000' from their intersections with the Treloar and Second Sun NE-SW veins. In this example, the cross veins have simply acted as guides along which solutions from the NE veins have replaced the limestone. (Figure 83, page 217)

It is a matter of common observations that abrupt changes in width of NE-SW veins take place in the area when these veins are traversed by cross veins (NW-SE). Veins in the E-W direction also exhibit variations in width which can be correlated with intersections with other veins. Nentsbury mine provides a good case of the variation in width of the NE-SW veins when intersected by Cross veins.
Plan of Nentsbury Mine, adapted from the mine-plan of the Veille Montagne Zinc Co., by kind permission.

To show the variation in width of mineral-stuff in NE-SW veins when traversed by N<SE veins.

Figure 83
An investigation of the Upper Weardale veins, for which Mr. Hill kindly supplied data from Weardale plans, sections and records, revealed that the same conditions hold over a wide area. The abrupt changes in width of NE-SW veins and E-W veins where they are intersected by cross veins (NW-SE) can be seen on the diagram on page 219. The Burtree Pasture vein is one of the most instructive in this district. The vein was very rich in the Great limestone, and was in places worked down to the Whin sill from the west end, near the Burtreeford disturbance, to the first cross vein. From this vein to the second cross vein, the vein was pinched out, as shown by two levels which were driven through this ground. After the second cross vein, upper strata became productive, and good ore was found in beds from the Grindstone sill to the Coal sills. After 1\% mile of productive ground, another cross vein was cut, and the vein from that point into Rookhope was uniformly closed and barren. Parallel to this barren stretch, however, runs the Wolfcleugh old vein, which was 6 - 8 feet wide, until, going eastwards, the Heights cross vein was cut. The Old vein closed up east of this vein, but at the same time, the Wolfcleugh New vein, to the south-east, became productive. A section showing the stopes in the Burtree Pasture vein appears on the next page.

The arrangement of productive ground in the three vein described above suggests an echelon; but owing to the great number of veins, it is difficult to pick out individual echelons, if indeed they exist at all. In the Lodgefield and Old Fell
Figure 84

Mineral Veins of Upper Weardale, showing the changes in width of mineral-stuff in NE-SW and E-W veins at their intersections with NW-SE veins.

Figure 85

Section of Burtree Pasture mine, to show the influence of "Cross veins" on the productivity of the Burtree Pasture vein. Black masses indicate stope-out ground.
vein system (the long vein-systems crossing figure 84 from SW to NE), there appears to be a general shift of the rich ground from the former vein at the west end to the latter at the east end. The Barbary portion of the Lodgefield vein is wide at the west, while the Old Fall is poor; whereas at the east end, the Boltsburn continuation of the Old Fall vein is very rich (having great flat deposits associated with it) while the Fulwood portion of the Lodgefield system, tried by crosscuts from Boltsburn mine, is definitely barren.

A similar investigation of the old plans and sections preserved in the Surveyor's office of the Veille Monagne Zinc Company at Nenthead yielded like results; the cross veins were found to have caused marked changes in the character of the NE-SW veins. The Rampgill, Scaleburn, Guddamgill, Brownley Hill and High Raise veins were all greatly impoverished west of their intersection with the Nent valley cross veins, especially the Old Carr's vein. The BarneyCraig, Low Coalcleugh, and Scraithcole veins were all cut off by the West Coalcleugh Cross vein; but the former two veins regained their productivity after intersecting the East Coalcleugh Cross vein. The Garrigill veins behave in the same way as those at Nenthead, as far as the evidence goes. The Tynebottom mine in the Browngill vein is bounded to the west by the Windshaw Bridge Cross vein, and to the east of the Tyne by a small cross vein. Thence eastward to Whitesike it was poor, but after the Whitesike Cross vein has been passed, the Browngill vein again became productive. The deposit at Ashgill Field was controlled by cross veins in the same way.
In the mines, the phenomena associated with vein intersections were frequently observed. At Esp's, a cross vein has produced a marked change in the width of the vein; from the west end to the intersection, the vein averages 6 - 8' wide; but after the cross vein it splits up into strings in which the aggregate width of mineral does not exceed 1'6". The results of the examination of the veins at Nentsbury have already been presented. At Sparke's Pasture trial, the sudden cutting off of the mineral by an insignificant cross vein is very noticeable. At Barbary, the big fluor spar deposit lies between a cross vein which can be seen in the Ireshopeburn near the drift mouth, and the Flushiemea Great Cross vein. A cross vein in Stanhopeburn mine could be seen to "bring in" the fluor spar deposit (20' wide) in the Red vein.

What is the explanation of the coincidence of change of width in a given vein and its intersection with another vein? Fundamentally it is obviously related to tectonic conditions, and some connection with either regional or local tectonics must be sought.

Leithart's mechanism is worth considering from this point of view. This mechanism provides a number of spaces in hard beds along which solutions would travel laterally, in addition to passing vertically through the veins. Suppose now a fault crosses the vein, bringing an impervious shale against the hard bed. Lateral movement of solutions would be prevented, and since it seems probable that lateral movement of solutions was at least as important as vertical
movement - perhaps even more important - the effect would be to cause the vein to be barren on the other side of the fault, unless solutions were supplied from the opposite direction on that side.

This explanation seems to meet the case for the Burtreeford disturbance. No vein is known to pass through this complex fold which would act as a most efficient barrier to laterally-moving solutions.

Figure 86: Role of the Burtreeford disturbance as a barrier to laterally-moving vein-solutions.

The following is the evidence - apart from that already presented on pages 105, 106 - for regarding the disturbance as a "barrier wall" between the two areas of mineralisation:

1. The Allenheads veins are cut off by the disturbance; although a level has been driven through the dyke, and trial levels have been driven across the line of the veins from Middlehopehead and Blackcleugh, they have not been found to the west.

2. Slackensike, Burtree Pasture and Sedling veins are
truncated by the disturbance, and have not been found to
the west of it. The Grassfield vein to the west does not
correspond with any of these in direction.

3. Levels driven west from Langdon Beck show that the
veins which are so abundant to the east definitely come to an
end at the disturbance.

There is only one case of two veins on approximately
the same line on either side of the disturbance - a vein in
Burnhope and the Wearhead vein. This may well be a coincidence,
for neither has been proved through the track of the
disturbance; indeed the old headings which were opened
out by the company constructing the Burnhope Dam, show that the
Burnhope vein dies out before reaching the disturbance.

A few examples of changes in the mineral-content of
veins at cross veins are known. Trestrail (1931) has described
one such case. In this instance, it is probable the cross
vein formed an impervious barrier between the two parts
of the NE-SW vein; open spaces in that vein were filled
by solutions travelling from the south-west in the portion
south-west of the cross vein, and by solutions from the north-
west in the north-west portion.

The deduction from Leithart's mechanism proposed here
will not, however, account for most of the phenomena of
intersection-influence; the field evidence shows that the
cross veins causing a profound change in width are often
very insignificant faults with, a throw of only a few inches,
as at Sparke's Pasture.
The area may be looked upon as a "chessboard", cut up into blocks by the vein-fissures. At a given horizon, a certain definite amount of total stretching, represented by width of vein material in the NE-SW and E-W fissures, was possible during the introduction of the minerals. This was not such that all fissures could be filled to a considerable width. Those actually filled would therefore be those first reached by the solutions under pressure. These would not necessarily be the same on either side of the cross veins, which are assumed on this hypothesis to have permitted small lateral movements of the blocks along them.

Cross veins do not always cause an alteration of width in other veins which they traverse; and upon the mechanism here proposed, there would be an equal chance in either direction. This is in accordance with the field evidence. The evidence presented in the previous section upon the restriction of wide veins to the near-surface region in which slight lateral movements were possible must be considered in the light of the facts which have emerged in investigating the horizontal variation of openings in the rock. It is suggested that the facts brought forward in the present section can best be explained by slight lateral movements of blocks along cross veins, as shown in the diagram above.

![Figure 37: The "Chessboard" arrangement of veins.](image)
The "heave" of a NE-SW vein by a cross vein must in some cases be ascribed to the process described. It is noticeable that in many instances in which a vein is shifted at an intersection, that there is no evidence of the lateral movement of the country rock over the distance of the apparent "heave". Such a case is found at Heights. Here the "Heights North Vein" appears to have been displaced to the north along the Heights Cross vein a distance of upwards of 1 mile. There is no evidence that the beds moved this distance; and it therefore suggested that the veins on either side of the cross vein are two different veins; and that each was closed after its intersection with the cross vein. It is therefore impossible to deduce from the phenomena of vein intersection the relative ages of the veins in the present area. Forster (1809) has already called attention to the puzzling and contradictory nature of the evidence when an attempt is made to do this. A glance at the 1" scale map of the veins accompanying this work will show that there is a consistent displacement of the veins at their intersection with other veins.

At Nentsbury, Brownley Hill, and Greenfield, however, there is evidence of post-mineralisation displacement of the cross veins along the NE-SW veins. Brecciation and slickensiding along the latter veins witness to the late date of these movements, which are of small extent. At Nentsbury there is no evidence of movement in the cross veins. This type of displacement is altogether different from that described
above; its magnitude is much less, and it represents
the result of the movements which gave rise to the
slickensides, probably in Tertiary times. It appears from
the evidence at Brownley Hill and Nentsbury that the
northern part of the local area moved slightly more rapidly
than regions further south (See Nentsbury plan, page 217).
Evidence of small displacements of the order of 10-15'
such as these was not forthcoming in other parts of the
Pennine region.

No satisfactory evidence of pre-mineralisation
displacement of veins at their intersection with
other veins was forthcoming; in all the cases investigated,
one of the two possibilities outlined above was adequate to
account for the evidence.

The present discussion cannot fruitfully be carried
any further from the results of the work so far done.
Sufficient has been said, however, to make quite clear
the dependence of the width of the veins, both vertically and
laterally, upon the regional tectonics, and upon the fact that
the vein-solutions ascended under great pressure. Confirmatory
evidence of the ascension of the solutions under pressure was
forthcoming at Boltsburn West Level, where shale has undoubtedly
been carried upwards in the vein by the solutions. (See fig.874a,
page 228). The identity of the shale inclusions was correlated
beyond possibility of doubt with the Low Coal sills shale,
a black carbonaceous shale; shales above the inclusions were
micaeous.
Chemical Factors controlling Ore-Deposition in Veins.

For the sake of completeness, the factors which were discussed in earlier chapters will be included here. These were the chemical factors:

1. The nature of the deposits at any given locality is determined by the position of the vein in the regional zonal sequence. Deposition was controlled by fall of temperature in the veins; this factor has controlled not the extent but the composition of the deposit.

