

THE GEOLOGY AND DEVELOPMENT OF MILL CLOSE MINE, DERBYSHIRE.¹

J. G. TRAILL.

ABSTRACT.

This famous old English lead mine works a lead-zinc deposit in Carboniferous limestone, under a shale capping. The orebodies, continuous for 15,000 feet, bear a striking resemblance to the "manto" deposits of Mexico. Ore solutions have taken the path of least resistance from source to surface and the course followed has been controlled by such factors as dip of the strata, jointing and faulting, presence of impermeable lava flows, existence of beds favorable to replacement. Ore is found underneath impermeable lavas and shales, with a vertical height of 100 feet or so, in a remarkable series of interconnecting orebodies, as veins, flats, pipes and caverns, along joints of three systems. Primary minerals are galena (with practically no silver), sphalerite (with 1 per cent cadmium), calcite, fluorite, and barite. Deep secondary mineralization may be accounted for by artesian circulation. Water flow is heavy.

INTRODUCTION.

AT the southern end of the Pennines—the range of hills that has been likened to the backbone of England—the Carboniferous limestone has been elevated in a great dome and is exposed as an inlier over an area roughly 20 miles long by 10 miles broad (Fig. 1). The Peak District of Derbyshire, as the region is called, is noted nowadays for its striking scenery, but in the past it was chiefly celebrated for its thriving lead-mining industry. The limestone massif, particularly in its eastern half, is riddled with old lead mines, but for years the only important producer has been the Mill Close Mine, at Darley Dale. In a country notably deficient in non-ferrous metal mines, Mill Close has long enjoyed a renown out of all proportion to the size of the mine.

¹ Presented before the Society of Economic Geologists, New York Meeting, Feb. 14, 1939.

The geology of the mine, however, is particularly interesting and worthy of detailed description. During its long life the mine has been written up more than once. There are the various memoirs of the Geological Survey [3, 8, 11];² Stokes made reference to it in 1881 [2]; and in 1896 Parsons gave a very full description of the orebodies then being mined [4]; Stuckey dealt with the mine in a magazine article in 1917 [9]; and it was referred to several times in Varvill's recent paper on Lead Deposits in the Pennine Limestones [17]. The object of the present paper is to bring the subject up-to-date and to give a comprehensive picture of the geological features. The orebodies bear a striking similarity to the "manto" deposits of northern Mexico, and even have some points of resemblance to the Mississippi Valley deposits of the United States. In Derbyshire, as in the United States, the question of the source of the ores is of paramount interest, but the published literature is strangely silent on this point, with the notable exception of Wedd and Drabble's paper [7] on the fluor-spar deposits. The memoirs of the Geological Survey contain valuable detailed descriptions of the old mines, but the lack of any reasoned theory about the origin of the ores, other than the statement that they are probably of late Carboniferous or Triassic age, must have contributed to the pessimistic conclusion that few orebodies of any size could be expected below the deep drainage levels. Developments at Mill Close during the past ten years have shown that the ore was deposited from ascending solutions, forced to take a zig-zag, slanting path towards the surface because of the presence in the limestone of a number of impervious lava flows (known locally as "toadstones"). The vagaries of these toadstones constitute one of the reasons why the structural geology of the mine is so interesting. The old theory that the ore was confined to the topmost layer of limestone, above the toadstone, has been exploded with the finding of bonanza orebodies beneath not only the upper toadstone, but several of the lower flows as well.

² Numbers in parenthesis refer to bibliography at end.

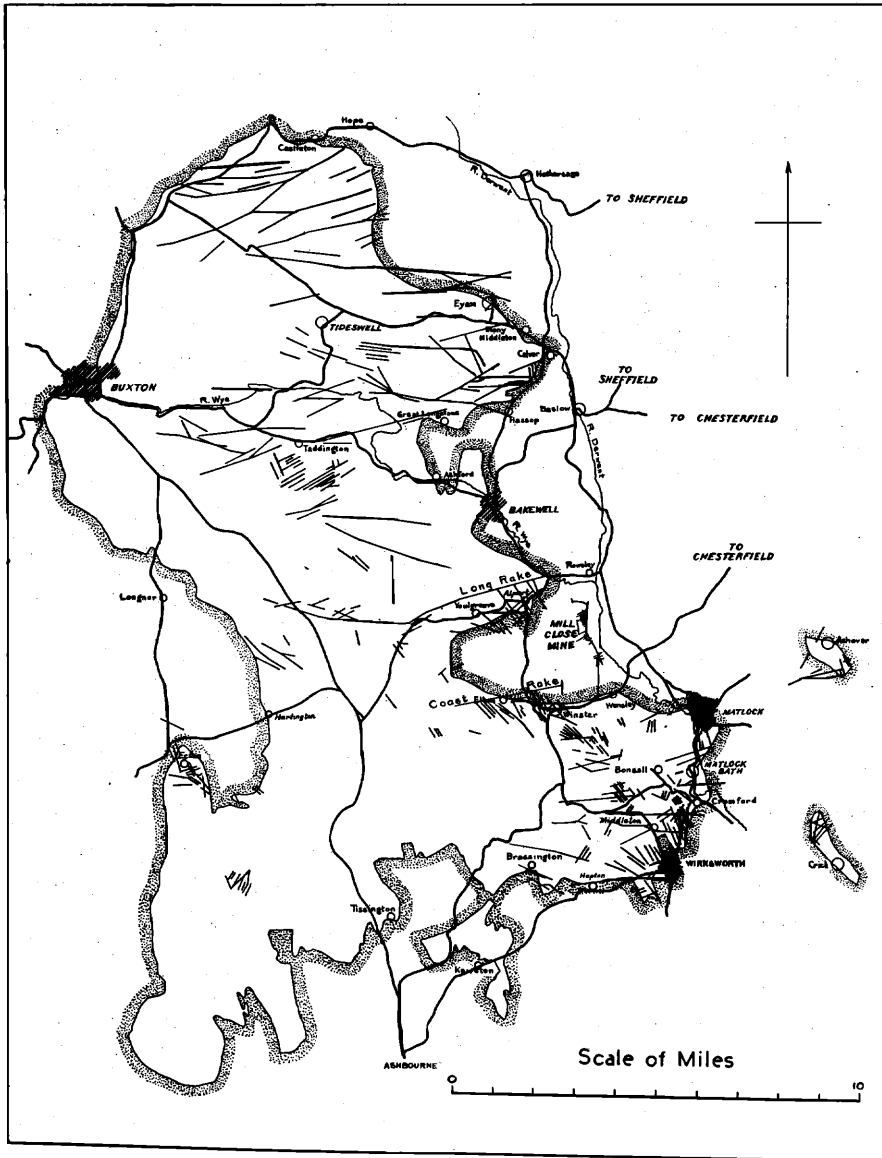


FIG. 1. Map of the Carboniferous Limestone of Derbyshire, showing the principal veins and the location of the Mill Close Mine.

HISTORY.

The history of lead mining in Derbyshire goes back to Roman times, but the Mill Close orebodies, hidden under their capping of shale, probably lay unworked until early in the eighteenth century. The Geological Survey [11] states:

The earliest operations of the Mill Close Mine may be 200 years old, and probably started as a continuation under the Yoredale Shales, of a group of surface workings on veins traversing the limestone outcrop south of Wensley village; these have ever since been followed progressively further north under the shale covering.

The London Lead Company, popularly known as the Quaker Company, was, during the eighteenth century, actively engaged in lead mining in many parts of England. A recent paper by Dr. Raistrick [18], of Newcastle, gives a detailed account of the Quaker Company's work in Derbyshire. It seems that the Quakers commenced work in 1720 on a number of veins in the neighborhood of Wensley and Winster, bought the old Mill Close Mine in 1743 for £1,050, and drove two "soughs" or drainage levels westwards from the River Derwent to unwater the bottom levels of the mines at Wensley and Winster. The first of these drainage levels was called the Mill Close Sough and the second was the better known Yatestooop Sough, which took 21 years to drive and cost £30,000. Reference to the longitudinal section (Fig. 3) will show how the strata dip steeply north of the Mill Close Sough, taking the ore-bearing limestone rapidly underfoot. A steam pumping engine was installed in 1748 to enable work to proceed below the adit level, and continued in operation until 1764, when work was stopped. The company was by this time cutting down on its operations in all areas except the north of England, and by 1778 all activity in Derbyshire had ceased.

According to the Geological Survey [11],

the mine subsequently lay idle for about 100 years, but it was reopened in 1859 by the late Mr. Wass. In 1861 ore began to be raised and has continued uninterruptedly to the present day, except for two years (1875-77) when the mine was temporarily drowned out. After Mr. Wass's death in 1886, his trustees took over the mine until 1919.

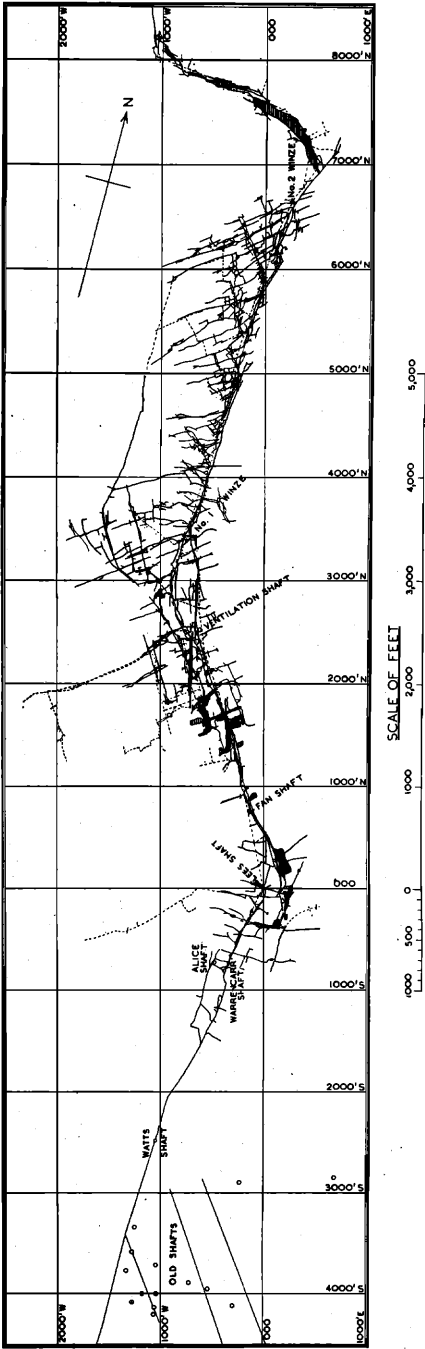


FIG. 2. Plan of Mine Workings. The dotted lines represent development crosscuts and drifts not in ore.

