

The Plynlimon Mines, Ceredigion, Wales, U.K; an integrated evaluation from new surface geological mapping and contemporary subsurface documentation

¹D.M.D.James and ²G.W.Hall

¹ 'Penparc', Cwmystwyth, SY23 4AG
Ceredigion, Wales, U.K.

² 'Abilene', Sheet Road,
Ludlow, SY8 1LR, England, U.K.

Abstract

The Plynlimon Mine yielded ca 3270 tons of lead concentrates between 1867 and 1897. No plans survive, almost the entire workings are flooded and no modern survey techniques seem to have been applied. There is however considerable data of apparent geological relevance in the contemporary archives of the Mining Journal. This data has been used to construct geological sections in the plane of the Main Lode and the major crosscuts, and the results then tested for consistency against similar sections independently constructed from new and detailed surface mapping. The same methodology has been applied to the unsuccessful venture in the adjacent sett at East Plynlimon, although data here is relatively sparse. Reconciliation of the surface and archival data sources proved fairly simple and the resulting appreciation of ore habitat is considered a considerable improvement on that which could have been arrived at from either of these sources if taken independently. Examples are given of the specific use of data from the Mining Journal which fit modern concepts of fault behavior and also of enigmatic references which can be interpreted when a modern surface survey is available. We suggest that a check with the Mining Journal should be an essential first step when planning new surveys in old mines.

Key words: Central Wales Orefield, Plynlimon Mines, Mining Journal, Ore habitat

Introduction

It is a truism that no investigation can be considered complete if it does not encompass all available lines of evidence. Studies of the industrial archaeology of metalliferous mine sites in Central Wales have long combined evidence from the surface remains with those from archival material, notably the Mining Journal (eg Bick, 1974-91; Hall, 1971; Hughes, 1981). A better understanding of ore habitat also seems likely to benefit from such an integrated approach.

Sharing this philosophy we set up independent evaluations of the Plynlimon mines from new surface geological mapping (DMDJ) and the evidence documented in the Mining Journal (GWH). Our objective was to see to what extent these approaches could be reconciled within observational error and whether or not any resultant increase in precision would assist understanding of the ore habitat and remaining prospects. Our conclusions are derived from the independent construction of geological sections along the plane of the principal lode and within the major crosscuts, after which we have agreed a reconciliation of these 'blind test' results to produce 'best estimate' sections. We are not aware of any geophysical or core-drill data at this site.

Our choice of these mines was governed by two factors. First there appeared to be potentially useful geological detail available in Mining Journal (MJ). Second, in this area of the Plynlimon massif there are only two major relevant rock types, a silty mudstone and a massive sandstone and these are both easily distinguishable in hand specimen

and of very different hardness, critical in setting bargains for drivage. This simplifies the surface mapping and affords a link to progress reports in the MJ. On the debit side much of the early development history, pre-1870, was not recorded in the MJ. Also the silty mudstones are essentially non-bedded and thus afford little control on folding. No plans of the workings appear to have survived (O.T. Jones, 1922, p 91). Our principal concern is with the successful Plynlimon Mine in the Tarennig valley. For completeness, we also treat the minor and unsuccessful adjacent operations at East Plynlimon. Figure 1 gives a synopsis of location and geology. The relevant topographic maps are O.S. Pathfinder sheets 927 and 928 (1: 25,000 scale).

General geology

The mines lie in the southeast flank of the Plynlimon Dome, an anticlinorial culmination composed of late Ordovician strata and surrounded by early Silurian strata, respectively termed the Van Formation and the Gwestyn Formation by O.T. Jones (1922). The area is covered by 1: 50,000 scale sheet 163 of the British Geological Survey (B.G.S., 1984); also by the 1:100,000 scale Mineral Reconnaissance Map (Nutt, 1974). Descriptions and interpretations of the rock types are given by James (1983) and Cave and Hains (1986). Figure 1 illustrates the modern stratigraphic nomenclature. The Gwestyn Formation away from the Plynlimon Dome is successively overlain by the Frongoch Formation and the Cwmystwyth Formation, which together yielded the majority of production in the Central Wales Orefield.