2. The chemical nature of the country rock.
The influence of the physical properties of the country rock has already been fully discussed. A note must be added on the chemical effect of the wall rock on precipitation. The banded structure is probably controlled in the first case by the country rock; but it is also possible that the amount of material precipitated was also influenced to some extent by the wall rock. In the case of limestones, it is certain that their chemically active nature would favour precipitation. Boydell has suggested that sulphide ores were coagulated from colloidal solution by calcium bicarbonate in the case of certain Lead-Silver-Zinc limestone replacement deposits in Mexico (1927). The liberation of calcium bicarbonate as a result of reaction between carbonated solutions and limestone must have taken place in the present area. Thus limestones would naturally be the most favourable ore-bearing horizons. They are, moreover, much more readily replaced by all
types of ore-minerals than any other kind of rock. Finlayson (1910b) conducted a series of experiments in order to compare the quantities of lead and zinc deposited from solutions of their salts by various solid materials. Limestone was shown to extract the metals much more readily than did shale, carbonaceous substances or silicates.

The easy replacement of limestone by ore-minerals contrasts strongly with the metasomatic alteration of the Whin sill rock, which is replaced only by carbonates. It thus seems to have exercised no influence in precipitating minerals other than the carbonates, which seem in some cases to have stopped up the fissure, thus preventing the passage of solutions to higher beds, as at Scordale.

There is no good evidence of precipitation having been caused by shales or carbonaceous rocks.

---

Figure 87a.
Shale inclusions carried upwards in vein: No. 3 Rise, Boltsburn West Level Mine. October 1931
Summary of Factors which have controlled vein-deposits.

The composition of any deposit was controlled by -

1. The distribution of temperature in the veins at the time of mineralisation; this has given rise to a zonal sequence in the deposits.

2. The chemical properties of the country rock, which have locally influenced precipitation from the solutions.

The extent of any deposit was controlled by -

1. The possibility of open spaces, which could be filled with mineral stuff, existing. This depended upon three major factors -

   i. The presumed continuance of regional compression during mineralisation, causing NW-SE, and E-S veins to be closed.

   ii. The regional doming, opening the NE-SW and E-W veins within the near-surface region, and causing them to become successively wider when followed from lower to higher stratigraphical horizons in this region.

   iii. The differing response of soft and hard beds to the tension set up during the doming giving rise to the "Non-regular" vein-structure. Wide veins are found only in hard beds, and thus deposition depended in addition upon the physical properties of the country rock. The throw of the Non-regular veins is characteristically small, and a relation exists between the displacement, the hade in shale, and the width of the vein.
2. The slightly earlier arrival of the solutions in some spaces than in others, causing certain veins to be wide and others narrow, owing to lateral movements along cross veins in the near surface region of the earth's crust, brought about by the pressure of the early solutions on the walls of the spaces filled by them.

3. To a very limited extent, precipitation controlled by the chemically active nature of limestone.
FACTORS CONTROLLING ORE-DEPOSITION

2. In Flat-Deposits.

The origin of the Flat-deposits is a problem which cannot be viewed apart from the general mechanism controlling vein formation, since these deposits occur only in association with veins. At the same time, the flats present some special problems, for they are by no means universally distributed throughout the area.

The first possibility to be examined is one suggested by the zonal sequence. It was thought probable that the solutions would be more active chemically in the lower zones than in the higher zones. Table XVI, page 232 summarises the mineral evidence for all the known flat-deposits in the North Pennines. 34 out of 38 occurrences contained fluor spar; 4 carried fluor spar and barytes, and only 2 (one doubtful) carried only barytes in the matrix. On the whole, then, the solutions were more active chemically in the fluor spar zone - a fact which is very easily accounted for by the assumption that the calcium of fluor spar was actually derived from the limestone by decomposition.

At the same time, it must not be supposed that this fact will account for the origin of the flat deposits, for the geological evidence shows that while deposits of this type are associated with a few of the veins in the fluor spar areas, a majority of the veins in these areas show only a very limited metasomatic effect on the country rock, and have
### Table XVI. Flat Deposits in the North Pennine Area

<table>
<thead>
<tr>
<th>Locality</th>
<th>Value</th>
<th>Minerals</th>
<th>State of vein above flat-horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Little limestone</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black Ashgill</td>
<td>m</td>
<td>G Z S Q</td>
<td>Unknown.</td>
</tr>
<tr>
<td><strong>Great limestone</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allenheads</td>
<td>R</td>
<td>G F Q S D</td>
<td>Definitely closed</td>
</tr>
<tr>
<td>BarneyCraig</td>
<td>VR</td>
<td>G Z F Q S D</td>
<td>Closed</td>
</tr>
<tr>
<td>Boltsburn</td>
<td>VR</td>
<td>G F Q S D</td>
<td>Definitely closed</td>
</tr>
<tr>
<td>Burtree Pasture West end</td>
<td>m</td>
<td>F Q G</td>
<td>Not worked; no stopes above 1st here.</td>
</tr>
<tr>
<td>Cowhaust.</td>
<td>m</td>
<td>F Q G Z S L</td>
<td>Denuded off</td>
</tr>
<tr>
<td>Esp's</td>
<td>mR</td>
<td>G F Q Z</td>
<td>Pinched out in Little 1st.</td>
</tr>
<tr>
<td>Flushtiamena</td>
<td>m</td>
<td>G B W F</td>
<td></td>
</tr>
<tr>
<td>Grasshill</td>
<td>p</td>
<td>B F G</td>
<td>Denuded off</td>
</tr>
<tr>
<td>Greenlaws</td>
<td>mR</td>
<td>F G Z Q S</td>
<td>Pinched out above flats</td>
</tr>
<tr>
<td>Grooveheads</td>
<td></td>
<td>L F Q G</td>
<td>Denuded off</td>
</tr>
<tr>
<td>Guddamgill</td>
<td>mR</td>
<td>Z G F Q</td>
<td>Poor in Coal sills.</td>
</tr>
<tr>
<td>Heights North</td>
<td>m</td>
<td>F Q G</td>
<td></td>
</tr>
</tbody>
</table>

- Denuded off
- Poor in Coal sills.
<table>
<thead>
<tr>
<th>Location</th>
<th>Symbol</th>
<th>Evidence</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holyfield</td>
<td>n</td>
<td>G A Q Z S</td>
<td>Closed in Coal sills and Little 1st.</td>
</tr>
<tr>
<td>Killhopehead</td>
<td>m</td>
<td>G Z F Q L</td>
<td></td>
</tr>
<tr>
<td>Middlehope Shield</td>
<td>m</td>
<td>L G F Q</td>
<td></td>
</tr>
<tr>
<td>Old Carr's South end</td>
<td>mR</td>
<td>F G Z Q S</td>
<td></td>
</tr>
<tr>
<td>Old Fall</td>
<td>p</td>
<td>L S F</td>
<td>Closed</td>
</tr>
<tr>
<td>Pike Law</td>
<td></td>
<td>F Q A G</td>
<td></td>
</tr>
<tr>
<td>Red Vein, Stanhopeburn</td>
<td>mR</td>
<td>L F G</td>
<td>No workings above 1st. at Shield—close</td>
</tr>
<tr>
<td>Scaleburn</td>
<td>R</td>
<td>F Q S G Z</td>
<td>Workings above 1st.</td>
</tr>
<tr>
<td>Soaresike</td>
<td>mR</td>
<td>F Q G</td>
<td>Closed in Coal sills</td>
</tr>
<tr>
<td>Slitt vein West Slitt</td>
<td></td>
<td>S G F</td>
<td></td>
</tr>
<tr>
<td>West Rigg</td>
<td></td>
<td>L F Q</td>
<td>Denuded off</td>
</tr>
<tr>
<td>Smallcleugh (Handsome Mea)</td>
<td>VR</td>
<td>D G Z Q F</td>
<td>Poor in Coal sills</td>
</tr>
<tr>
<td>Snaigill</td>
<td>m</td>
<td>B F G</td>
<td>Closed</td>
</tr>
<tr>
<td>Sparke's Pasture</td>
<td>pm</td>
<td>F G Q L</td>
<td>Denuded off</td>
</tr>
<tr>
<td>St. Peter's</td>
<td>mR</td>
<td>F G Z Q</td>
<td></td>
</tr>
<tr>
<td>Swinhope</td>
<td>m</td>
<td>G Z Q S</td>
<td></td>
</tr>
<tr>
<td>West Pasture</td>
<td></td>
<td>L Q F G</td>
<td></td>
</tr>
<tr>
<td>Williams</td>
<td>R</td>
<td>F Q S G Z</td>
<td></td>
</tr>
</tbody>
</table>

**Four Fathom Limestone**

<table>
<thead>
<tr>
<th>Location</th>
<th>Symbol</th>
<th>Evidence</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Esp's, West end</td>
<td>mR</td>
<td>G Z F Q S</td>
<td>Fairly good in Great 1st.; closed in Little 1st.</td>
</tr>
</tbody>
</table>
**Scar limestone**

<table>
<thead>
<tr>
<th>Location</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashgill Field</td>
<td>R F Q G Closed in Slaty Hazle</td>
</tr>
<tr>
<td>Greenlaws</td>
<td>m F Q G S Closed</td>
</tr>
<tr>
<td>Park (reported)</td>
<td>B G</td>
</tr>
</tbody>
</table>

**Tynedbottom limestone**

<table>
<thead>
<tr>
<th>Location</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashgill Field near Tyne</td>
<td>p F G Q S Denuded off</td>
</tr>
<tr>
<td>Dufton</td>
<td>mR B GA -</td>
</tr>
<tr>
<td>Rodderup Fell</td>
<td>mR F Q G Definitely closed</td>
</tr>
<tr>
<td></td>
<td>immediately above flats in all beds</td>
</tr>
<tr>
<td>Tynedbottom</td>
<td>mR F Q G No workings</td>
</tr>
</tbody>
</table>

**Metamorphosed Melmerby Scar limestone**

<table>
<thead>
<tr>
<th>Location</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scordale</td>
<td>m B FG Pinches out</td>
</tr>
</tbody>
</table>

---

**Key:** G, galena; Z, blende; F, fluor spar; B, barytes; W, witherite; Q, quartz; S, siderite; L, limonite; D, dolomite; A, aragonite.

**Summary**

<table>
<thead>
<tr>
<th>Type</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Little limestone</td>
<td>1</td>
</tr>
<tr>
<td>Great limestone</td>
<td>29</td>
</tr>
<tr>
<td>Four Fathom limestone</td>
<td>1</td>
</tr>
<tr>
<td>No. of veins in the area... 584</td>
<td></td>
</tr>
<tr>
<td>Scar limestone</td>
<td>3</td>
</tr>
<tr>
<td>No. of veins with flats...39</td>
<td></td>
</tr>
<tr>
<td>Tynebottom limestone</td>
<td>4</td>
</tr>
<tr>
<td>Melmerby scar Lst.</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong>: 39.</td>
<td></td>
</tr>
</tbody>
</table>
failed to give rise to flat deposits.