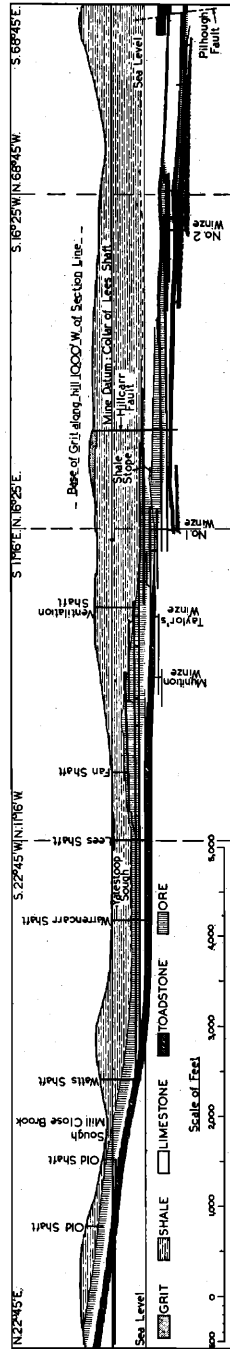


FIG. 3. Longitudinal section along the main line of ore deposition.

The present owners, the Mill Close Mines, Limited,³ acquired the property in 1922 on the recommendation of the late Dr. Malcolm Maclaren, and have worked the mine continuously since that time. Operations in recent years have been on a substantial scale; about 10,000 tons of ore are mined per month, and mine and smelter employ over 700 men.

PRODUCTION.

The mine has produced, since it was reopened in 1859, over 400,000 tons of lead concentrates averaging about 82 per cent lead. More than half of this total appertains to the last nine years (Table I). Some 30,000 tons of zinc concentrates have also been produced, and the increase of zinc content in the ore has been so marked since 1935 that the current production of zinc concentrates actually exceeds that of lead concentrates. Fig. 4 shows in graphical form the production year by year since 1904.

TABLE I.
PRODUCTION, MILL CLOSE MINE, 1861-1939 (LONG TONS).

Period	Lead Concentrates		Zinc Concentrates Total
	Total	Annual Average	
1861-1887.....	36,035	1,440	?
1888-1893.....	±15,000	±2,500	?
1894-1903.....	42,052	4,205	?
1904-March, 1920.....	67,394	4,190	7,516
Apr. 1920-March, 1929..	24,565	2,730	±1,600
Apr. 1929-March, 1938..	222,041	24,670	21,573
	407,087		30,689

STRATIGRAPHY.

Dr. Malcolm Maclaren said of Mill Close that the geology of the district had a much more obvious bearing on ore-deposition than is generally the case with metal mines. For that reason a fairly detailed account of the local geological features is necessary for a complete picture of the ore occurrences. Much has

³ Technical control lies with the New Consolidated Gold Fields, Ltd.

been written about the Carboniferous limestone of Derbyshire since the publication in 1811 of Farey's comprehensive report [1]. The memoirs of the Geological Survey dealing with North Derby-

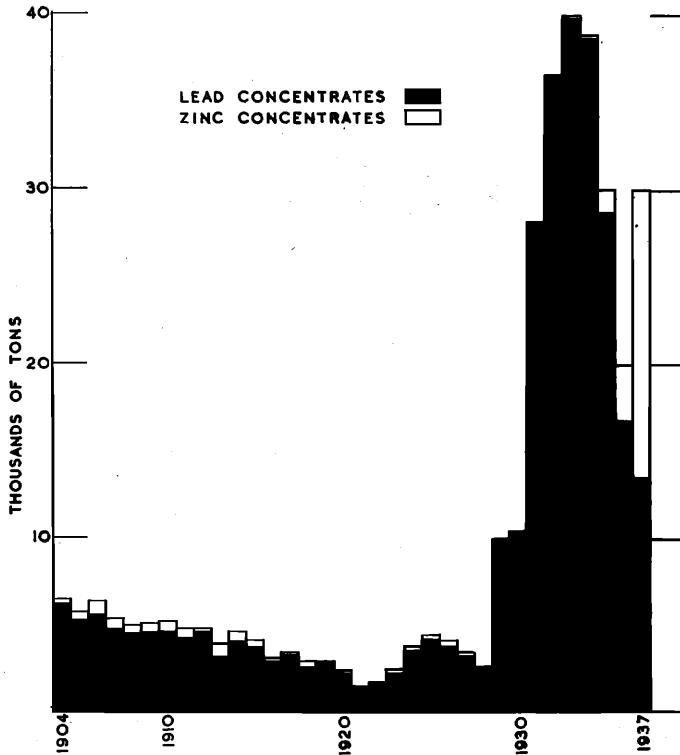


FIG. 4. Production Graph. 1904-1937.

shire [3] and the Northern Part of the Derbyshire Coalfield [8] describe these areas; and a valuable paper [15] by Professor Fearnside and others, published in 1932, summarizes all the information available at that date. The writer hopes shortly to publish some notes on the local stratigraphy as seen in the mine workings, and on the relations of the various toadstones that have been discovered at Mill Close during the past few years. The stratigraphic sequence given in Table 2 has been simplified from these notes.

TABLE 2.
SIMPLIFIED STRATIGRAPHIC SEQUENCE.
Mill Close Mine.

System	Series	Formation	Thickness in Feet	Character of Rocks
UPPER CARBONIFEROUS	MILLSTONE GRIT	Kinder Scout Grit	150-200	Thickly-bedded sandstones; coarse grits.
		Grindslow Shales	±700	Formerly classed as Yoredale Shales and Grits. Black, argillaceous shales with thin grit band, and a bed of black limestone.
		Shale Grit		
		Edale Shales		
LOWER CARBONIFEROUS	LIMESTONE SERIES	First Limestone	146	31' of thinly-bedded, dark, cherty limestone—the "Black Beds." 115' massive, white limestone; darker toward base; numerous shell beds.
		Upper Toadstone	0-76	Amygdaloidal dolerite lava.
		Intermediate Beds	14	Light limestone with shaley partings and shelly bands.
		Alport Toadstone and Intermediate Tuff	1-90	Basalt with some amygdaloids, passing into thin, green tuff.
		84 Limestone	35	Coarse-grained, nearly white limestone.
		103 Toadstone	0-22	Amygdaloidal basalt lava.
		Second Main Limestone	132-155	Base of dark, thin-bedded cherty limestones, merging above into massive, light limestone. A sudden change to dark, thin-bedded, shelly and coralline limestones, with chert, grading upwards into massive light limestone again.
		Upper 129 Toadstone	1-28	Hard, dolerite lava.
		129 Limestone	40	Very coarse-grained, pure, light-color limestone.
		Lower 129 Toadstone	10-26	Hard, dolerite lava.
		10-Foot Limestone	10-31	Very coarse-grained, pure, light-color limestone.
		144 Pump Station Toadstone	+50	Hard, amygdaloidal, basalt lava. Base not exposed.
		Limestone	+1000	With toadstones?

It will be seen that the divisions in the Carboniferous Limestone Series are based on the "toadstone" sheets found at various horizons rather than on fossil contents. One reason is that the stratigraphy of the Matlock district, and particularly of the limestones now being exposed at the lowest levels of the mine, has not yet been worked out in detail by palæontologists. Another reason is that these toadstone lava flows are of the greatest importance in determining the course of the ore.

The Edale Shales.—This is the name now accepted for the

shales that rest upon the Carboniferous limestone in Derbyshire, which used to be classed as belonging to the Yoredale Group. They are black, argillaceous shales with thin bands of black, bituminous limestone, particularly near their base. Their significance from an economic point of view lies in their impermeability. The result is that they formed an effective dam to ascending solutions, which were compelled to seek a rising path towards the surface along such channels as were available *underneath* the shales. An objectionable feature of the shales, from a mining point of view, is that they give off quantities of methane, making safety lamps necessary in the upper levels of the mine and making good ventilation essential.

The Carboniferous Limestone has been very fully described by Bemrose [5] and by Wedd and Drabble [7], as well as by Gibson and Wedd [8]. Wedd and Drabble estimate the thickness of the limestone with its intercalated toadstone flows to be at least 1,500 to 1,700 feet. The base is not exposed, and whether it rests upon the Old Red Sandstone or on the Silurian is a matter of conjecture. Moreover, it is known from fossil evidence that the thickness of Carboniferous limestone that outcrops in Derbyshire represents only the upper part of the series as exposed in southwestern England, near Bristol.

The Toadstones.—The most striking feature of the limestone series is the way it is divided up into alternate layers of limestone and toadstone (Table 2), but the latter do not, as was formerly supposed, form continuous sheets over the whole district. Individual toadstones show pronounced variations in thickness and die out within a few miles. The largest known flows may attain a thickness of 100 feet or more, and have a horizontal extent of five or six miles. Beyond the edge of a flow proper its horizon is marked by a thin "wayboard" of shale or tuff, which may extend for miles. In the 400 feet depth of limestone penetrated by the Mill Close workings, at least seven thick toadstones and seventeen such wayboards have been recognised, and it is known from the evidence of other districts that lavas occur in the limestone series down to a depth of about 700 feet. They are ex-

tremely irregular in occurrence, and there must be dozens of hidden volcanic necks scattered throughout the district, besides the few that outcrop. A widespread igneous magma probably underlies the whole region, and one can imagine that, during the time throughout which the uppermost 700 feet of limestone were being deposited, there was intermittent volcanic activity over a fairly large area. A period of quiescence would be followed by an ejection of lava or tuff, forming a bed of toadstone neither very extensive nor thick. This outburst would be followed by another period of quiescence, which in its turn would be succeeded by another outpouring of lava at a different place. Some of the "squirts" from the magma below failed to reach the surface and formed the sills described by Dr. Bemrose [6]. No sills have as yet been encountered at Mill Close.