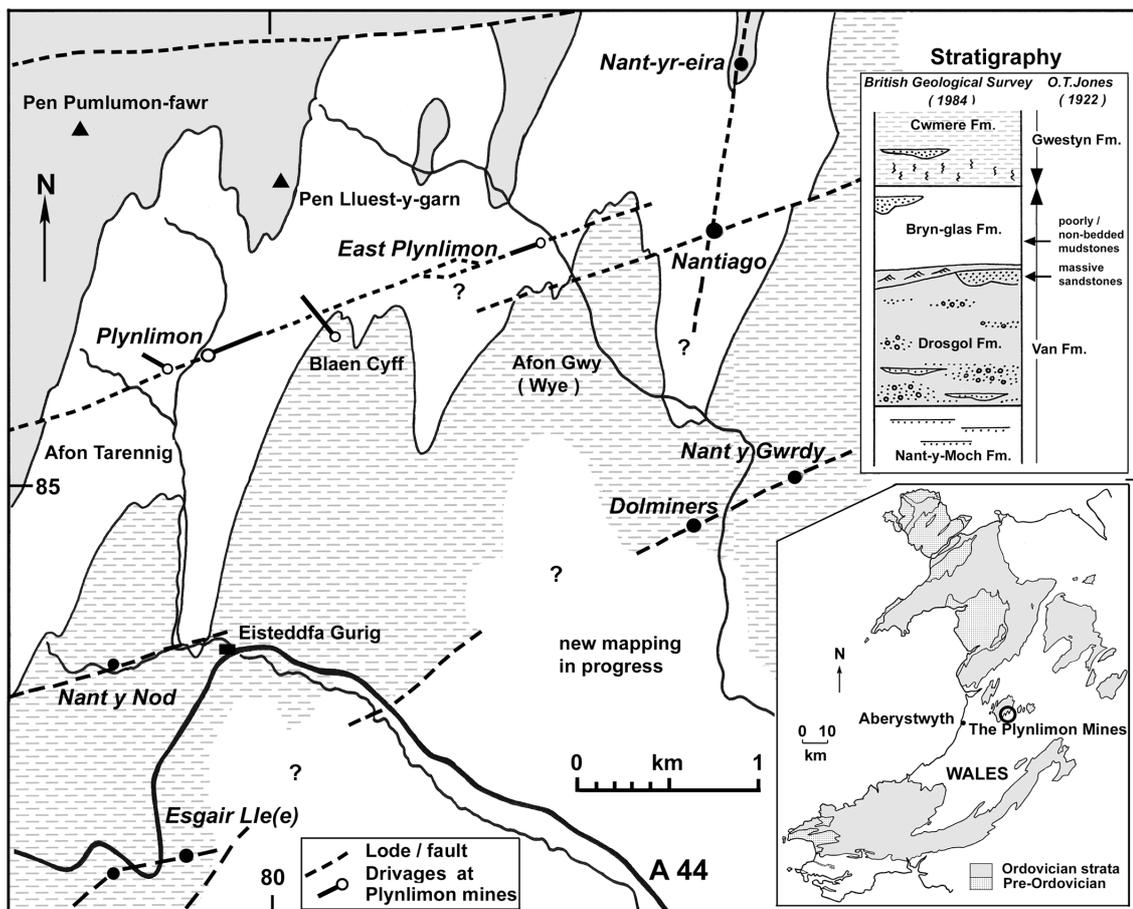


Figure 1: Location maps for the Plynlimon mines and nearby mines of geological relevance combined with a simplified geological map. Inset figures show the host rock stratigraphy and the general geographical situation in Wales.

The host strata were deposited as turbidites and mass-flows in a deep marine basin. They were folded and cleaved during the regional Acadian deformation of the Welsh Basin ca 396 million years ago (Sherlock et al, 2003) which preceded the first phase of mineralisation at ca 390 million years ago (Fletcher, Swainbank and Colman, 1993), probably that termed the A1 mineralisation by Mason (1997). Most of the lodes in the Central Wales Orefield map as mineralised dextral oblique dip-slip faults, commonly with dips of 55° - 70° but locally approaching the vertical. They display many textural features suggestive of fracture propagation through strata with abnormally high pore fluid pressure (Phillips, 1972, 1986) and their variable width and barren / mineralised zonation is a consequence of processes of asperity bifurcation and tip-line bifurcation set out by Childs, Watterson and Walsh (1996). Although many lodes with small throws are apparently laterally continuous over large distances, such colinearity is now thought of in many circumstances as due to coalescence of smaller faults, often via relay structures (see Cartwright, Mansfield and Trudgill, 1996).