The Rampgill-Barneycraig vein-system provides a clue to the situation. The Rampgill portion of the vein, from Nenthead to the Bounder End cross vein, was without flats, but was a large scale vein, which carried ore bodies in all hard beds from the Slaty Hazle to the Upper Slate Sill. The character of the vein-system changes entirely after traversing the cross vein mentioned, and great flats appear in the Great limestone; meanwhile, the workings above that horizon cease - indeed the Barneycraig vein seems to die out entirely above the Firestone sill. The workings in the Fell Top limestone coal at Whetstone Mea, operated until recently by the Weardale Lead Company, were directly above one of the richest parts of the Barneycraig flats in the Great limestone; but no trace of the vein was found in the colliery.

Similarly at Boltsburn, where the richest flats ever known in the Pennines were worked, the vein definitely pinched out above the limestone. The case of Boltsburn must be considered in detail (see section on accompanying tracing). From the main shaft (not shown on section) almost to the Redway rise, stopes extended up to the Firestone sill; the vein was generally better in the thick coal sills sandstone than in the limestone. There were no flats in this part of the mine. With the appearance of the smaller flats, in the neighbourhood of the Redway rise, the vein ceased to carry much above the Coal sills sandstone. Then in the neighbourhood
of Hopeburn shaft, the Coal sills sandstone passed laterally into shales (see sections, page 201), and the great flats appeared. The vein was cut in the shaft at the Firestone horizon, but was closed and did not carry mineral material.

Again, at Rodderup Fell, where there are smaller flats in the Tynebottom limestone, these are situated below ground in which the vein was entirely unproductive, as sections showing the old workings in the mine, now preserved in the mine office, show.

These examples suggest that there is some connection between upward impoverishment in the vein and the appearance of flats in the nearest limestone below. The Allenheads veins confirm this suggestion. Here large scale flats were wrought in the Great limestone at the east end of the mine. A level called the "Fawside level" was driven above the Firestone horizon and cut the following veins with which flats were associated in the limestone below:

- Wentworth,
- Grindstone,
- Coronation,
- Henry's,
- Henrietta (See Fig. 88, next page)

These were tried in the sandstones above the Great limestone, but, according to the Mine Reports, in all cases proved unproductive and without minerals. On the other hand, at the west end of the mine, where there were no large flats, the veins carried well in these beds.
In the Coronation vein, where the flats were present in the Great limestone, the vein was 9" wide in the Coal sills, and was not considered worthy of trial. When the flats in the limestone disappeared, the vein became 3' wide at the Coal sills horizon.

Figure 88
Plan of Allenheads mine, adapted from S. Smith (1923 p. 66)
To show the disposition of flat-deposits (shaded black) and of exploration levels and cross-cuts.

Collection of data from all parts of the area entirely confirmed the view that flats occur in association with vein which are closed above the horizon of the replacement deposits. Table XVI summarises the evidence.
It must therefore be concluded that the formation of flats was related to special conditions of upward closing in the veins with which they are associated. The evidence bearing on the vein-solutions, so far assembled, points to their having ascended under great pressure from a deep-seated source. So long as there was easy upward relief of pressure, the solutions would continue to ascend, depositing minerals in their passage through the veins. When, however, upward relief of pressure ceased to be possible, they would be forced to penetrate the country rock, there initiating the metasomatic process on a large scale. The results of the penetration of the rock by the solutions in this way contrast strongly with the slight metasomatism caused by them when ascending in the veins in the ordinary way. Limestone would be much more readily penetrated than any other type of rock; great metasomatic deposits are therefore confined to that material without exception.

It is impossible to ascribe the obstruction in the veins to any single cause. In some cases, mere plugging-up of the vein with shale material may be the reason. In this connection, it is notable that when the Great limestone is overlain by thick sandstones, as at Jeffreys and Shildon (See sections page 201), it contains no flats, whereas when there is a thick shale cover, flats occur as in Alston Moor, the Allendale and Weardale. Further, veins in which Leithart's mechanism has failed to operate seem to be most favourable for flat formation; that is, the "Regular" veins, with a large throw, as at Handsome Mea (Smallcleugh Cross vein, 30' throw)
and at old Carr's (44' throw). In these cases, the probable reason lies in the fact that the displacement would cause the thin hard beds above the Great limestone to be brought into contact with shales, thus virtually closing the veins above that horizon. Veins with a small throw also tend to be narrow, as already shown. The Boltsburn vein throws only 2' NW or SE, and changes direction some five times in the flat regions; thus the vein here would be subject to very little opening upon the mechanism of vein-formation proposed.

Finally, it is possible that the veins in which the upward closing required for flat formation has taken place may be correlated with the "unsuccessful" veins—i.e., those in which the solutions arrived slightly later than those in adjacent veins. The first-arrived solutions are assumed to have ascended during the regional doming, and they may be said, not to have caused the doming, but to have controlled the particular local application of the regional horizontal tension set up. Now if solutions arrived under pressure after no further stretching of the area was possible, then they would be forced to penetrate the country rock, giving rise to replacement deposits. However, it is certainly not the case that all "unsuccessful" veins have associated with them flat deposits. There remains, therefore, some indeterminate factor which caused great quantities of solutions to be supplied to a few veins slightly later than the main supply of solution to most of the veins. While
it would be interesting to speculate upon the possible mechanism of this process, it is felt that perhaps too many highly speculative hypothesis have already been advanced in the present chapter. However, whatever the explanation of the flat-deposits may be, the field evidence of their association with veins which close upwards as well as downwards, and veins which have either an abnormally large or small throw, must be the basis upon which to work, and here, as in the case of the vein deposits, ore deposition has been controlled by tectonics. The composition of the deposits is again controlled by the regional zonal distribution of minerals, and there seems to have been a much greater tendency for flats to form in the fluorspar zone than in the barytes zone.
IX. THE GREAT SULPHUR VEIN-SYSTEM.

The Great Sulphur vein of Alston Moor, known to a former generation of miners as the "Backbone of the Earth" is the most conspicuous of all North Pennine veins; indeed it is the only one which, without human aid, has made a prominent surface feature. This unusual vein outcrops from Dargill Bridge on the Alston - Middleton-in-Teesdale road, to the summit of Welmerby Fell on the Escarpment, a distance of about nine miles. It is seen not only in the many streams which cross it, but also on the slopes and sometimes even on the tops of the fells.

An exhaustive study of the Great Sulphur vein has been made by the late Lloyd Thompson (1915), whose work also contains an account of the scanty previous work on this vein. As, however, his work has unfortunately remained unpublished, an outline of his findings will be presented here. To these a few confirmatory and additional points can be added.

The Great Sulphur vein, according to Wallace (1863) is "unique in its great width and mineral character" and with this conclusion Thompson concurs, describing it as "the single representative of its group of one". His work contains a full account of all the exposures of the vein. Table XVII page 242 is a summary of Thompson's observations on width, throw

---

1 It is my intention to prepare an abridged account of Thompson's work for publication as soon as possible.
and mineral content of the vein -

Table XVII. Summary of Thompson's observations on the Great Sulphur Vein.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Throw</th>
<th>Width</th>
<th>Mineralogy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dargill Bridge</td>
<td>Series of small faults</td>
<td></td>
<td>Q tr.Cp</td>
</tr>
<tr>
<td>Sidehead Sike level</td>
<td>? 150'N</td>
<td>168'</td>
<td>Q Pr</td>
</tr>
<tr>
<td>Sir John's level</td>
<td>150'N</td>
<td>112'</td>
<td>Q P (Cp)</td>
</tr>
<tr>
<td>River South Tyne</td>
<td>120'N</td>
<td>270'</td>
<td>Q P Pr(Cp G)</td>
</tr>
<tr>
<td>Dorthgill</td>
<td>120'</td>
<td>270'</td>
<td>Q</td>
</tr>
<tr>
<td>Noonstones</td>
<td>120'</td>
<td>1200'</td>
<td>Q</td>
</tr>
<tr>
<td>Crossgill</td>
<td>130'N</td>
<td></td>
<td>Q P</td>
</tr>
<tr>
<td>Duffergill</td>
<td></td>
<td></td>
<td>Q</td>
</tr>
<tr>
<td>Stannersgill</td>
<td></td>
<td>440'</td>
<td>Q</td>
</tr>
<tr>
<td>Cashburn</td>
<td>600'N</td>
<td>120'</td>
<td>Obscured</td>
</tr>
<tr>
<td>Blackburn</td>
<td></td>
<td>108'</td>
<td>Q P</td>
</tr>
<tr>
<td>Swarth Beck</td>
<td>250'N</td>
<td>150'</td>
<td></td>
</tr>
<tr>
<td>Smittergill</td>
<td>220'N</td>
<td>30'</td>
<td>Q P Pr</td>
</tr>
<tr>
<td>Aglionby Beck Head</td>
<td>small</td>
<td></td>
<td>Q L</td>
</tr>
<tr>
<td>Knapside branch</td>
<td>150'N</td>
<td></td>
<td>Q P G Pm</td>
</tr>
<tr>
<td>Melmerby Fell top</td>
<td>0</td>
<td></td>
<td>Q blocks</td>
</tr>
</tbody>
</table>

Key: Q, quartz; P, pyrite; Pr, pyrrhotite; Cp, chalcopyrite; G, galena; L, limonite; Pm, pyromorphite.
The following observations are also recorded in Thompson's work -

1. The vein consists of a plexus of strings and small veins which individually seldom carry more than 3' of veinstuff, and usually carry much less. Much country rock is thus included between the margins of the vein. The throw is usually taken by the southernmost fracture.

2. The mineral stuff is characteristic of this vein alone and differs greatly from that found in the normal Alston Moor lead veins. In the deeper parts of the vein it consists of a curious intergrowth of pyrite and quartz, with pyrrhotite and sometimes very subordinate quantities of chalcopyrite and galena. The intergrowths (Fig 89, next page) were found difficult to account for. In the upper parts of the vein, quartz was the sole mineral; a zonal sequence was thus recognised -

2. Quartz alone

1. Quartz and Sulphides.

An analysis of the pyrite gave the following results -

<table>
<thead>
<tr>
<th>Element</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>43.10</td>
</tr>
<tr>
<td>Fe</td>
<td>39.35</td>
</tr>
<tr>
<td>Cu</td>
<td>0.11</td>
</tr>
<tr>
<td>Zn</td>
<td>0.02</td>
</tr>
<tr>
<td>Co</td>
<td>? tr</td>
</tr>
<tr>
<td>Ni</td>
<td>tr</td>
</tr>
</tbody>
</table>

Gangue (SiO₂) 18.56 101.14
Simultaneous deposition of pyrite and quartz is postulated.

3. Alteration of the country rock consists of -
   (i) Deposition of silica on the grains of sandstones.
   (ii) Silicification of limestones.
   (iii) Production of a white decomposition-product from
       the Whin sill; particularly well seen at
       Aglionby Beck Head.

4. The minimum temperature of formation is held to have been 200°C; this is inferred from observations on the relative sizes of inclusion cavities and their bubbles (following a method devised by Sorby); and from the presence of coarsely crystalline quartz.