It would be pertinent at this stage to summarize the proofs that the toadstones of Mill Close are lava flows and not sills.

The principal evidences are:

- (a) Their wide extent in comparison with their thickness.
- (b) No transgression of overlying or underlying beds.
- (c) Abundance of vesicles in the upper half.
- (d) Recognisable pillows, showing that the lavas were laid down under water.
- (e) Marmorization of the underlying limestone, to a depth of 1. to 3 feet, but none above.
- (f) The development of a shell bed, or a bed of nodular limestone immediately above a toadstone, pointing again to submarine conditions.
- (g) A marked change in the character of the limestones overlying some toadstones, indicating a change in the conditions of sedimentation coinciding with the toadstone horizon.

Two of the flows (the Upper and Lower 129 Toadstones) seem to have been extruded, in places at least, on a partly eroded beach, but all the others are submarine lavas, and good examples of pillow structure are encountered.

Regarding the petrography of the toadstones, the Mill Close lavas may be described either as basalts or as olivine dolerites, depending on their structure. Those having a doleritic or subophitic texture are olivine dolerites; the fine-grained, black varieties are basalts. Most of them—not all—are highly vesicular, and somewhat altered.

The toadstones tend to weather at their upper and lower surfaces into clay, especially where they have been exposed to the action of mineralizing solutions. They form, except where cut by fault fissures, impermeable layers similar to the shales in their effect on ascending mineralizing solutions, so that each toadstone is the roof of a potential ore-bearing horizon. Of the six toadstones shown in Table 2, ore has been found in turn beneath all but the lowest, which has not been bottomed.

The Limestones.—For a comprehensive account of the limestones, the description given by Wedd [8] could not be bettered, so it is given here in full:

The Dibunophyllum zone (D of Dr. Vaughan's classification) alone is represented. The topmost beds of the limestone often show . . . a gradual upward transition into the shales. The line of division between the limestone and shale formations therefore becomes in places rather indefinite. The higher beds of the limestone always contain layers of tabular or nodular chert. . . . Occasionally two of these bands by approximating to each other betray a lenticular bedding not otherwise discernible.

The greater part of the limestone (except the upper beds) . . . consists of a pale rock, creamy white, light bluish-grey or fawn-colored. It is a comparatively pure limestone where not subsequently dolomitized or silicified.

In microscopic structure it ranges from a fine-grained, calcareous mud, with sponge spicules and foraminifera, through microgranular and microoolitic types to more coarsely granular limestone with rolled shell fragments and little pellets of detrital limestone. Parts of it have a coarsely crystalline appearance owing to the inclusion of innumerable calcite-organisms, chiefly crinoid ossicles. The dark parts of the limestone probably owe their color to argillaceous impurity, and it is often noticeable that this color is deeper near shale bands, and that the rock for a few feet above a toadstone has a much darker tint than the succeeding beds.

Dolomitization, which does not follow stratigraphical lines . . . locally involves great masses of the limestone over a considerable area. The more dolomitized limestone generally takes a light brown or yellowish hue.

Minute quantities of petroleum and bitumen sometimes partially fill the cavities of brachiopods. In the case of corals, it is chiefly in the more dolomitic rock that the spaces between the tissues are hollow and contain specks of bitumen.

While the limestone and its fauna suggest formation in a comparatively shallow sea, occasional evidence is afforded of the proximity of land, *e.g.* by the local occurrence of an underclay with calamites above the upper lava, and of a thin coal and underclay in the higher beds of the limestone.

The foregoing description applies to the Matlock district, a few miles southeast of the mine, but in general it is equally applicable

to the Mill Close district, with one or two important differences. In the first place, the Mill Close sequence contains not one, but three distinct series of cherty limestones. The uppermost, which lies immediately below the shales, at the top of the First Limestone, corresponds to the one mentioned by Wedd. The other two are both found in the Second Main Limestone. Each shows a gradual transition upwards from thinly-bedded, dark, cherty limestones into massive, light-colored beds. The upper of the two contains numerous bands of dark, shelly and coralline limestones in addition to the layers of chert nodules.

The dolomitization mentioned by Wedd has not been found at Mill Close. Many samples suspected of being dolomitic have been analyzed but always with negative results. The silicification referred to—which involves the development of microscopic crystals of secondary quartz throughout the limestone—is also unknown in the Mill Close district.

STRUCTURE.

The broad anticline or dome that forms the dominant structural feature of the limestone area has already been mentioned. In the Mill Close district the anticlinal axis strikes roughly NW-SE, and it was as a result of adjustment to folding in this direction that the northwest system of gash-veins was developed. Dr. Maclaren assigned the north system to the same folding movement, at a slightly later period.

Later still, a minor north-south crumpling along the eastern flank of the main dome formed a series of broad folds, striking E-W, and gradually dying away westwards in the direction of the main N-S anticlinal axis.

Dr. Maclaren said: It was probably as an end result of this transverse crumpling that the great "rakes" (E-W cross veins) of Derbyshire were formed. This vein-system is obviously much more persistent in depth than the two gash-vein systems already mentioned, since an inspection of the geological map indicates that many of these rakes, especially in the north, still show on the fairly deeply-eroded crest of the anticline while the members of the shallower NW and N systems that were probably originally there are eroded from the crest of the anticline and are confined to the borders of the shales, where erosion has naturally been less extensive. . . . The average strike of the rakes is ENE-WSW, parallel to the minor folding. They are generally strong faults.

The Mill Close workings are located in the southern limb of one of the minor E-W synclines, between the Coast Rake and the Long Rake, where the orebodies have lain hidden underneath their capping of shale and grit. The local structure, then, is that of a trough pitching gently eastward, with a length of four miles from its western rim to the Derwent River and with a breadth between the Long Rake and the Coast Rake of $2\frac{1}{2}$ miles. That the syncline was far from symmetrical was not apparent at the time Dr. Maclaren made his examination. At a distance of two miles north from the Coast Rake, the strata still dip northwards, so that the eventual rise towards the Long Rake is bound to be rapid. This circumstance has invalidated Dr. Maclaren's conclusions, which were, briefly:

(1) That the mineralizing solutions rose from the south; (2) that the synclinal axis of the trough (which he supposed to lie between Lees Shaft and Ventilation Shaft) was the most likely line along which to prospect; (3) that orebodies would be confined to the First Limestone; (4) that other NW joints parallel to the Mill Close Fault and west of it would be found to carry ore.

Although subsequent work has proved Dr. Maclaren to be wrong, his reports are still a model of logical reasoning on the data available at the time he made his examinations (1920 and 1923), and they are still referred to frequently by the mine staff.

Joints and Faults (Fig. 5).—The limestone, as a result of the folding just described, is honeycombed with joints which, however, fall naturally into three systems. The first is the NW system of gash-veins, ranging in strike from NNW to WNW, and the second is the north-striking system. "The third system" to quote Dr. Maclaren again "has a general strike of ENE-WSW, with minor variations from this general direction. This system comprises by far the greater number of veins, ranging in strength from the great rakes (Long Rake and Coast Rake) down to the numerous 'scrins' or stringers which intersect the members of the other two systems." All are potential ore-carriers, and the main

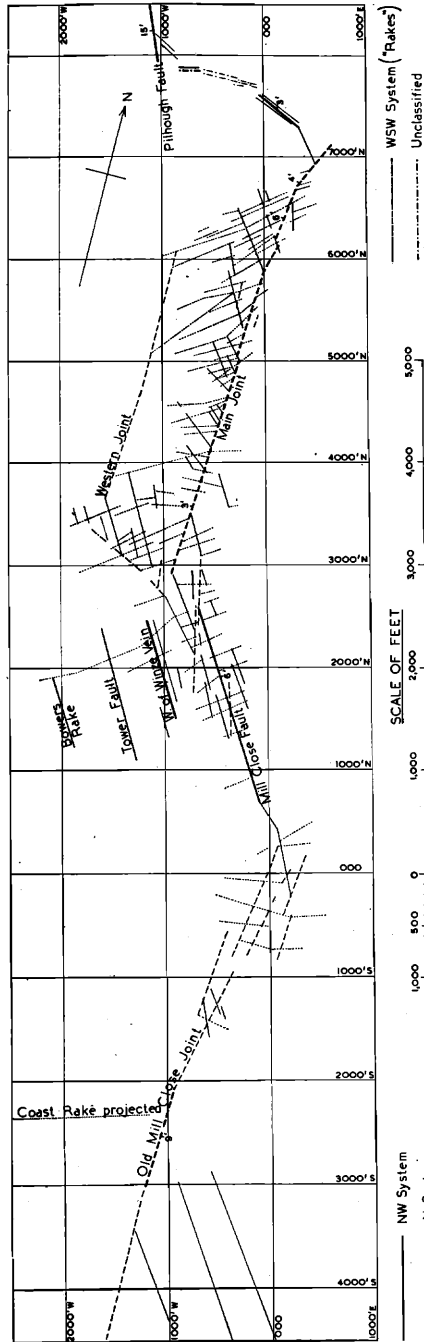


FIG. 5. Sketch plan of the joint systems at Mill Close. Known faults are indicated by heavy lines, and the throw in feet is given, where known.