The mines are situated on the outcrop of the poorly / non-bedded silty mudstones of the Bryn Glas Formation which in this area of the Plynlimon inlier overlies a massive sandstone with an intervening section of ca 5 metres of thin bedded sandstones and mudstones. The thickness of the massive sandstone at the mine site would be expected to be ca 25 - 30 metres based on control to the north (James, 1983, fig 5). Data from the MJ in fact constrain it to be ca 35 metres but as the sandstones lie on a gently channeled base this local value is not necessarily in conflict with the values nearby. Farther to the east, thickness estimates based on the present survey are also broadly consistent with previous work, namely ca 35 -40 metres at the East Plynlimon workings in the Wye and ca 45 -50 metres at Nantiago.

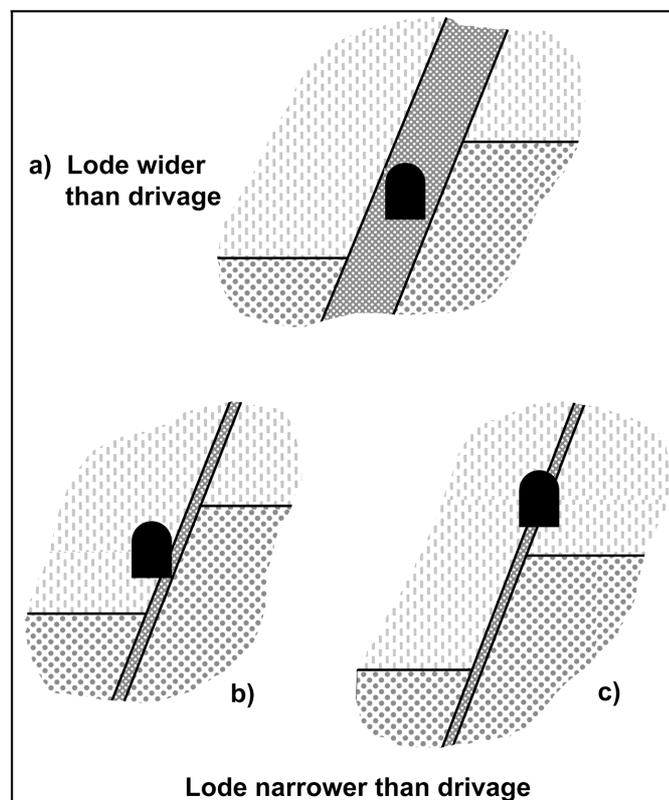


Figure 2: Differing sampling of lode rock and country rock according to the relative widths of the lode and the requisite drivage width. In a, there is no sampling of country rock save what may may form gangue in the lode system; in b and c country rock is sampled but its position in either footwall, hanging wall, or both, is indeterminate.

Geological interpretation of the MJ records suffers from a potential sampling problem. In the case that the lode is wide enough for concurrent drivage / stoping, the lithology / bargain rates (which generally correlate directly) will relate to the lode fill only and may bear no relation to lithology in either footwall or hanging wall. Where the lode is appreciably narrower than ca one fathom, as at Plynlimon, working space requires that drivage will be made concurrently in the country rock, preferentially in the least resistant rock-type, the lode material then being stripped out to the side (see Figure 2). We have tried to take account of these principles when interpreting the MJ: as a generalisation the mudstone (' killas ') at Plynlimon seems to have attracted drivage bargains of ca £5-7 / fathom whereas rates of £10-12 / fathom correspond fairly well with situations where we believe massive sandstones to be present in both footwall and hanging wall.

Brief history of mining operations

Figures 1 and 3 show the areal extent of the workings. They lie in remote upland country ca 550 metres above sea level where, despite rainfall of ca 250 mm / year, small catchment areas severely restricted use of water power.