5. The vein is later than the Sir John's vein at Tynehead, since it was found to cut clean through that vein, no traces of the latter being found in it. The Sir John's vein unchanged in composition, was again found on the south side shifted some 20 fathoms. Thompson suggests for consideration the view that the Sulphur vein may have been formed in Miocene times as a late product of the cycle of igneous activity to which the Cleveland dyke belongs.

A re-examination of this interesting vein has entirely confirmed the observations made by Thompson; there are, however, a few points which must be added -
The first and most interesting fact is that when the mineralisation of the Sulphur vein is considered in relation to that of the normal veins, it is found that it does not in any way conform with them. Its mineral content, when plotted on the mineral distribution maps cuts right across several zones. This fact suggests that it is either earlier or later than the normal mineralisation. Confirmation of Thompson's view that it is later is obtained from several sources.

The Great Sulphur vein itself does not carry more than a few isolated specks of galena. On the other hand, the branch of the vein which runs from Aglionby Beck Head to Knapside has contained a fair quantity of that mineral, with pyromorphite. A more significant feature is the presence of quartz, pseudomorphous after barytes, in that vein both at Aglionby Head and at Knapside. In the former case, the pseudomorphs have the outward form of the rounded stalactitic variety of barytes (characteristic of the normal lead-veins); the examples from the latter locality show the replacement of barytes which had previously replaced limestone, with quartz. The crystals form of the barytes is perfectly preserved and it is difficult to distinguish the material from the barytes in limestone found at the Dufton mines (see page 146, fig.45). A thin section (T 30) of the Knapside material showed that the pseudomorphs contained a fine-grained mosaic of quartz, individual pseudomorphous being joined up by tiny strings of quartz. (See Fig 90).

Pseudomorphs of this sort are entirely unknown in the normal lead veins; further, quartz is of earlier...
Figure 89
Intergrowth of Iron sulphides and quartz, partly weathered out; from the Great Sulphur vein.
Re-photographed from a photograph by Thompson (1915)

Figure 90
Sketch to show quartz pseudomorphs after barytes, which has replaced limestone.

Knapside vein, on Knapside.
Approx. 1/4 natural size
and not later occurrence in the sequence than barytes in the normal veins. It is therefore suggested that the Knapside vein was originally filled by the normal mineralising solutions, and lay within the barytes-galena zone. At a later time the Great Sulphur vein was formed, and re-opened this vein, replacing the barytes (a low temperature mineral) with quartz.

Further evidence of a similar nature is forthcoming at Smittergillhead. Here a supposed continuation of the Rodderup Fell vein has been worked from its intersection with the Great Sulphur vein to the south-west. No evidence of the nature of the junction could be obtained; but the Sulphur vein in its exposure showed only quartz and iron sulphides. The spoil heaps from the lead vein show an assemblage of galena, blende and purple fluor spar brecciated and enclosed by the typical quartz-pyrite \( \rightarrow \) pyrrhotite) assemblage of the Sulphur vein. The whole weight of this evidence, taken in conjunction with Thompson's observations in Sir John's mine, is in favour of the Sulphur vein having been introduced at a later date than the normal lead veins.

Smythe's analysis of the altered whinstone from Aglionby Head (1930 p.118) suggests that the Great Sulphur vein-solutions were markedly different from those of the normal lead veins. The main difference in the altered rocks lies in the presence of a high percentage of iron oxides and no carbonate-minerals in the Aglionby rock. All three analyses of normal white whin show a high percentage of carbonates. Carbonates are correspondingly absent from the
Sulphur vein itself; but iron compounds are present in quantity. On the other hand, sulphides and quartz are absent from the altered rock. Smythe suggests that the solutions were rich in carbon dioxide and oxygen, and that the effect of metasomatic action was to open the rock up to weathering agencies.

This view seems to me to deserve a little extension. It must be remembered that the Aglionby Head white whin is adjacent to the Knapside vein intersection with the Sulphur vein. If the views herein expressed with regard to the Knapside vein are correct, then the Whin rock must have suffered two periods of metasomatic alteration by vein solutions. In the first, it would presumably be converted into a white whin similar to that at Force Burn, and rich in calcite. The Sulphur vein solutions (which cannot on the field evidence be considered to have contained much carbon dioxide) would convert this calcite into siderite, since they were rich in iron. Recent weathering would change the siderite into limonite, in which state it now occurs in the altered rock. Some such process as this would account for the unusual nature of the altered rock. The limonite formed in this process was at one time mined forumber at Aglionby head, so that the quantities of materials involved have been considerable.

A part of the contents of the Smittergillhead and Knapside veins was derived from the solutions which produced the Sulphur vein-stuff; nor are these the only veins
which must be correlated with that system. Two small NNE-SSW were discovered crossing the Black Burn above its junction with Smittergill; these have exactly the same composition as the Sulphur vein, and form a marked contrast with the neighbouring lead veins at Greencastle Tarn, and further down the burn. A level driven into one of these small veins failed to find anything but quartz and iron sulphides. Further, it is considered that the great preponderance of quartz in the Clargillhead N-S vein and in that part of the Sir John's vein near Clargillhead may be due to later reopening and filling by the Great Sulphur vein solutions. The Stow Crag N-S vein may also belong to this suite.

The Great Sulphur vein is not, therefore, alone in its class, though the other veins are very insignificant compared with it. The NNE-SSW and N-S veins represent the set at right angles to the main tension fissure and correspond with the set of insignificant vein formed at right angles to the "Quarter-point" (E-W) veins during the normal mineralisation.

The curious intergrowths of quartz and iron sulphides first described by Thompson are worthy of some consideration. The extraordinary likeness between weathered specimens of this intergrowth and the epimorphs of marcasite found in the oxidation zone of the lead veins is at once apparent. At the same time, repeated search has failed to disclose the usual "woody texture" of marcasite in the sulphides of the vein. It is hoped that at some future date it will be possible to apply the Stokes test to the sulphide materials, in order to decide definitely whether marcasite is present or not.
Pyrrhotite also crystallises in tabular masses, which would undoubtedly give rise to epimorphs of the type described, when the sulphide was weathered out. The question of whether more pyrrhotite is present than is usually supposed is worthy of further investigation. Thompson found only about 2% in the total iron sulphide (using a bar magnet) at Tynehead.

Summary.

The Great Sulphur Vein-system consists of a great tension vein up to 1200' wide, consisting of a plexus of smaller strings, and with a maximum downthrow to the north of 600', running in the "Quarter-point" (E-W) direction; and a number of insignificant veins at right angles. The vein is later in age than the normal mineral veins of the area, which it traverses, and has in certain cases reopened; it represents a much more local phase of activity than the normal mineralisation. It contains two zones, the deeper one consisting of intimately intergrown quartz and iron sulphides, the upper zone containing quartz alone. Very small amounts of chalcopyrite and galena also occur; these may have been derived from earlier mineral veins traversed by the Sulphur vein solutions. Metasomatic alteration of the Whin Sill has taken place, and differs in certain important respects from that due to the normal vein-solutions.
XII. THE AGE OF THE DEPOSITS.

The evidence which relates to the age of the North Pennine Ore Deposits (apart from the Great Sulphur vein system) will now be considered in detail:

1. The veins cut all Carboniferous beds from the lowest Carboniferous basement series up to the Coal Measures, and also the Whin Sill. They represent a single epoch of mineralisation.

2. A few isolated examples of ore-minerals are known to occur in the Magnesian limestone series of East Durham, of Permian age.

Galena occurs at Blackhall Rocks, as streaks intimately associated with dolomite and calcite. The two latter minerals are widespread throughout the limestones and are certainly the results of solution and re-precipitation within the rock, which has suffered much brecciation. There is no vein to be seen, nor is the mineral associated with any fissuring save that accompanying the brecciation, and the absence of ordinary gangue minerals of the mineral veins is noteworthy. It seems impossible to advocate any other mode of origin than deposition from the circulating groundwaters from which the secondary carbonate minerals were also deposited. A level was driven in a short distance from the cliffs here, but it has collapsed, and nothing more is known about it.

Dr. C.T. Trechmann, who kindly showed me the galena streaks mentioned, also informed me that he has found streaks of
brown fluorspar in the limestone at Hartlepool. These also were unconnected with fissuring, and strongly suggested a supergene origin. The occurrence of tiny fluorspar crystals as the nuclei of ooliths in the Upper Magnesian limestone, also investigated by him, confirms this view.

Smythe (1922) has described an occurrence of barytes in the Magnesian limestone at Marden, near Cullercoats, where it was found in the form of a bed, and not in veins.

Finally, native copper is said to have been found in a pocket in the Lower limestone at Raisby Hill quarry, near Coxhoe. None of the material remains, as it was quarried away, but the brecciated region in the quarry is still to be seen. This is in every way similar to the "solution gashes" widely found in the Magnesian limestone, and described by Lebour (1934) and Woolacott (1917); it does not resemble a vein in any respect. Chalcopyrite, enclosed in dark limonite (P 173) and associated with malachite was found, but no native copper, and it is not impossible that this material was mistaken for native copper at the time of the discovery of the pocket. Unhappily, no investigation of the occurrence was made by geologists at the time when it was found. The limonite enclosing the chalcopyrite enters into a rude crustification structure with malachite and calcite, and cements fragments of the breccia. No other ore-minerals were found, but gypsum is known to occur in the quarry. Trechmann (1925) has shown that gypsum and anhydrite occur in the Magnesian limestone series under Hartlepool and elsewhere, and considers that these minerals were formerly more widespread in the limestones than they now are.
Hydration of the anhydrite, associated with expansion, is considered to have caused much of the brecciation, and gypsum has mostly been removed in solution. The whole evidence is strongly in favour of very extensive circulation of solutions and deposition of calcite and dolomite. It is suggested that the ore minerals in the Permian rocks were introduced into their present positions by the agency of the same solutions.

They may have been derived ultimately from either of two sources, from veins hitherto unexposed, which cut the Permian rocks, or from veins in the Carboniferous rocks which were exposed at the time of formation of the Magnesian limestone. It has been shown that minute amounts of fluor spar and the sulphides are in time dissolved by the surface waters; these may have been carried into the Permian sea (in which extensive chemical deposition was taking place) and there precipitated, to be re-arranged by a process akin to lateral secretion, in more recent times.

Of the two veins, the second seems to be preferable. If true veins existed in the Permian, some example should be visible in this system, which is well exposed. Moreover, no fractures comparable with the vein fissures are known in the Permian, though there is an ill-developed joint system at Raisby Hill, without a consistent direction of jointing. It has already been shown that the vein-fractures were probably in existence before the deposition of the Magnesian limestone. The basin-structure of the Coalfield, tentatively correlated with the dome of the Alston block (page 215) was definitely in existence before
the Permian rocks were deposited. If then the correlation of the vein-fissures and the doming be accepted, the veins must be considered as Pre-Permian.

3. Neither authigenic nor allochthonous barytes or fluor spar have been detected in the Yellow sands at the base of the Permian system by Hodge (1932). The veins do not therefore cut the Yellow sands, and were not exposed in the areas from which the Yellow sands were derived. This does not, however, constitute an insuperable objection to their exposure at a later stage in Permian deposition.