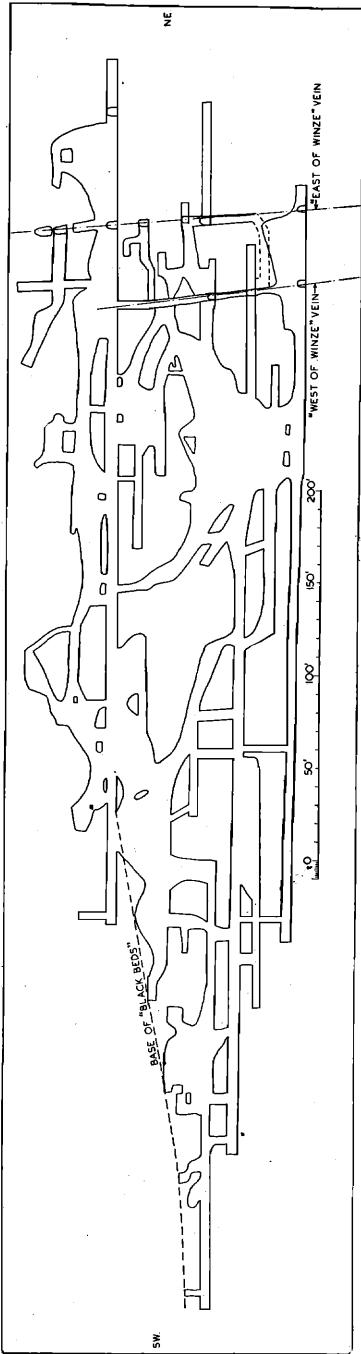


FIG. 6. Longitudinal section of orebody in Squares E7 and E8 (N 2175, W 930 to N 1965, W 1365).

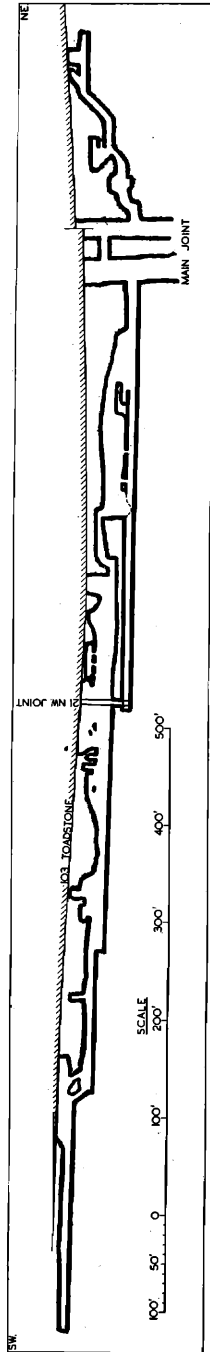


FIG. 7. Longitudinal section of 22 SW stope (N 6615, E 425 to N 6025, W 995).

line of ore deposition makes several changes from one system to another in its course from north to south, as will be seen from Fig. 5.

Most of the joints, where not subsequently enlarged by solution or mineralization, are mere cracks or joint planes in the limestone, but a few are true faults with vertical displacements of 6 to 8 feet, or, exceptionally, 15 feet. Fig. 5 indicates the throw of the known faults in the mine. It is interesting to note that the majority of the faults belong to the N system, a few to the NW system, and none to the rake series. Formerly, a complicated system of block faults was hypothesized to explain an apparent downthrow in one of the toadstones, but a detailed examination of the district in question has shown that there are two separate toadstones 35 feet apart and that the supposed faults do not exist. Faulting may be said to be relatively unimportant at Mill Close, but such faults as do exist have an economic importance because of the relatively easy path they present to mineralizing solutions—easy, that is, in comparison with those narrow joints on which no movement has taken place. Open fissures are much less common in toadstone than in limestone, partly because of the insolubility of the igneous rocks, partly because of the way they tend to break less cleanly and then decompose into clay; but, nevertheless, several instances have been found at Mill Close where the existence of an open channel on a fault has permitted ore-solutions to rise from below a bed of toadstone to a higher horizon.

That most of the faults seen underground have a horizontal as well as a vertical throw is indicated by the presence of horizontal striæ on their walls. The extent of the horizontal movement is not believed to be great, having regard to the relatively undisturbed nature of the beds with their gentle dips, and the small vertical displacements on the faults. In several cases this seems to be borne out by facts. For example, in a winze below the 129-fathom level, north of No. 2 Winze, the Lower 129 Toadstone was found to be of equal thickness on the two sides of the fault (Fig. 8). Since the toadstone hereabouts shows rapid variation

in thickness, any considerable horizontal movement along the fault would show up a difference in thickness of the toadstone on the two sides of the fault. As no difference is found, the probability is that the horizontal throw is not great.

Dr. Maclaren mapped and described some large faulted blocks of Millstone Grit at the surface, and showed them to be due to landslips, since two⁴ of the "faults" were found underground to have no displacement. This is in line with the explanation given by the Geological Survey in the North Derbyshire Memoir [3], as follows:

Many cases have been noticed at the foot of hill slopes formed of soft shales and capped by massive sandstones. Frost, springs, and underground streams soften and carry away the shales, and huge masses of the sandstone, thus deprived of their support, break off along joints, and slide or topple down into the hollow below.

OREBODIES.

General Features.

Much has been written about the irregular forms assumed by the limestone replacement deposits of Derbyshire in general, and of Mill Close in particular, but it was not until Varvill's paper [17] appeared in 1937 that any account was given of the course followed by the ore.

The old accounts contain much space devoted to the question of whether or not the ore was cut off in depth by the toadstones. Generally it is, but the occurrence of ore in some mines *underneath* the toadstone was hard to explain. It seems strange nowadays that the "old men," knowing how impermeable the toadstones were, should not have realised that their ore deposits lay on a slight slope, and were fed from the lower end. Much useless development has been carried out, from ancient times up until quite recent years, in searching for the downward extensions of known orebodies vertically underneath them, often below a thick lava flow. Thousands of feet have been driven on barren joints which, less than 200 feet higher, were the locus of rich orebodies.

⁴ The Chapel "fault" and the Hillcarr "fault." The third side is bounded by the Tower fault.

This in spite of the fact that the miners have known, for more than sixty years, that the way to find new ore is to follow the known orebodies laterally wherever they may lead. By far the most important characteristic of the ore is its remarkable continuity, yet this notable feature has never been commented on, either in the Memoirs of the Geological Survey or in the various papers already mentioned. It has already been stated that ore has been found beneath no fewer than five successive toadstones, as well as below the shales. Yet, through all these steps, and for a distance of 15,000 feet from the outcrop to the far northwest end of the mine, the orebodies, though ramifying, have been continuous. Every ton of ore that has been mined has come from the main orebody or from one of the numerous connecting branches. Even orebodies that have been discovered by cross-cutting—and they are few—have been found afterwards to join up with known ore.

In an article [12] that appeared 13 years ago and which was described by Spurr [13] as “the most important single paper on economic geology, both from the practical and the theoretical standpoint, which has been published for many a long day,” Prescott outlined the characteristics and underlying principles of the limestone replacement deposits of northern Mexico, and showed how erroneous were the ideas regarding their nature that had prevailed up to that time. He attacked the commonly accepted statements that the ore was found in cavities in the limestone joined by narrow, almost imperceptible cracks, which, if followed, would lead from one orebody to another, and that the orebodies were enlargements of these fissures, generally at the junctions of two or more of them. The errors and misconceptions he exposed are identical with those that have been rife in Derbyshire, and the picture he substituted as the true one—which soon came to be generally accepted, with only slight modifications—might have been written of Mill Close, so exactly does it fit the conditions. For example, Prescott emphasized the continuity of the orebodies and their rising course, from where they enter the favorable limestones at depth to where they reach the

surface, or until they gradually become extremely attenuated. The upward course of an orebody, he said, is controlled by the following factors: (a) favorability of certain limestones, due to composition or texture; (b) posture of the beds; and (c) pre-mineral fissures. Another principle, difficult of corroboration in the case of such a ramifying deposit as Mill Close, is that the cross-section of an orebody varies gradually by small increments, and generally increases slightly with depth.

Prescott made one rule that does not apply at Mill Close. He said that the analysis of each orebody was distinctive and, broadly considered, invariable, and gave interesting examples of how some "mantos" were traced to their parent "chimney" by a comparison of representative analyses. That this is not true of Mill Close may have something to do with the great range of the Mill Close manto—15,000 feet as compared with mantos up to 12,000 feet long described by Prescott—or it may be due in some obscure way to the presence of the toadstones, but in any case it does not affect the striking similarity in structural features between deposits so far apart.

Prescott stated that no replacement deposit in his experience followed a single fissure throughout its whole length, but that orebodies would leave one fissure for another, and would in places follow an irregular course, apparently without control. He maintained that the importance of fissures in determining the course of the ore had been greatly exaggerated, and that their role in primary deposition—as distinct from their function as channels of secondary mineralization—was a very minor one. Now, the Mill Close manto—for its resemblance to the Mexican deposits entitles it to the name "manto"—jumps from joint to joint; even the main line of deposition changes direction four times. In this respect it falls in line with Prescott's observations, but fissures evidently play a rather more important part in Derbyshire than in the Mexican deposits. It is likely that, had the impermeable toadstones not been present to check the upward flow of the mineralizer, it would have risen directly along the convenient upward path offered by the open fissure, until it met the overlying shales.

Three years after the publication of Prescott's article, there appeared Fletcher's equally important one [14], dealing with the same district. It is the present writer's belief that this latter article supplies the key to the origin of the lead deposits in Derbyshire. This is sufficient justification for setting down at length a number of extracts from Fletcher's article, as follows:

A lead-silver orebody in its manto and precedent phases always follows the course of least resistance from its igneous source to the surface.

Should the igneous intrusion be truly batholithic and not penetrate to the surface, the mineralizer will ascend the most opportune simple break or break intersection in the limestone, in vein or chimney form, until it encounters a favorable horizon. It will then follow this favorable horizon, displaying in its passage through it the characteristics of a manto deposit, until it arrives at the surface. . . .

In the manto phase the stratum chosen for invasion by the mineralizer is chosen because of its texture or composition and the course of the mineralizer through that elected stratum is determined by folding, faulting, and fracture. . . .

Factors which reduce resistance to the invading force of the mineralizer in the favorable horizon are structural factors, and, in the order of their importance, are fracture, folding, and faulting. In the thicker mantos, the evidence of control may have been obliterated in certain formations by the replacement that occurred along its course, but the control almost certainly did exist and did determine the course of the orebody in its migration through the favorable horizon.

The truth is that fractures, faults, and structure control the course of mineralization within the favorable horizon. They may permit escape from that horizon at any point, but only at one point do they permit access to it.

Should more than one favorable horizon exist, these same fractures may again become of importance where they traverse those horizons and may again control channels of mineralization in them.

These manto orebodies travel uphill and so are likely to outcrop in the anticlinal elements of structure. Anticlinal folding . . . leads to the development of fractures and faults which furnish the channels for ore deposition.

Faults along which considerable displacement has occurred are likely to act as dams in the ore channel and deflect its course. It is a fact not realized by most geologists that at least 90 per cent of such faults in the Mexican Cordillera are pre-mineral, and hence do not mechanically offset the orebodies that abut them.

A fault is more likely than a fracture to be the channel of entry used by the mineralizer in reaching the favorable horizon. Being a plane of displacement, a fault cuts deeper than a fracture, which is only a simple break. Summarizing, a favorable bed, often dolomitic, usually in an anticlinal attitude and traversed by fractures, constitutes the typical environment of a silver-lead orebody in its manto phase.

Fletcher goes on to show that the manto phase represents only

one element in a unity, of which the other members are, in descending order (1) a vein or chimney; (2) a contact deposit; and (3) a breccia or fracture deposit in an underlying igneous intrusive. It is extremely unlikely, on account of the heavily watered nature of the limestone in Derbyshire, that mine workings will ever penetrate deep enough to find out whether these same conditions exist there. Even the presence of a batholithic intrusion can only be conjectured, but Rastall says [10, p. 303]:

It must be remembered, however, that the Pennine Chain is an anticlinal structure, which must be somehow supported from below, and this support may be afforded by the intrusion of a granitic bathylith along the axis of the anticlinorium.

The Orebodies in Detail.

The First Limestone, South of Lees Shaft.—The little that is known regarding the orebodies south of Watts Shaft indicates that the ore was found in a number of joints, in the white limestone underlying the black beds. The principal joint here belongs to the N-striking system, but a number of subsidiary NW joints lying east of it also seem to have carried ore.

North of Watts Shaft the steep dip of the beds carried the ore-bearing horizon rapidly deeper. The ore seems to have been mainly confined to the same N-striking fissure as before, and near the top of the same white portion of the First Limestone. At both Watts Shaft and Warrencarr Shaft it has been proved that no ore exists in the fissure below the toadstone. Near Warrencarr Shaft, where the dip flattens out, is the first instance of the branch orebodies that become so important farther north, with ore wholly or partially filling solution cavities along crossing joints.

Between Warrencarr and Lees Shafts, where the beds are flat, there is an extensive development of ore in joints of all three series, forming a sort of crossover from the N-striking main joint to one belonging to the NW series and known as the Mill Close Fault.

The First Limestone, North of Lees Shaft.—North of Lees Shaft, the ore follows the NW-striking Mill Close Fault, with the

beds beginning to rise again. This rise is the beginning of a small anticline (Fig. 3) and is accentuated by a thickening of the limestone a little farther north, caused by a local unconformity at the shale-limestone contact. In this zone, which is the one described by Parsons, most of the ore was found in the main vein, but parallel and crossing joints, "flatlings," and caverns lined with ore became increasingly important about 1,500 to 2,000 feet north of Lees Shaft. The flats were evidently formed by the solution of especially favorable beds of limestone, particularly where overlain by an impervious "wayboard." They did not persist far from the parent fissure. Some of the caverns here were quite extensive, with calcite and ore minerals lining the walls and roof, and blocks of limestone and broken gangue covering the floor. Parsons says that the caverns supplied much of the best ore, but this is not in accordance with the evidence of the old miners, who assert that the masses of calcite and broken limestone seriously lowered the grade of ore from these caverns. The main vein varied considerably in width and in character, in places assuming a banded structure and in other places widening into caverns. Where banded, the order of deposition of the minerals, according to Parsons, was: sphalerite, fluorite, barite, galena, calcite, pyrite.

On the Mill Close fault the ore persisted up into the black beds, and even into the shales; in general, the greatest distribution of ore occurred just below the black beds. At Lees Shaft the ore bottomed about 50 feet below the black beds; farther north the height of ore was greater, but on crossing joints the bottom of the ore rose as it receded from the main vein. Fig. 6 shows a section of a typical joint of the SW system, with the base of the ore rising towards the southwest to meet the dipping roof until the ore practically dies out in that direction.

Opposite Ventilation Shaft the SW "scrin" called the Chapel "fault" formed an important crossing vein. North of this, ore was mined in a network of little SW and NW veins and died away northwards along two parallel joints of the N-striking system, called the Main Joint and the Western Joint respectively. One unusual feature of this area deserves mention. This is the

so-called "shale stope," in which ore was worked in a narrow fissure up into the shales for 100 feet or more before it pinched out. The joint belongs to the SW system, and may be observed on the plan at co-ordinates N 4000, W 1000. It coincides with the axis of a minor anticline, which may account for the fissure in the shales. When the mineralizing solutions reached the crest of the anticline under the shales, their strong ascensive urge would play its part in forcing the solutions up into the narrow crack in the shales.

The 84 Limestone and Second Main Limestone No. 1 to No. 2 Winze.—By 1929 practically all of the known ore in the First Limestone had been, or was almost, worked out. There remained only a stretch of good ore in the floor of the bottom (73-fathom) level, at co-ordinates N 3400, W 770. A winze was sunk in this ore against a heavy flow of water, and it was found that the toadstone had died out, and that the ore persisted northwards at a lower level, capped by a thin bed of tuff (the Intermediate Tuff). Bonanza ore was followed along the N-striking Main Joint from No. 1 Winze to beyond No. 2 Winze, a distance of 4,000 feet. For the first 2,000 feet, the Intermediate Tuff formed the roof, and then another lava flow (the 103 Toadstone) came in from the northeast, at a horizon 35 feet lower, and formed the roof of the ore from there northwards. The walls of the vein were very irregular, but the average width of ore in the Main Joint was about 15 feet. The bottom of the ore rose in a gradually-ascending, fairly regular line from No. 2 Winze back southwards to No. 1. Where topped by the 103 Toadstone, the ore had a height of about 85 feet; farther south, below the Intermediate Tuff, it was 120 to 130 feet high.

In this latter stretch there was an interesting development of flats or "flattings" off the Main Joint near the base of the ore. These flats were found, as a rule, only on the western side of the Main Joint, and extended 50 feet or more from the parent vein, giving the orebody an L-shaped cross-section. The flats were found in a bed of coarse-grained, pure limestone capped by a thin wayboard, and Varvill has shown how their shape was influenced

by the jointing of the limestone. These flats form a good example of the favorability or partiality of certain beds, to which reference will be made later.

Concurrently with the development of the Main Joint itself, ore was being opened up in a number of branch veins on a series of "scrins" or "rakes" (*i.e.* SW-bearing joints) west of the Main Joint. These branch veins had a width of about 6 feet and a height, where they left the Main Joint, of about 60 feet. The same limiting bed that formed the roof of the ore in the Main Joint also acted as the capping for these branch orebodies. The base of the ore was irregular, but rose gradually towards the southwest until it reached the roof, forming in longitudinal section, an elongated wing-shaped orebody, for which Varvill [17] has coined the name "wing deposit." Some of these wing deposits attain a length of 800 feet, or in extreme cases 1,300 feet, and the regularity with which they occur is remarkable. All did not contain equal quantities of ore: some have been found to extend from the irregular floor line up to the limiting roof bed as sheets of practically solid vein-material, with only a few pillars of unaltered limestone; others only touched the limiting bed in places, and contained a large proportion of limestone in large and small pillars; others again consisted of nothing more than a series of ramifying "pipes." Fig. 7 is a longitudinal section of one of the longer of these rakes.

The 103 Toadstone, which overlies the area about No. 2 Winze, dies away to the southwest, and these branch orebodies, which have become rather attenuated by the time they reach the edge of the flow, jump up 35 feet to the Intermediate Tuff and take on a new lease of life. Work is still proceeding southwestwards on rakes that were first discovered more than four years ago. The area as a whole has been responsible for important tonnages of ore.

Complementary to the rakes, and forming a sort of "backbone" pattern, are the northwest series of joints, shown on the plan. The ore is similar, but the wing-shaped form characteristic of the rakes is missing. The bottom of the ore along these north-

west joints follows an up-and-down line, the lowest points corresponding with the intersections of the (SW) rake joints.

A few of the rake joints carry ore for a short distance northeast of the Main Joint, but the amount of ore developed on this side is negligible compared with the large quantities found on the western side. This remarkable feature is difficult to explain, but it may simply be that the mineralizing solutions, flowing upwards from north to south, found it easier to branch off into the diverging SW joints than to make the acute turn to the NE.⁵ The widespread distribution of ore in the SW and NW joints (*not* faults) west of the so-called Main Joint (which is really a fault) is contributed to by three factors, namely: (1) The posture of the overlying toadstone beds in this area permitted mineralizing solutions to rise to the southwest as well as along the Main Joint to the south; (2) The NW and SW joints were well developed, providing the necessary channels for solution and infilling; (3) The 84 Limestone and the upper part of the Second Main Limestone are both pure, rather coarse-grained limestones, very susceptible to replacement. Had there been, instead, a thinly-bedded, dark, siliceous limestone, the area of ore-deposition would have been much restricted, possibly to the Main Joint itself.

North of No. 2 Winze, no southwest branches have been found to date. The ore followed the north-striking Main Joint for some 600 feet, but as a narrow fissure-filling, with a gradually rising base line. Four years ago, it became apparent that the orebody was dying away in this direction, and a stretch of ore in the floor of the 112 fm. level was selected as a likely looking spot for the downward continuation of the ore towards its source. Ore was followed in a winze down through the Upper 129 Toadstone to the next limestone bed, the 129 Limestone (Fig. 8).