4. Versey (1925) has found fluor spar in the Yellow sands of Yorkshire. Holmes (1927) points out that this fixes the age of the Yorkshire Pennine mineral veins. Since these are similar in every respect to those of the Alston block, there is no reason to suppose that they are of a different age. This again confirms the Pre-Permian age advocated for the veins.

5. While studying the heavy minerals of the Penrith sandstone of the Vale of Eden, Mr. A.E. Phaup found detrital barytes (unpublished results). This suggests that some of the Pennine barytes veins may have been exposed at the time of formation of the Penrith sandstone. The absence of fluor spar in the sandstone is readily accounted for by the fact that that mineral occurs at only one locality in the Pennine Escarpment - at Scordale - and erosion could hardly have reached the fluor spar zone in the veins there in Permian times.
6. The Cleveland (Tertiary) dyke cuts through the Doukburn vein near Crossgill (and not near Tynehead as stated by several authors). The first mention of this fact is due to Phillips and Louis (1896). The vein mentioned is known as the East Cross Fell vein further west, and is a member of the normal vein series.

7. Finlayson (1910a) has pointed out that the igneous intrusions of the Hercynian epoch were associated with much ore formation, as in Cornwall, while the activity of the Tertiary epoch was apparently unaccompanied by any ore-deposition. He therefore relates the mineral deposits in the British Carboniferous rocks to the former period. The more recent work on the British Tertiary Igneous centres (Mull, 1924; Arran, 1924; Ardnamurchan, 1930) has failed to disclose the presence of any vein deposits in or near these areas, save some barytes in Glen Sannox, Arran (1928). No details are known about this occurrence, save that it consists of a number of veins cutting lower C.R.S. rocks. It is by no means necessarily connected with Tertiary activity.

8. Goodchild (1890) has advocated a Tertiary age for the North of England Ore deposits, because of the absence of evidence of post-mineralisation disturbance in the vein material. His contention that there have been no relative vertical movements of the vein-walls since mineralisation is entirely supported by the present work; but as it has been shown that horizontal adjustments have taken place in almost all the veins, and in view of the absence of ores from the Tertiary centres, Goodchild's contention does not appear to be
justified.

Summing up, it may be said that the weight of the evidence is in favour of the view that the primary minerals were injected during the Hercynian crustal movements, in the interval between the intrusion of the Whin sill, and the deposition of the major part of the Permian series.

The age of the Great Sulphur vein-system is more difficult to fix than that of the normal veins. It is definitely later than these, but may well belong to the Hercynian epoch, representing a later phase; or it may be Tertiary in age. Thompson argues from the fact that it is parallel to the Cleveland dyke (Tynehead member) that it belongs to the latter epoch. It must be pointed out, however, that there are many quarter-point veins (E-W) belonging to the normal series, in the same direction. The only valid argument which can be applied at present to this vein is that used by Finlayson, and on this score, it must be regarded as Hercynian. The absence of any comparable deposit in the Permian and Triassic rocks of the Vale of Eden, which are traversed by the Armathwaite member of the Cleveland dyke, and the total lack of any similar occurrences in the Tertiary igneous province, seems to be conclusive.
XIII. ORE-GENESIS.

The evidence from all sources has now been presented, and it remains only to discuss the theoretical and practical implications of the results of the investigation. The present chapter will be devoted to a consideration of the fundamental problem in ore-genesis, namely the source of the primary solutions from which the minerals were deposited. The three possible sources have already been mentioned; the solutions may have been:

(i) Meteoric waters; which derived their mineral-content from the country-rock, and deposited the material in the veins, in the "zone of cementation".

(ii) Hydrothermal solutions derived from the Whin sill, representing the last stage in its magmatic evolution.

(iii) Hydrothermal solutions derived from a sub-Pennine magma, the rocks formed from which have not yet been revealed by denudation. This magma may have been (a) the parent magma of the Whin sill, in depth, which has differentiated towards granitic products or (b) a separate granite magma. The ultimate source of the ore-minerals may have been in the magma itself, or from sediments, by assimilation, or from some "sub-magmatic" source, as suggested by Gregory (1931). It is only possible to speculate upon such subjects as these; the main object of the present chapter is to decide to which of the three possible classes (i) - (iii) the solutions belonged.
(i) **Hypothesis of Lateral Secretion.**

1. **Wallace** (1863) considered that there existed a relation between the richness of the veins, the topography and a number of anticlinal axes in the Alston Moor area. Structural investigation has failed to reveal the axes, and it has been shown that the variations in productivity and also the downward impoverishment of the veins may better be accounted for by the influence of tectonics upon ore-deposition.

2. **Watson** (1900) has brought forward evidence of the modern formation of fluorspar, quartz and other minerals. It is suggested that the instances described by him were unusual cases in that reducing agents were present. No evidence whatever of the modern formation within the so-called "zone of cementation" of primary vein-minerals was discovered even in veins where the circulating groundwaters could have obtained plentiful supplies of the minerals from higher levels. (Chapter V)

3. **Finlayson** (1910) has shown that certain of the constituents of the ore-minerals occur in Pennine rocks in small quantity -

<table>
<thead>
<tr>
<th>Mineral Type</th>
<th>Fluorine (%)</th>
<th>Lead (%)</th>
<th>Zinc (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone, Nenthead</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone, Rookhope</td>
<td>0.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone, Alston</td>
<td>.0015</td>
<td>.001</td>
<td></td>
</tr>
<tr>
<td>Limestone, Nenthead:in vein</td>
<td>.012</td>
<td>.040</td>
<td></td>
</tr>
<tr>
<td>Do 70' from vein</td>
<td>.0005</td>
<td>.001</td>
<td></td>
</tr>
</tbody>
</table>
R «nevertheless considers that, on account of the close similarity of the veins in granite, slate, volcanic rocks and limestones in the various mining fields of Britain, and on account of the high silver-content of the galena as compared with that of the supposed supergene lead ore deposits of America, lateral secretion is not adequate to account for the origin of the deposits.

4. The banded structure in the veins and the regional zonal distribution of minerals, which is unrelated to the country rock, cannot be explained upon this hypothesis. The similarity, for example, of the witherite veins in the Coal measures and in the Whin sill, shows that the mineral-composition of the veins is independent of the country rock. (Chapters VIII and VI)

5. The results of lateral secretion in the Permian rocks in which solution and deposition connected with the groundwater-circulation have been very much more active than in the Carboniferous limestone series, have been to produce only insignificant concentrations of ore-minerals. (Chapter XII)

6. The relative amounts of calcium carbonate and lead in limestones should lead to the formation of deposits containing chiefly calcite. (Chapter V).

It is concluded, therefore, that the hypothesis of lateral secretion is entirely inadequate to explain the origin of the North Pennine ore deposits; a magmatic source must therefore be sought.
(ii) **Derivation from the Whin Sill.**

The presence of a series of dykes and sheets of Quartz-dolerite, injected into the area just before the introduction of the ore-deposits suggests at first sight that there may have been some direct genetic connection between the two.

1. **Miss Sweet** (1930) has argued for the derivation of the deposits from the Whin magma on account of the supposed coincidence of the barytes localities with the outcrops of the sill, and dykes. Detailed examination of the distribution of minerals in the area has shown that no systematic connection of this kind exists. Moreover, it is clear that the regional zonal arrangement of deposits is independent of the Whin sill and its associated dykes.

2. Late hydrothermal veins are known in the Whin sill. These consist of chlorite, quartz, calcite, pyrite and occasional zeolites such as pectolite, and are in no way similar to the mineral deposits. For this reason the latter cannot represent a hydrothermal stage in the evolution of the Whin sill magma.

3. The mineral veins traverse the sill, metasomatically altering it. They are known both above and below the sill. Chemical examination of the altered rock by Finlayson (1910) and Smythe (1930) has failed to reveal more than very small quantities of lead and zinc. Similarly the amount of barium in the Whin rock as determined by Harwood (1928) and Smythe (op. cit.) is very small. Fluorine is absent from the Holy Island dyke, which is not in the present area, but is connected with the Whin sill (Harwood, Op. cit.) :-
has suggested that the iron of the northern veins may have been derived from the Whin sill as a product of the metasomatism of the sill by the vein-solutions.

The whole weight of the evidence is thus very much against direct hydrothermal origin from the Whin sill.

(iii) Derivation from a deep-seated magmatic source

1. The regional zonal distribution of minerals in a series of concentric "domes of mineralisation" is such that it cannot be accounted for except by derivation of the solutions from two main centres lying on either side of the Burtreeford disturbance, with possible subsidiary centres north of the Tyne near Fourstones, and at Scordale. These imply derivation of ores from a sub-Pennine magmatic source. The main centres lie on a roughly east and west line which apparently coincides with the supposed long axis of the Pennine done. (Chapter VI)

2. This sub-Pennine magma was probably not the parent magma of the Whin sill; this conclusion is suggested by (i) the absence of fluorine from, and the paucity of lead, zinc and barium in the Whin rock; (ii) the fact that nowhere is a case known of basaltic magma have given rise to deposits of the Pennine type.

3. The Whin sill magma is known to differentiate towards a granitic rock type, and in places the sill contains as much as 5-6% of micropegmatite (Holmes, 1928; Smythe 1930). There is thus the possibility that the ores were derived from an acid magma produced by differentiation from the parent magma of the Whin sill; but in view of the small percentage of acid rock
their waters. Lindgren does not include fluor spar among the minerals of his lead-zinc deposits which have originated independently of igneous activity, but states that it occurs in near surface, intermediate and deep zones, as well as in contact metamorphic and pegmatitic types of deposits.

6. Barytes is not generally considered to be a mineral of igneous origin; but a recent case described by Fitch (1931) shows that it occurs associated with witherite in veins which can be traced to a granite boss near El Portal, Mariposa county, California. On approaching the granite, the barium minerals are replaced by calc-silicate minerals in the veins. There is thus no reason for regarding the presence of barytes as prejudicial to the case for igneous origin of the minerals. Brammal (1931) has brought forward strong evidence in favour of the view that at least the greater part of the barium in the Dartmoor granites and veins was ultimately derived from shale, assimilated by the magma. Such a process may have operated beneath the Pennines; to consider this process, however, is going a step further back than is necessary for the present discussion.

It is therefore concluded that the solutions represented juvenile magmatic waters derived from a Hercynian sub-Pennine magma. The deposits are classed (according to Lindgren's classification) as "deposits formed near the surface by ascending thermal waters, in genetic connection with igneous rocks" since they were formed at a depth of not more than 4000' below the surface.
XIV. SOME ECONOMIC APPLICATIONS.

Much of the information discussed in the previous chapters has been familiar to many generations of Pennine miners, having been handed down from one to the next as a series of empirical rules about the veins. It has been my task in carrying out the present investigation to become conversant with such rules, and to test them and re-interpret them in a scientific light. In a sense, then, the present thesis is a synthesis, in modern terms, of the accumulated experience of some centuries of mining. Repetition of the data already present is unnecessary in this chapter; the bearing of it upon mining-practice is sufficiently obvious. But certain entirely new conclusions have been reached as a result of the regional study. These are generalisations from the observed facts over the whole area, and as such are of interest from an economic point of view.

The factors which are considered to have controlled ore-deposition were summarised in chapter X. Were it possible to forecast the total effect of all of these in any given area, then it would be possible to forecast the location, extent, and value of new ore bodies in all parts of the Pennines. Such omniscience cannot yet be achieved, for certain of the factors are manifestly indeterminate. The present work does not therefore claim to have produced an infallible system for finding ore-bodies.

Nevertheless, it is claimed that an application of certain of the principles here established will materially
<table>
<thead>
<tr>
<th>Zone</th>
<th>Example of Mine</th>
<th>Values in %</th>
<th>Lead</th>
<th>Zinc</th>
<th>Fluorspar</th>
<th>Barytes</th>
<th>Witherite</th>
</tr>
</thead>
<tbody>
<tr>
<td>v</td>
<td>Ushaw Moor</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hartside and Long Fell</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>iv</td>
<td>Lunehead</td>
<td>1-2-2.5</td>
<td>5-8</td>
<td>0</td>
<td>0</td>
<td>90-95</td>
<td>75-80</td>
</tr>
<tr>
<td></td>
<td>Settlingstones</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Silverband (W)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Greenhurth</td>
<td>10-15</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nentsbury: (east end) (intersections)</td>
<td>2-5</td>
<td>2-5</td>
<td>0</td>
<td>60-70</td>
<td>5-15</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>iii</td>
<td>Rampgill, Barneycraig</td>
<td>10-20</td>
<td>10-20</td>
<td>5-10</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Allenheads</td>
<td>10-15</td>
<td>1-2</td>
<td>10-15</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Boltsburn</td>
<td>10-20</td>
<td>.5-1</td>
<td>10-20</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rodderup Fell flats</td>
<td>8-10</td>
<td>0</td>
<td>10-20</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stanhopeburn</td>
<td>2-3</td>
<td>0</td>
<td>60-70</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>i</td>
<td>Sedling</td>
<td>2-3</td>
<td>0</td>
<td>60-70</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values are here expressed in percentage of total vein-mineral or replacement material in the case of flats.
ECONOMIC GEOLOGY

I. LEAD AND FLUORSPAR

Productive lead deposits (zone II, III)

Lettered black; field coloured yellow.

Fluorspar : productive deposits lettered purple.
Nentsbury mine affords an example. The solutions have here ascended via the intersection of four NE-SW veins with four NW-SE veins, and have spread out in all directions. Thus very rich galena deposits occur near the intersections, but these give place to barium compounds away from the intersections, and the east foreheads which are heading for the outer region of the barytes zone, are very discouraging as far as lead ore is concerned. It is of course possible that further intersections with cross veins beyond these foreheads may have allowed the solutions to ascend; but once the drivages are deeply into the barytes zone, experience all over the area shows that the chances of finding much galena are remote.

(ii) Rich zinc mines are confined to zone (iii) in the area west of the Burtreeford disturbance. The Nenthead and West Allendale mines have produced huge quantities of blende.

(iii) Rich fluor spar mines occur only in zone (i), east of the Burtreeford disturbance. The relative amounts of lead and fluor spar in these mines is shown by the following figures -

<table>
<thead>
<tr>
<th></th>
<th>Lead produced tons</th>
<th>Fluorspar produced tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedling</td>
<td>3438</td>
<td>105,000</td>
</tr>
<tr>
<td>Stanhopeburn</td>
<td>2380</td>
<td>113,000</td>
</tr>
</tbody>
</table>

Lead is thus a useful by-product to the spar-mining; but to work these mines for lead only would be quite impossible.
II. ZINC AND BARYTES

Productive Zinc deposits (zone iii), lettered black; field coloured brown.

Barytes: productive deposits lettered green.
(iv). Pure barium compounds occur in zone (v) but in zone (iv), large barytes deposits with subsidiary galena, which forms a valuable by-product, occur. One of these is being worked at Lunehead, another at Scorndale.

Sufficient has been said to indicate the prime importance of an exact knowledge of the zonal limits over the area, for future prospecting operations. Fortunately, wide tracts still remain untried within the belt of rich lead mines; the country lying between East Allendale and the Derwent; that south-east of the Rampgill-Borneycraig workings; and the stretch south-east of the termination of the present workings in the great Nent Cross veins may be cited as examples. It may be wondered why the last-mentioned example is quoted in view of the fact that these veins have become unproductive; but since it is well known that cross veins become barren away from NE-SW veins, it is suggested that drivages in these veins might well reveal new intersections. Veins from Littlegill and Killhope must cut across these NW-SE veins beyond the head of Wellhope (Weardale). The chief disadvantage of most of the untried ground is in inaccessibility, and this no doubt accounts for the fact that it remains intact.

2. The "weight of hill" has always loomed largely in the North Pennine miner's thinking, and to this cause most of the changes in character of the veins are popularly ascribed. The influence of topography, as seen in the limits of the oxidation, is quite rightly explained in this way. The secondary
effects are confined to within 150-250' of the surface, and when a vein is followed laterally into a hill, the change from secondary to primary minerals is seen. West level, at Rookhope affords an admirable example. Prolonged secondary alteration seems to have leached out most of the galena from that part of the mine nearest the surface, but at the west end rich galena deposits are appearing beneath the oxidation zone, associated with unaltered siderite. (See also page 76). The extension of the "weight of hill" theory to account for the distribution of primary minerals in the veins, and the richness or poverty of the veins, is, however, without justification. Great emphasis has been laid on the fact that no consistent relation between the richness of primary deposits and the topography can be proved, in the present work because it is felt that this is a matter of some importance from the point of view of future development, especially in the case of mines like St. Peter's, in East Allendale. Here the workings will for some miles become deeper when carried along laterally, and will pass beneath the Allendale-Derwent watershed. There seems, on the regional evidence, to be no topographic reason for the non-continuance of this deposit.

3. Sinking in veins is a different matter. Given a wide vein in a hard bed like the great limestone, without flats, it may be taken for granted that at each lower hard bed, the vein will be successively narrower. More than sufficient expenditure on deep trials has been incurred already to demonstrate this fact conclusively, and further deep sinkings should be confined to exceptionally wide veins, with many untried hard beds not
far below.

4. On the other hand, when a vein in a hard bed above the Great limestone appears pinched out and poor, there is a twofold possibility -

   a. The vein may be equally poor in the limestone.
   b. It may carry rich flats at that horizon. There is only one guide in this case - the throw should be less than 2° or more than 20° (so that Leithart's mechanism has not worked) for the chance of finding flats to be considerable. The finding of flats must, however, remain very much a gamble; even geophysical prospecting of the "earth-resistively" type would encounter considerable difficulties in revealing them except fairly near the surface, on account of the pinching out of the vein above the limestone. It is possible, however, that seismic methods might be more successful.

5. In the flat deposits, there is a general tendency for calcite to increase towards the outer margins, and it is thus sometimes useful as an indicator of the approaching outer limit of the deposits. Much fluorspar seems to be a favourable sign.

6. The possible bearing of the theory of deposition by reaction between disperse phases in colloidal solution and the wall rock upon the amount of "pre-fluorspar" silica has already been described. (page 170-)

7. It seems impossible to forecast the effect of intersection
with a cross-vein on any given vein or flat. If the vein should be closed, however, after intersection with a cross vein, there is good reason for believing that a parallel vein will have become productive, and cross cuts should therefore be put out, even if the original fissure still continues. (Chapter X)

8. Barytes is always best worked below the surface, since in the "gossan" except in unusual cases like Long Fell, it is very much iron-stained. (Chapter V).

Resources of the Area

Lead Ore.

At the time of writing, five lead mines are ready to work, but only one - Nentsbury - is producing ore. The others are St. Peter's, Fsp's, Rodderup Fell and West level. Boltsburn mine, for many years the greatest lead-producer in Britain, was closed during the early part of the investigation. There are in addition a few small trials, where work is occasionally carried on, as at Burnhead, Stotsfield Burn, Wager Burn, Coldberry, and near Ashgillhead. The prevailing price of lead is so low at present that successful mining in most localities is impossible. The mines mentioned above contain fairly considerable reserves, and a rise in price would lead to resumed activity, and possibly even to a reopening of Boltsburn.

In addition to the ore-reserves actually blocked out or requiring development in the mines, there remain wide
areas of unproved ground, as already mentioned. There is good reason to suppose that large deposits must yet remain undiscovered, since there is no geological reason for the restriction of the deposits within the "rich-lead" area to the localities in which they are found. The apparent restriction of veins to the lower slopes of many valleys, as seen on the one-inch map must chiefly be explained by the fact that haulage or pumping charges became too great for further development to be possible in many mines, especially in those in which the veins were cut off by cross veins, as at Allenheads east end, Greenlaws, and Killhope. The direction in which the productive veins are to be found yet remains to be discovered in these three, and other cases.

None of the old mines, the workings in which were examined during the present investigation, held out any prospect for reopening, but the mine at Greenhurth, now inaccessible, is generally thought to contain considerable reserves; an efficient pumping-plant or deep drainage level is required, and some means of transport from this very lonely place.

To sum up therefore: it is held that the area is by no means exhausted, though in the centuries of mining that are past, almost all the easily accessible deposits have been wrought. Given an improved price for the metal, there is every reason to suppose that mining will revive and flourish for many years to come.
**Zinc Ore.**

The zinc ore in the Nenthead mines seems to have been exhausted, after having been for many years successfully wrought. Reserves of this material, however, remain untouched, or very little developed at the following mines: Greenhurth, Willyhole, Lady's Rake, the Tees mine near Moor House, and Smittergillhead. In some of these cases (notably Willyhole and Lady's Rake) efficient means of separating the ore from the gangue are important, especially when the gangue contains witherite. Flotation plants should enable this separation to be accomplished, and by use of them, certain other mines including Hunstanworth, Mentsbury and Esp's could produce blende as a by-product.

**Copper Ore.**

The copper mines of the area have never been of great economic importance, and under present conditions, offer no possibilities whatever.

**Fluorspar.**

Considerable reserves of fluorspar remain. Five mines have produced this material recently, but up to twelve years ago, many others were operated. The five mentioned are Sedling, Barbary, Stanhopeburn, Elmford and Groverake, and in all these except Barbary there are resources for many years work. At Hunstanworth, huge veins of this mineral can be seen in Whiteheaps mine.
Barytes.

Large deposits of workable barytes are abundant in Upper Teesdale, Inversdale, and along the Escarpment. Lunehead mine is producing at present, and Scordale has recently been reopened. Hartside, Long Fell and Cowgreen - in addition to many other veins, like the High North Edge, Snaisgill and Trough veins could be worked to advantage. Barytes, somewhat iron-stained, has been worked by a series of excavations in a vein in Foul sike, near Hunstanworth.

Witherite.