The 129 Limestone, No. 2 Winze Northwest to Pilhough Fault.

⁵ This theory finds some support in the distribution of branch orebodies in the First Limestone between Lees Shaft and Warrencarr Shaft. The branch veins here cut across the main vein at right-angles, and branch orebodies are about equally well developed on the two sides. The same argument holds true of the area south of Ventilation Shaft, when it is taken into account that the main north-south ore stream was here split between several joints of the NW system, forming a zone 200 feet wide, with ore in crossing veins fairly well developed on both sides of this zone.

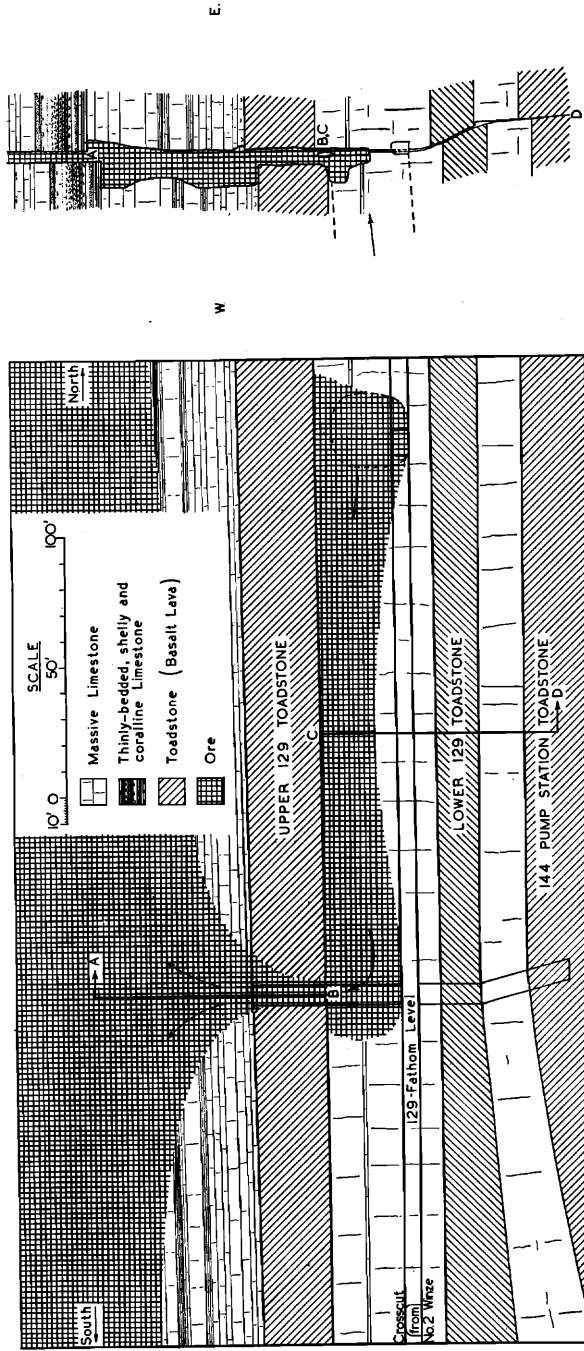


FIG. 8. Longitudinal and cross sections of the main orebody, just north of No. 2 Winze, showing the pipe of ore beneath the toadstone, the "vent" in the toadstone and the vein above. Note the abrupt contraction of width at the point "A" in the cross section, where the vein enters the unfavorable shelly and coralline limestones.

—From the winze just mentioned, the ore was followed northwards along the Main Joint for 200 feet in the form of a pipe beneath the Upper 129 Toadstone. It then turned abruptly to the northwest as a downward slanting cavern about 20 feet in diameter and 400 feet long, lined with ore and calcite, and later swung around nearly to a westerly line. Here, in the 40-foot thick 129 Limestone, between two toadstones, occurred a large orebody different in shape and mineralization from any en-

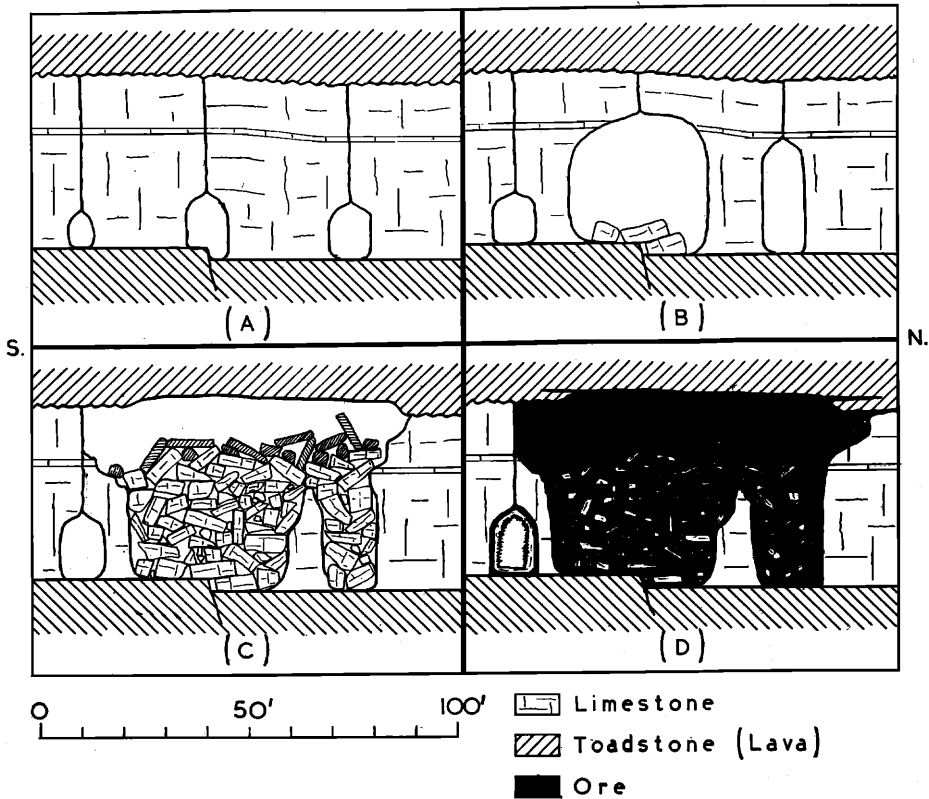


FIG. 9. Stages in the formation of the big orebody at the 129-fathom level.

- (A) Cavernizing beginning along the joints.
- (B) Caverns growing higher and wider.
- (C) The roof collapses.
- (D) The final orebody.

countered previously. As to its shape, the orebody was a typical manto, with a height of 40 feet and a width of 80 to 100 feet. The mineralization differed from that of higher horizons in that zinc predominated, whereas previously lead had been more important. Moreover, much of the ore was obviously a true metasomatic replacement instead of the customary cavity filling. Masses of fine-grained black sphalerite were encountered, very different from the usual brown variety. Blocks of partially replaced limestone were tumbled higgledy-piggledy, and masses of decomposed toadstone with ore minerals occupied the spaces between (Fig. 9). Most of the galena was concentrated along three parallel SE-NW lines, which seemed to represent the pre-existing fissures along which the mineralizer travelled.

The history of this orebody seems to have been somewhat as follows:

- (1) Folding along a NW-SE axis to produce the NW-striking joints in the limestone, with the axis of the fold pitching NW at a low angle.
- (2) Cavernizing of the limestone on either side of these joints by the mineralizing solutions, confined to this horizon by the overlying and underlying toadstones, and arising from NW to SE (Fig. 9A).
- (3) Cavernizing extending outwards from the joints, and upwards towards the roof, forming eventually an inclined cavern about 20 feet in diameter, similar to that found between the orebody and No. 2 Winze (Fig. 9B).
- (4) Further cavernization upwards to the overlying toadstone would leave the latter unsupported, allowing masses of it to fall into the cavern along with blocks of limestone (Fig. 9C).
- (5) The whole area would now resemble a large tunnel filled with fallen blocks, through which the mineralizing solutions could percolate as they ascended. Metasomatism of the limestone blocks would proceed apace; examples have been seen in all stages from unaltered limestone to masses that have been completely replaced by very fine fluorite and sphalerite.
- (6) Rapid bleaching and decomposition of the fallen blocks of toadstone by the mineralizing solutions, forming a soft matrix for the galena.
- (7) Finally, the crystallization in the remaining cavities of calcite and the brown variety of sphalerite, to form, with the galena, the usual type of cavity filling (Fig. 9D).

The orebody continued as described for about 400 feet, and then broke up into two or three parallel veins, still occupying the 40 feet of height between the Upper and Lower 129 Toadstones. The orebody has been followed to the far northwest end of the

mine, below the 144-fathom level where, though extensive, the ore has so far been poor in grade. The proper ore channel has not, perhaps, been followed, and is being sought for by current exploration work along the N-striking Pilhough Fault.

The 10-Foot Limestone.—Below the big orebody described above, a fair quantity of low-grade zinc ore has been mined in the thin limestone bed that lies between the Lower 129 Toadstone and the 144 Pump Station Toadstone. The ore, with its masses of calcite and coarsely crystalline sphalerite, seems to be a cavity-filling and not a metasomatic replacement. In one or two places it is connected by narrow fissures with the orebody above. It has not been followed as yet down the dip towards its source.

FAVORABLE AND UNFAVORABLE BEDS.

In lead-zinc replacement deposits in limestone the partiality or otherwise of the limestone to replacement is important, and seems to depend on such properties as composition and texture. Prescott's definition of a favorable bed is a characteristically practical one. He says:

To avoid a long and intricate discussion of the physical or chemical properties and the exact factors that may render a bed favorable, such will be defined only as a bed in which ore occurs in unusual quantities, or one, identical in all characteristics, which, through some accident of location, was not subjected to mineralization.

On this basis, the favorable beds at Mill Close are the following:

- (1) The massive, light-colored limestone underlying the cherty series in the First Limestone.
- (2) The whole of the 84 Limestone.
- (3) The uppermost 40 feet of the Second Main Limestone.
- (4) The coarse-grained, light limestone near the middle of the Second Main Limestone.
- (5) The 129 Limestone.
- (6) The 10-Foot Limestone.