The North Pennine witherite is justly famous, and Settlingstones has been the largest producer of Witherite in Britain for many years. It is idle at present, but will no doubt re-open. The Ushaw Moor deposit is occasionally worked, and a similar deposit has recently been discovered at South Moor colliery. Reserves of this mineral sufficient to supply many years' demand are visible in the mines mentioned, and others undoubted exist in the Alston and Hexham districts.
XV. CONCLUSIONS.

1. The ore deposits of the North Pennine area occur in fissure veins which traverse rocks ranging from the basement beds of the Carboniferous up to the Coal Measures. (Chapter II)

2. The Hercynian epoch of crustal movements affected the area in two phases. During the first, regional top-compression towards the north-east produced a series of compressional folds running NW-SE and two conjugate sets of major joints, one set being parallel to the compression-direction, the other at right angles to it. The Whin sill and related dykes were injected at this time. The compression has been regarded as causing rotation of the "Alston block" in a clockwise direction; this probably continued into the second phase, during which normal faulting first appeared, to be followed by differential uplift of the area into a dome. At the same time, East Durham was folded into a structural basin. The doming set up horizontal tension, and the fissures so produced were filled by the vein-solutions.

Vein-fissures occur in four directions, two of which were almost closed (NW-SE and N-S) and two open (NE-SW and E-W) at the time of mineralisation. (Chapter III)

3. The principal minerals in the deposits are galena, zinc blende, fluor spar, barytes, with erite and carbonate minerals, chalcopyrite and quartz. The first four mentioned are much more generally abundant than the others. Rarer minerals also occur. (Chapter IV.)
4. The minerals were distributed in a series of "domes of mineralisation" from two major centres, one west and one east of the Burtreeford disturbance. Subsidiary centres possibly occur near Fourstones and at Scordale. The outward succession of the zones corresponds with fall of temperature in the veins. (Chapter VI)

5. Metasomatic alteration of limestone and quartz-dolerite occur wherever mineral veins have traversed these rocks. Alteration of sandstone is rare, and no chemical change was produced in shales. (Chapter VII)

True metasomatic replacement deposits are found in limestones, and in one case in a sandstone; these contain all species of primary minerals. Metasomatic replacement of the quartz-dolerite by the waste-products of the reactions which took place between the rock and the vein-solutions has occurred, but the sulphides and the dominant gangue minerals (fluorspar and barytes) do not replace the dolerite.

6. The deposition of ores in individual veins, in addition to being controlled by falling temperature, was influenced by some more local causes, perhaps to be referred to reaction between disperse phases in colloidal solution and the wall rock, and mutual reaction between disperse phases. Banded structures resulted. The minerals were deposited in a sequence of ranges not differing essentially from those produced on a regional scale by the zonal distribution. (Chapter VIII).

7. The vein solutions may have contained the vein minerals in colloidal solution, or in true solution. Each possibility
has both merits and disadvantages. In addition to the substances now found in the veins, alkalis and hydrogen sulhide, and a considerable amount of carbon dioxide, were present in the solutions. (Chapter IX)

8. After the conclusion of the main period of mineralisation, the Great Sulphur vein system, of much more local occurrence than the normal veins, consisting of a large vein running E-W and several insignificant veins running N-S, was produced. (Chapter XI)

9. Tectonic influences controlled the formation of spaces in which the solutions were able to deposit minerals. Owing to the connection with the doming, the veins have a general "V" section; and owing to the differing response of soft and hard rocks to tension, the veins have steeply in the former and are closed; and have only a slight hade and are open in the latter. E-W and NE-SW veins sometimes change in width abruptly at their intersection with cross veins. This phenomenon is probably due to slight lateral movements of blocks bounded by the fissures, caused by the earlier arrival of the solutions under pressure in some veins than in others. (Chapter X, i)

10. Where free upward relief of pressure was possible, the solutions continued to ascend; where, however, they were dammed-back, extensive metasomatic replacement of limestone, single case, of sandstone, took place, giving rise to flat-deposits. (Chapter X, ii).
11. The normal Pennine deposits were formed during the Hercynian period of earth-movements; the Great Sulphur vein-system probably belongs to a slightly later phase of the same epoch. (Chapter XII)

12. The ores originated not from meteoric waters, nor from hydrothermal solutions from the Whin sill, but from juvenile solutions derived from a sub-Pennine magma. These were wholly responsible for the deposition of the primary minerals. The parent magma was probably "acid" in composition (granitic), since the geochemical assemblage in the veins is similar to that known to have been derived from granites in other parts of the world. (Chapter XIII)

13. The deposits were probably not uncovered by denudation until Middle Permian times. Small amounts of ore-mineral-material in the Magnesian limestones have been re-distributed in more recent times by groundwaters. (Chapter XII)

14. Upon the deposits reaching the zone of circulating groundwaters, important chemical changes in the composition of the veins were produced by oxidation and allied processes. Secondary enrichment could only be proved in a single isolated case. (Chapter V)

15. Earth-movements during the Tertiary period gave rise to horizontally striated alickensides, and caused small horizontal displacements of veins to take place.

16. The results of the investigation can be applied usefully in working and searching for new mineral deposits in the area.
XVI. ACKNOWLEDGEMENTS.

It is very difficult to express adequately my great gratitude to Professor Arthur Holmes, under whose direction this work was carried out. His ever ready assistance and constructive criticism have proved an unfailing source of inspiration.

My best thanks also due to Dr. J.A. Smythe, with whom I have spent some delightful days in the field, for allowing me facilities for carrying out metallographic work in his laboratory at Armstrong College, and for his help both with this work and with chemical work. I wish to thank also Mr. C.E. Pearson for his assistance during my stay at Armstrong College.

To the owners, managers, and officials of the Pennine metalliferous mines, I wish to tender my sincere thanks, not only for allowing me to have free access to their mines, but also for their generous hospitality. Among these gentlemen, Mr. R.S. Willis, Managing Director, Weardale Lead Company; Mr. Amos Treloar, General Manager for the Veille Montagne Zinc Company, Nenthead; Mr. J. Alvin Hill, Surveyor to the Weardale Lead Company; Mr. P. Blight, Surveyor to the Veille Montagne Zinc Company; Mr. C. Heaps, Manager for Hunstanworth Mines Ltd.; Mr. J. Reynolds, Brough; Mr. T. W. Maddison, Boltsburn; Mr. Park, Sipton; Mr. Milburn Peart, Sedling; Mr. Liverick, Hensbury; Mr. Mathuggle, Rodderup Fell; Mr. Percy Widdas, Ushaw Moor; Mr. G. Trestrail, Settlingstones; Mr. Amos Treloar, Jnr.; Mr. Bradley and Mr. Peart, Barbary; Mr. Walton, Billingshield, must be mentioned; and to all others who have assisted me in the mines, I
am very grateful.

Mr. Hill and Mr. Blight have assisted me greatly, not only in the field and in the mines, but also in examining plans, sections and records of mines, and in giving me the benefit of their helpful criticism. To them a special word of thanks is due.

Mr. friend, Mr. George Wherry, has helped greatly in the arduous task of measuring the joint-directions; for his assistance and cheerful company I am duly thankful.

I am also grateful to Dr. W. Hopkins for discussing problems of stratigraphy and structure with me, and to Dr. C. T. Trechman for demonstrating on occurrences of ore-minerals in the Permian system to me.

Mr. G. W. O'Neill has rendered valuable services in preparing the thin sections, some of the negatives and all of the prints used in this work.

Mr. G. Herdman, Rev. Norman Walton, and Mr. J. Millikan, and many other gentlemen in all parts of the field, too numerous to mention by name, have assisted me by giving me information about the old mines. I am thankful to them.

Finally, I have great pleasure in acknowledging with thanks the generosity of the Durham County Council in awarding me a Senior Exhibition for two years in succession, and so making financial provision towards the accomplishment of the investigation here recorded.
XVII. BIBLIOGRAPHY.

Allen, R.T., J.L. Crenshaw, J. Johnson and E.S. Larsen
1912 "Die mineralischen Eisensulfide"

Allen, R.T., J.L. Crenshaw and R.R. Kerwin
1914 "The Stockes method for the determination of pyrite and marcasite."
Am. Jour. Sc. xxxviii

Balk, R.
1925 "Primary structure of granite massive"

Bastin, E.S. et aliter
1931 "Criteria of age-relations of minerals, with especial reference to polished sections of ores"
Econ. Geol. xxvi No. 6 pp 561-610

Boydell, H.C.
1925 "The role of colloidal solutions in the formation of mineral deposits"
Bull. 1st Min. Met. pp 1-108
1927 "Operative causes in Ore-deposition"

Bramnal, A.
1931 in "The genesis of ores in relation to petrographic processes"
Brannmal, V.
1921  "The mining, manufacture and uses of barytes
      in the neighbourhood of Appleby, Westmorland."

Brough J
1929  "On rhythmic deposition in the Yoredale series"
      Proc.Univ.Durham.Phil.Soc. viii.Pt.2,
      pp 116-125.

Cantrill T.C., R.L.Sherlock and H.Dewey
1919  "Sundry unbedded iron ores"

Carruthers, R.G., and R.W.Pocock
1922  "Fluorspar"

Carruthers R.G.
1923  "Lead and zinc ores of Durham, Yorkshire and
      Derbyshire"

Cloos, E
1932  "Structural survey of the granodiorite south of
      Mariposa, Cal."

Davison, E.H.
1921  "The primary zones of the Cornish lodes"
      Geol.Mag. lviii pp 505-512.

1930  "Mineral Associations in the Cornish tin lodes"
      Mining Mag. xliii No.3 p.143
DeRance C.E.
1873  "The occurrence of lead, zinc and iron ores in some rocks of carboniferous age in the north-west of England"

Geol. Mag. x Part 1 pp 64-74
Part 11 pp 303-309

Dewey, H.
1925  "The mineral zones of Cornwall"

Proc. Geol. Assoc. xxxvi 2 p 107

Dubey V.S., and A. Holmes

"Estimates of the ages of the Whin sill and the Cleveland dyke by the Helium method"

Nature 124, pp 477-478

Dunham, E.C.
1931  "Mineral deposits of the North Pennines"

Proc. Geol. Assoc. xiii 3, pp 274-281

1931 in "The genesis of ores in relation to petrographic processes"

Pan-American Geologist lvi 4 pp 287-288

1932  "Quartz-Dolerite Pebbles (Whin sill type) in the Upper Brockram"

Geol. Mag.

Dwerryhouse A.R.
1902  "The glaciation of Teesdale, Weardale, and the Tyne valley, and their principal tributary valleys"

Q. J. G. S., lviii pp 572-608
Egglestone M.W.

1907-8  "The Occurrence and commercial uses of fluor spar"


Emmons W.H.

1913  "The enrichment of the sulphide ores"

    U.S.G.S. Bull 529

1917  "The enrichment of ore deposits"

    U.S.G.S. Bull 625

1918  "Principles of Economic Geology" New York

Fairbanks E.E.