It is significant that all of these "favorable" beds consist of massive, light-colored, more or less coarse-grained limestones. The dark, thinly-bedded, cherty or shelly and coralline limestones are not as favorable as those noted above. This does not mean that no ore is found in the more impure limestones; all are capable of

replacement to a greater or less degree, but orebodies in the dark, thinly-bedded limestones tend to be small and irregular, except along fault fissures. The widespread development of branch orebodies between Nos. 1 and 2 Winzes would not have been possible without the presence of a thick bed of favorable limestone lying nearly flat and with toadstone above to act as a limiting bed.

Fletcher [14] stresses the importance of favorable beds. In the Mexican replacement deposits, a number of the best orebodies are found in dolomitic limestones, but it is Fletcher's belief that magnesian content is in no way an essential feature of a favorable horizon, and that the property of these beds that lent itself to magnesian replacement was the same one which later made them amenable to replacement by the mineralizer. It is their texture, and not the magnesian element of their composition, which was responsible for the mineralizer's invasion. The words he used to sum up the essential characteristics of a favorable bed might have been written about Mill Close. He says:

Favorable horizons, where not dolomitic, are pure and reasonably thick. Thin beds and those high in silica, alumina, and carbon are unfavorable. In other words, where conditions at the time of deposition of the limestone fluctuated rapidly, resulting in thin and impure beds, they were unfavorable. Propitious horizons occur where conditions were only slowly changing over long periods of time and especially where they favored the building up of reefs now represented by thick members of the deposited series.

As will be seen from Table 2, the First Limestone has about 30 feet of dark bluish-grey to black cherty limestone, known locally as the "black beds," immediately underlying the shales. Below this the limestone is relatively pure, light colored and thickly bedded. On the line of the Mill Close Fault the ore persists up through the black beds to the base of the shale, and even, in places, up into the shale itself. On the southwest branch veins, which lie along joints and not faults, the ore generally stops short at the bottom of the black beds. Even the strong tendency of the mineralizing solutions to rise was unable to overcome the resistance of the cherty limestone to replacement. Stuckey [9] gives illustrations of these cases.

Below the middle of the Second Main Limestone there is a

pure, massive bed of crinoidal limestone that provides one of the most striking local examples of favorability to replacement, at the 112-fathom level, just north of No. 2 Winze (Fig. 8, point "A"). In the crinoidal limestone the orebody attains a width of 17 feet, and in the overlying dark limestone the width is abruptly contracted to a bare 4 feet.

Table 3 gives the analyses of a number of typical limestone specimens, from various horizons throughout the series. The

TABLE 3.
ANALYSES OF LIMESTONE SAMPLES.

No.	H ₂ O	SiO ₂	Fe ₂ O ₃ +FeO	Al ₂ O ₃	CaO	MgO	(Na, K) ₂ O	MnO	F	CO ₂ *
1	0.08	2.82	0.15	1.05	52.82	0.59	0.21	0.50	0.20	41.4
2	0.08	11.16	2.50	0.46	47.63	0.23	0.84	0.24	Nil	36.5
3	0.06	4.66	0.22	1.52	51.62	0.76	0.37	0.28	Nil	40.3
4	0.02	1.36	0.31	0.13	54.48	0.61	0.10	0.03	Nil	42.9
5	0.09	0.50	0.20	0.13	54.70	0.57	Tr.	0.19	0.05	43.3
6	0.03	0.54	0.11	0.28	54.60	0.62	Tr.	0.06	0.02	43.4
7	0.02	0.40	0.05	0.08	55.01	0.45	Tr.	0.15	0.03	43.4

* CO₂ accurate to about 0.5 per cent.

DETAILS OF SAMPLES.

No.	Taken from	Position in Series	Description	Favorable (F) or Unfavorable (U)
1	248' down Lees Shaft	At bottom of "black beds"	Fine-grained, hard, brown limestone.	U
2	440' down Lees Shaft	1' below Upper Toadstone	Hard, siliceous, grey, marmorised limestone.	U
3	63' down No. 1 Winze	1' above Intermediate Tuff	Light-colored, siliceous, shelly limestone.	U
4	87½' down No. 1 Winze	24' below top of 84 Limestone	Coarse-grained, nearly white limestone.	F
5	105' down No. 1 Winze	4' below top of Second Main Limestone	Fine-grained, light brown limestone.	F
6	117' down No. 1 Winze	16' below top of Second Main Limestone	Fine-grained, light brown limestone.	F
7	172' down No. 1 Winze	71' below top of Second Main Limestone	Fine-grained, dark brown limestone.	U

purity of the favorable limestones is notable, but one of the samples marked "unfavorable" (No. 7) is even purer, from which it would seem that color and texture provide a better guide to favorability than does composition.

MINERALIZATION.

Primary Minerals.—The principal primary minerals are galena, sphalerite, pyrite, calcite, fluorite, and barite. The galena occurs as crystals or masses in a calcite gangue, mostly in the form of a continuous rib, but rarely disseminated in small ($\frac{1}{8}$ ") cubes in the calcite. The proportion of silver in the galena is very low, only 1 to $1\frac{1}{2}$ ounces per ton.

Sphalerite has a wide distribution, persisting along joints for a long distance beyond where the galena content ceases to be payable. In the First Limestone, sphalerite [3] was the earliest ore mineral, succeeded by fluorspar, galena, barite, calcite and pyrite. Lower down, most places undoubtedly show sphalerite as being later than the galena. The customary order is calcite, galena, calcite, blende, calcite. Fig. 11 is a cross-section of a typical small pipe in which the order of deposition is difficult to determine. In general, there seem to be two ages of sphalerite in the mine, one older and one younger than the galena. Certainly, there are two varieties of the mineral, one (the later) occurring as a band of large honey-colored to brown crystals in a calcite gangue, the other (the earlier) as a fine-grained, black, metasomatic replacement of fluoritized limestone. The fine-grained "black jack" has only been found in the big 129-fathom level orebody. The sphalerite of the 10-Foot Limestone below resembles the first type in its occurrence along with calcite as a cavity filling, but its color is black, like the 129 level type. These differences may be due to variations of temperature, but there is room for investigation here. Even the brown crystals have streaks of black in them, and both types under the microscope are seen to contain numbers of minute specks of chalcopyrite (?) averaging $1/10$ mm. diameter or less. Both types of sphalerite are exceptionally pure,⁶ averaging about

⁶ Indications to date are that the brown variety is somewhat purer than the black, as might be expected, but the difference is not great.

65 per cent Zn along with a valuable 1 per cent Cd. Only at the 129-fathom level is there any intermixing of galena and sphalerite (as in Fig. 10) and a high-grade flotation concentrate is made from the ore without difficulty.

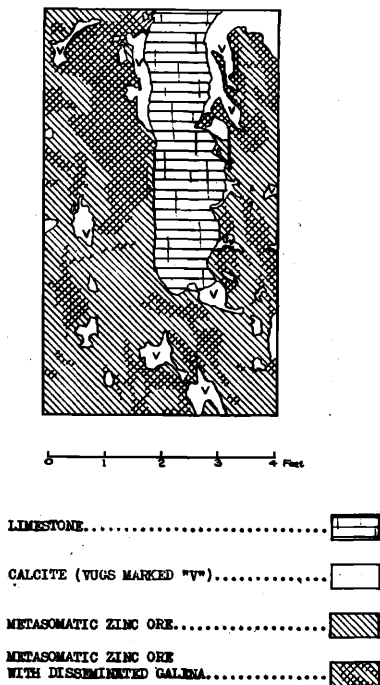


FIG. 10. 129-fathom level. A fallen block of limestone surrounded by ore of the metasomatic replacement type.

Pyrite, fluorite, and barite were evidently more plentiful at higher levels than they have been in recent years. Pyrite, where found, generally occurs as narrow veinlets in areas containing little or no lead ore. Parsons mentions a rib of pyrite nearly a foot thick as commonly occupying the center of a banded vein, but this feature was missing in Stuckey's time. Cubes of pyrite are common in many of the toadstones, within a few feet of the upper and lower contacts. Marcasite occurs as a fine dust-like film on the surface of, and in layers inside, crystals of fluorite

and calcite. Fluorite crystals, speckled with marcasite, were common in the First Limestone. In the lower limestones crystalline fluorite is rare, except near the extremities of branch orebodies, where it is usually associated with sphalerite and greenockite. A dark band, an inch or so in width, commonly seen in the limestone adjacent to the ore, and formerly assumed to be due to silicification, has been found to be caused by fluoritization. Barite is

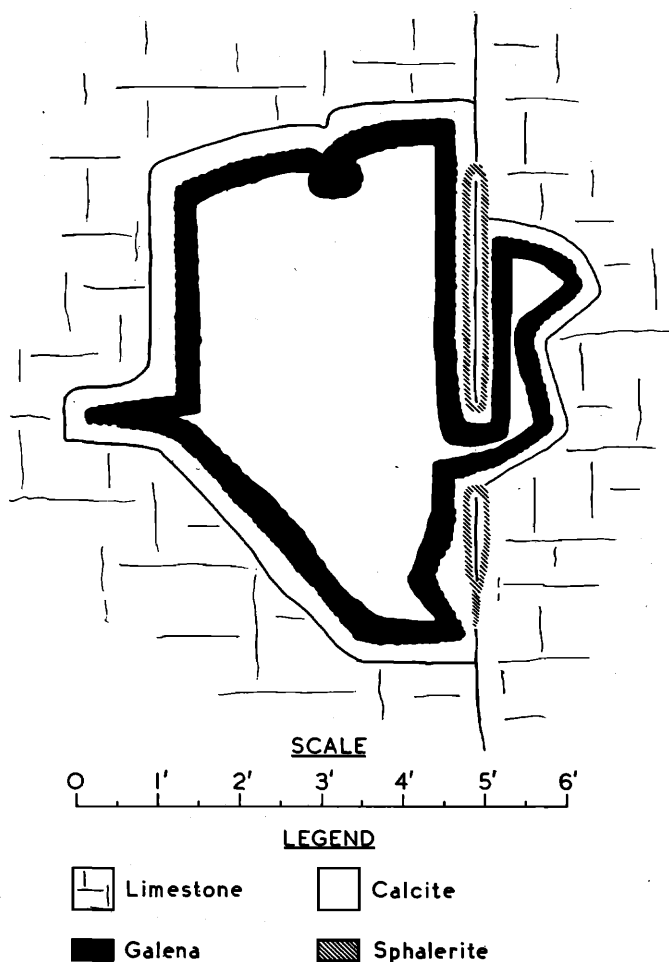


FIG. 11. Cross section of a small pipe, 93-fathom level (N 5190, W 370).

never seen at the lower levels, but was fairly common in the older parts of the mine, where it occurred in bands of pinkish "caulk" or as white crystals of cockscomb spar.

Calcite is the almost universal gangue mineral, occurring as white masses, and as large "dog-tooth" crystals lining every cavity. Twinned crystals, including the so-called Mill Close twin, characterized by its re-entrant angles, are common.

Secondary Minerals.—Calamine (called hemimorphite in Britain), $(\text{ZnOH})_2\text{SiO}_3$, is the commonest secondary mineral, and one of the last to have been deposited. It occurs as a thin superficial coating of small crystals on the faces of calcite crystals. Some beautiful platy specimens have been formed by the subsequent solution of the calcite.

Cerussite is fairly common throughout the mine, in the form of small colorless tabular crystals, commonly twinned, scattered over the surface of massive galena. The crystals rarely exceed $\frac{1}{8}$ inch in size.

Greenockite, CdS, occurs as a bright yellow incrustation on the surface of other minerals, and in cracks in them, where sphalerite has been undergoing alteration. The crystalline variety has not been found at Mill Close.

Dundasite, hydrozincite, and aurichalcite are secondary minerals of rare occurrence, that have been noticed at various times. There is a possibility that some of the zinc sulphide is the secondary, hexagonal form, wurtzite, but this remains to be proved.

A notable feature about the secondary minerals is their occurrence at the lowest levels of the mine, 1,200 feet below the surface, and 500 feet below sea level. In other words, the Mill Close manto is, for all its length, still in the zone of oxidation.

WATER.

In any low-lying mine in limestone, such as Mill Close, water will always be an important factor. The quantity pumped at Mill Close has risen from 1,000 imperial gallons per minute in 1887 to 1,600 in 1920; 2,000 in 1929; 2,350 in 1932; 4,300 in 1937; and 5,550 in 1938.

Apart from the high cost of dealing with so much water at all times, the possibility of closing down temporarily during periods of low metal prices is ruled out.

There are a few compensating advantages, however. As regards power, the big pumping load makes for a high load factor. The temperature gradient, because of the water, is low. But the greatest value of the water is the way it can be used to aid development. A new flow in one place coincident with a cessation of flow somewhere else indicates a connection. Deductions can be made from the distinctive analyses and temperatures of water from different sources. In ore-bearing ground, it is usually wise to seek the source of the water, because it follows the most open channel available, and so would the mineralizing solutions have done, as a general rule.

It should be noted, however, that not every water-bearing fissure is worthy of exploration. Every open fissure in the limestone will contain water, but not all contain ore. Much fruitless exploration work would be avoided if this axiom were more generally realised.

In February, 1938, a fault (since named the Pilhough Fault) was encountered in driving west on the 144-fathom level. The tremendous inflow of silt and water that followed was too great for the pumping plant at that level, with the result that the water rose almost to the 103-fathom level before it could be checked, and more than a month was needed to dewater the workings. The permanent increase to the inflow was 1,000 gallons per minute.

The toadstones seal off the limestone into watertight layers, except where the toadstones die out or where open fault fissures give access from one layer to the next. The result is a series of perched water tables—each lying on top of a toadstone—above the main water table. The flooding of a year ago was the result of letting in the water from one of these perched water tables, from which the workings had previously been protected by the overlying toadstone.

South and west of the mine the limestone surface reaches an

elevation 900 feet or so above the level of the River Derwent, which controls the ground water level. This circumstance, along with the alternation of permeable and impermeable layers, and the presence, near the river, of open fault fissures, gives the conditions necessary for artesian circulation. This is put forward as a possible explanation of the extreme depth of the oxidized zone, and may even explain the original cavernization.

SOURCE OF THE ORES.

The author finds himself in agreement with Wedd and Drabble's conclusion "that local circumstances in Derbyshire agree best with the hypothesis of deposition, in fissures and to a small extent as a metasomatic replacement of the country rock, from a heated aqueous solution containing gases and forced up from a great depth, possibly in connection with the later phase of igneous activity." It has not been possible to determine the temperature of the mineralizer by microscopic methods, but unaltered coal seams indicate that the temperature was comparatively low.

The rising course followed by the ores has been stressed, and it has been shown how the ascensive force was never in abeyance, even the flatter parts of the deposit having a slight rise from the source towards the outcrop. In this connection two further points might be mentioned. The first is that wherever the overlying limiting bed (toadstone, wayboard, or shale) had such a low dip that it permitted only a very slight ascent for the mineralizer, the horizontal spread was considerable. Areas of large horizontal spread are: No. 2 Winze to No. 1 Winze, No. 1 Winze to Ventilation Shaft, and Lees Shaft to 750 feet south of Warren-carr. From the longitudinal section (Fig. 3) it can be seen that these are areas where the dip of the overlying beds is low. The second point is that, in the flatter-lying parts of the deposit, the bottom of the ore in the narrow rake-joints always rises on a slope that is steeper than the slope of the ore in the main joint adjoining.

Present development, at the far northwest end of the mine, is exploring the Pilhough Fault, the potential importance of which

takes three possible forms, namely: (1) As a channel for ascending ore-solutions leading to the known orebodies nearby. A fault which cuts deep is the most likely channel of entry for the mineralizing solutions; (2) As a possible lateral connection between the known orebodies and a source farther north; (3) As a channel leading upwards—possibly to the base of the shales—to another manto deposit like Mill Close, which might lead to the rich but shallow mines of Alport, a mile to the west.

GEOLOGICAL MAPPING.

The routine geological work, from the sectioning of main shafts and winzes, and of intermediate rises and winzes, to the detailed study of the intervening drives, is almost identical with the method used at El Potosi Mine, Chihuahua, Mexico [16], and need not be described here. The present writer's proposed paper will include a complete series of vertical sections, for anyone interested in the local stratigraphy.

ACKNOWLEDGMENTS.

Thanks are due to the directors of the Mill Close Mines, Ltd., for permission to publish this paper. The author also wishes to acknowledge the help he has received from the publications listed in the bibliography attached; from Dr. Maclaren's reports; and from Mr. L. B. Williams, general manager of the Mill Close Mines, Ltd.

ASSISTANT MANAGER,
MILL CLOSE MINES, LTD.,
DARLEY DALE, DERBYSHIRE, ENGLAND,
April 14, 1939.

BIBLIOGRAPHY.

1. 1811: FAREY, J.: General View of the Agriculture and Minerals of Derbyshire.
2. 1881: STOKES, A. H.: Lead and lead mining in Derbyshire. Trans. Chesterfield & Midland Inst., Vol. VIII.
3. 1887: GREEN, A. H., AND STRAHAN, A.: The geology of North Derbyshire. 2nd ed. Mem. Geol. Survey.
4. 1896: PARSONS, C. E.: The deposit at the Mill Close Lead Mine. Trans. Fed. Inst. Min. Eng., Vol. XII.

5. 1899: ARNOLD-BEMROSE, H. H.: A sketch of the geology of the lower carboniferous rocks of Derbyshire. *Proc. Geol. Assoc.*, Vol. XVI.
6. 1907: ARNOLD-BEMROSE, H. H.: The toadstones of Derbyshire; their field relations and petrography. *Quart. Jour. Geol. Soc.*, Vol. LXIII.
7. 1908: WEDD, C. B., AND DRABBLE, G. C.: The fluorspar deposits of Derbyshire. *Trans. Inst. Min. Eng.*, Vol. XXXV.
8. 1913: GIBSON, W., AND WEDD, C. B.: The geology of the northern part of the Derbyshire coalfield. *Mem. Geol. Surv.*
9. 1917: STUCKEY, L. C.: Lead mining in Derbyshire with special reference to the Mill Close Mine. *Min. Mag.*, Vol. XVI.
10. 1923: RASTALL, R. H.: The Geology of the Metalliferous Deposits.
11. 1923: CARRUTHERS, R. G., AND STRAHAN, A.: Lead and zinc ores of Durham, Yorkshire, and Derbyshire. *Mem. Geol. Survey—Special Reports on the Mineral Resources of Great Britain*, Vol. XXVI.
12. 1926: PRESCOTT, BASIL: The underlying principles of the limestone replacement deposits of the Mexican province. *Engineering and Mining Journal*, Vol. 122.
13. 1926: SPURR, J. E.: Lead-zinc chimneys in limestone. *Eng. and Min. Jour.*, Vol. 122.
14. 1929: FLETCHER, A. R.: Mexico's lead-silver manto deposits and their origin. *Eng. and Min. Jour.*, Vol. 127.
15. 1932: FEARNSIDES, W. G., AND OTHERS: The geology of the eastern part of the Peak District. *Proc. Geol. Assoc.*, Vol. XLIII.
16. 1934: WALKER, H. A.: Mining methods and costs at El Potosi Mine, Chihuahua, Mexico. *U. S. Bur. Mines. I.C.* 6804.
17. 1937: VARVILL, W. W.: A study of the shapes and distribution of the lead deposits in the Pennine limestones in relation to economic mining. *Trans. Inst. Min. and Met.*, Vol. XLVI.
18. 1938: RAISTRICK, A.: Mill Close Mine, Derbyshire, 1720-1780. *Proc. Univ. of Durham Phil. Soc.*, Vol. X, Part 1.