1928  "Laboratory investigation of ores" New York

Finlayson A.M.

1910A  "The metallogeny of the British Isles"

    Q.J.G.S. lxvi pp 281-298

1910B  "Problems of ore deposition in the lead and zinc veins of Great Britain"

    Q.J.G.S. lxvi pp 299-328

Fitch A.A.

1931  "Barite and Witherite from near El Portal, Mariposa co., Cal.

    Amer. Mineralogist svi 10 pp 461-468

Forster W.

1809  "A section of the strat from Newcastle on Tyne to Cross Fell, with Remarks on mineral veins"

    1st. ed. Newcastle

    2nd. ed. Newcastle, 1821

    3rd. ed. revised Rev. Wm. Nall, Newcastle 1833
Goodchild, J.G.
1889
"Some observations on the mode of occurrence and genesis of metalliferous deposits"
Proc.Geol.Assoc. xi pp 45-69

Hall, T.C.F.
1922
"The distribution and genesis of lead and associated ores in western Shropshire"
Mining Mag. xxvii pp. 201-209

Hedley, W.P.
1931
"The Lower Carboniferous"
Proc.Geol.Assoc. xlii 3 pp 232-238

Hickling, H.G.A.
1930
"The geological structure of the English Pennines"

Hodge
1952
"The Pennian Yellow Sands of North-East England"
Proc.Univ.Durham Phil.Soc. viii 5 pp 410-459

Holmes, A. and H.F. Harwood
1928
"The age and composition of the Whin sill and related dykes of the North of England"
Min.Mag. xxi 122 pp 493-542

1929
"The Tholeiite dykes of the North of England"
Min.Mag. xxii pp1-52

Hopkins, W.
1931
"Coal Measures"
Proc.Geol.Assoc. xlii 3 pp 238-245
Kemp, J.F.
1921  "The zonal distribution of ores concentrically around an igneous mass of igneous cent"
      Econ. Geol. xvi p.474
1922  ibid  xviip.46

Kendall, J.D.
1893  "The iron ores of Great Britain and Ireland"
      London
1921  "Lateral distribution of metallic minerals"
      Mining Mag. pp 75-80.

Kendall, P.F.
1902  "The Brockrams of the Vale of Eden"
      Geol. Mag. Dec. iv lix pp 510-513
1914  "Cleat in coal-seams"
      Geol. Mag. Dec. vi i, pp 49-53
1922  "The Physiography of the Coal swamps"

Lebour, G.A.
1875  "On the limits of the Yoredale series in North-east England"
      Geol. Mag. pp 539-544
1884  "On the breccia-gashes of the Durham coast and some recent earth-shakes at Sunderland"
1886  "Outlines of the Geology of Northumberland and Durham"
      Newcastle.
Leithart, J.

1838 "Practical observations on mineral veins, with the application of several new theoretical principles to the art of mining"

London and Newcastle.

Linck, G.

1903 Neues. Jahrb. B.B. xvi p.495

Lindgren, W.

1907 "The relation of ore deposits to physical conditions"

Econ. Geol. ii pp 103-127


Lomax, J.

1925 "Further researches on the various types of pyrites in coal"

Colliery Guardian 129 pp 1317-1318

Louis, H.

1917 "Lead mines in Weardale, Co.Durham worked by the Weardale Lead Co.Ltd."

Mining Mag. xvi pp 15-25.

Mellor

1927 "A Treatise on Inorganic chemistry" London

Nall, W.

1903 "The Alston Mines"

Nevin, C.M.

1931 "Principles of Structural Geology" New York

Nicholson, H.A. and J.E. Marr

1891 "The Cross Fell Inlier"

Q.J.G.S. xlvi pp 500-518

Niggli, P.

1929 "Ore deposits of Magmatic origin"

Translated by H.C. Boydell London.

Oliver, W.

1863 "Map of the Lead Measures in the County of Durham and part of Northumberland and Cumberland.

London.

Pateno E and A. Massuechelli

1904 Gazz. Chim. Ital. 34 i p.389

Pateno E and D. Vita


Peel, R.

1900 "Notes upon an occurrence of barytes in a 20 fathom fault at New Brancepeth Colliery"

Colliery manager and Journal of Mining Eng. xvi pp 55-58

Phillips J.A. and H.Louis

1898 "A Treatise on Ore deposits" London

Posnjak E and H.E. Merwin

1919 "The hydrated ferric oxides"

Amer. Jour. Sc. xlvii pp 311-348
Raistrick, A.


Rastall, R.H.

1923A "Metallogenetetic Zones" Econ Geol xviii 2 pp 105-121


Rohleder, H.P.T.


Sales, R.


Seidell

1919 "Solubilities" New York

Sherlock, R.L.


Siebenthal

Simpson, J.B.

1904

"The probability of finding workable seams of coal in the Carboniferous limestone formation beneath the regular Coal Measures of Northumberland and Durham"

Trans. Inst. Min. Eng. xxiv pp 549-571

Smith, S.

1912

"Report of the Committee on the Carboniferous limestone formation of the North of England, with special reference to its Coal resources."


1923

"Lead and Zinc ores of Northumberland and Alston Moor"


Smyth W.W.

1858

"Iron ores of Great Britain"

Mem. Geol. Surv. part i London

Smythe, J.A.

"Minerals of the North Country"

1921

"Fluorspar" The Vasculum, Newcastle-on-Tyne. 8 p.19

1922

"Barium minerals" Ibid 8 p.90

1923

"Galena" Ibid 9 p 89

1923

"Sulphides" Ibid 9 p.7

1924

"Chalcopyrite and Ullmannite" Ibid 11 p 7

1926

"General considerations and origin of calcite"

Ibid 12 p.143

1926

"Oxides of iron and manganese" Ibid 13 p.20

1927

"Miscellaneous" Ibid xiv p.12
Smythe, J.A.

1930  "A Chemical Study of the Whin Sill"

    vii 1 pp 17-150

Sopwith, T.

1829  "Geological sections of Holyfield, Hudgill Cross
      vein and Silverband lead mines"

      Newcastle

1833  "An account of the Mining districts of Alston Moor,
      Weardale and Teesdale" Alnwick

1864  "On the Lead mining districts of the North of
      England"

      Trans.N.Eng.Inst.Min.Eng. xiii p.188

Spencer, L.J.

1910  "On the occurrence of Alstonite and Ullmannite in
      a barytes-witherite vein at the New Brancepeth
      colliery, near Durham.

Spurr, J.E.

1907  "A theory of ore-deposition"

      Econ.Geol. ii pp 781-95

1923  "The ore-magmas" (2 vols) New York

Stille

Sweet, J.M.

1930  "Notes on British barytes"

      Min Mag. xxii 129 pp 259-270
Taylor, J

1833  "Report on the present state of knowledge respecting mineral veins"


Teall, E.J.H.

1884  "On the chemical and microscopical characters of the Whin sill"

     Q.J.G.S. x1 pp 640-657

Thompson, L.M.

1915  "The Great Sulphur Vein"

     Unpublished thesis submitted on work as holder of Research Studentship, Armstrong College.

Tolman C.F. and Clark J.D.

1914  Econ.GeoL xix pp 585-6

Tomkieff S.I.

1925  "The structure of aragonite"

     Min.Mag. xx 110 pp 408-434

Trechmann, C.T.

1925  "The Permian formation in Durham"

     Proc.Geol.Assoc. xxxvi p.135

Trestrail, G.

1930  "The witherite deposit at the Settlingstones mine, Northumberland"

     Bull.Inst. Min.Met No.315 pp 1-10

Trotter, F.M.

1929  "The Glaciation of Eastern Edenside, The Alston block and the Carlisle plain"

     Q.J.G.S. lxxxv pp 549-572
Trotter, E.M.

1928  "The Alston Block"

Geol. Mag. lxv • 772 pp 433-448

1932  "Geology of the Brampton district"

Mem. Geol. Surv. London

Turner, J.S.

1927  "The Lower Carboniferous succession in the Westmorland Pennines and the relation of the Pennine and Dent faults"

Proc. Geol. Assoc. xxxviii pp 339-374

Versey, H.C.

1925  "The beds underlying the Magnesian Limestone in Yorkshire"


1927  "Post-Carboniferous movements in the Northumbrian fault-block"

Proc. Yorks. Geol. Soc. xx1 pp 1-16

Wallace, W.

1863  "The Laws which regulate the deposition of lead in veins" London

1865  "The growth of Flos Ferri or coralloidal aragonite"

Q. J. G. S. xx1 1 pp 413-421

1890  "Alston Moor—its pastoral, its mines and miners"

Newcastle.
Wager, L.R.

1929A "Metasomatism in the Whin sill of the North of England"

Part I. Metasomatism by lead veinsolutions.

Geol. Mag. lxvi pp 97-110

1929B Do

Part II. Hydrothermal alteration by juvenile solutions

Ibid. pp 221-238

1931 "Jointing in the Great Scar limestone of Craven and its relation to the tectonics of the area"

Q. J. G. S. lxxxvii 3 pp 393-434

Watson, S.

1900 "Recent mineral deposits and their relation to vein-formation"

Trans Weardale Nat. Field Club. l i pp 57-61

1904 "The Boltsburn Flats- their interest to the student of nature"

Ibid l ii pp 146-150

Willis, Bailey

1923 "Geologic Structures" New York

Wilson, Eastwood, Pocock, Wray and Robertson

1915 "Barites and Witherite"


Winch, N. L.

1816 "Observations on the geology of Northumberland and Durham"

Q. J. G. S. & London.
Woolacott, D.

1912
"The Stratigraphy and Tectonics of the Perian of Durham (Northern area)


1923
"On a boring at Roddymoor Colliery, near Crook.

Co. Durham.

Geol. Mag. pp 50-62

Zies, E.G.

1929
"The Valley of Ten Thousand Smokes"

Nat. Geog. Soc. papers

14 pp 1-76
Map References

The one-inch scale map of veins which accompanies the present thesis is drawn upon the following Geological Survey quarter sheets -

102 NE; 102 SE; 102 NW; 102 SW; 103 NW;
103 SW; 106 SE; 106 SW; 105 SW.

In addition to the veins mapped upon these sheets by H.M. Geological Survey, those recorded on the corresponding six-inch sheets have been added together with other veins, the positions of which were ascertained from field evidence, and from the following sources -

Map of the Weardale Lead Company’s Royalty, by J.A. Hill;
Mine Plans in the possession of the Weardale Lead Company,
Wearhead; the Veille Montagne Zinc Company, Nenthead;
the Runstanworth Mines Ltd., Runstanworth; Lord Alnwick...
Estate Office, Allenheads; and from various private individuals.

Map of the Lead veins of Alston Moor, by W. Wallace, 1863

Map of the Lead Measures, by W. Oliver, 1862
Figure 91: "Shoad" ore (Galena from the boulder clay) Ellershope; found by Mr. J. A. Hill

Figure 92: Photomicrograph of polished surface of old slag from Ellershope, to show dendrites of metallic lead. X 25