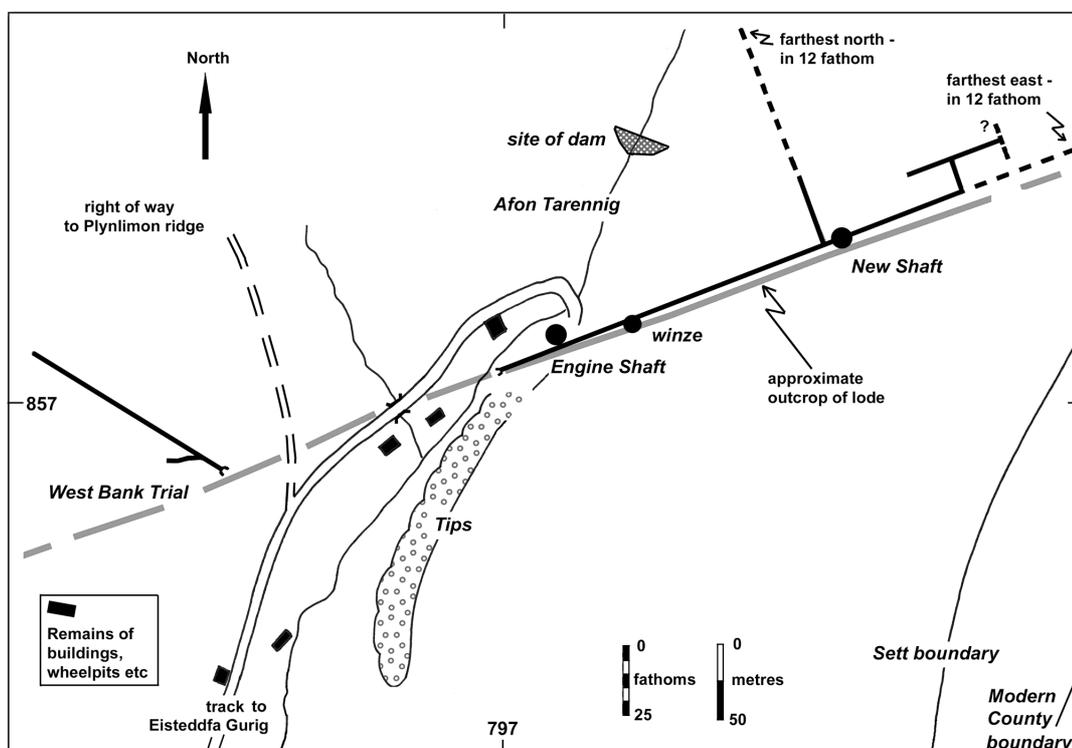


Figure 3: Map of the Plynlimon Mine with plan view of workings at adit level and with selected surface features including those affording geological control. The dip of the lode is not sufficiently well constrained to draw accurate plan views of successively offset deeper levels. The North Lode was apparently discovered ca 50 m upstream of the dam but is not now visible at outcrop there. The Main Lode is still visible in adit but not in the bed of Afon Tarennig. Grid marks are O.S. sheet SN 78.

All but half-a-dozen of the many mines of the Central Wales orefield are of ancient origin, and some are known to have been worked so far back as 1,500 B.C. Plynlimon is one of the few newcomers, first appearing as an entry in the annual Lists of Mines for the year 1864, under the ownership of a Mr. G. Williams. No further information is available until 1866, when the Mineral Statistics show a sale of 60 tons of what was then called

(dressed) lead ore, nowadays 'concentrates', that is, galena, lead sulphide, separated from waste rock and other minerals, ready for market.

In May 1867 a letter from Absalom Francis appeared in the *Mining Journal*, in which he referred to the discovery "some few months since" by a "poor miner" of a "rich rib of lead ore in one of the brooks crossing the Plynlimmon range of mountains". He added that it had been sold to a Birmingham company (for some thousands of pounds), under the management of Captain James Richards, of the Devon Great Consols. This was the Royal Plynlimon Mining Company. They developed the mine vigorously, driving the adit level eastwards along the course of the lode for 155 fathoms, almost all of which was in ore, putting up a 40 foot diameter water-wheel, and sinking an engine-shaft to 24 fms. below the adit, although they did little work at that depth. In the next three years they sold a total of about 1,000 tons of galena for about £13,000, which may well have yielded them a modest profit, but no accounts or reports from the mine were published in the *Mining Journal*.

However, in April 1870 they sold the mine and plant to the newly-formed Plynlimmon Mining Company (Limited), apparently for about £19,000. This concern had a nominal capital of £27,000 in 12,000 shares of £2.25, which were readily subscribed for. At the time the adit end was in ore, but had been stopped for lack of ventilation, while the 12 east was poor. Their first necessity was to put up another water-wheel, of 50 foot diameter, the original wheel alone not being powerful enough to pump as well as draw rock and ore from the shaft and drive the crusher.

The 12 fm. level east almost immediately entered a good run of ore, worth 2 tons of galena per fm., profitable ground in those days. Once the new pumps were installed the 24 was pushed on east in high anticipation, as they expected a long run of good ore underneath that already found in the adit and 12. But here things went wrong. Although the association of valuable ore ground with particular rock types had long been known in the Pennine orefields, with their repeated successions of limestone, grit, and shale, in mid-Wales, with its great thickness of less obviously differentiated rocks, no one had got to grips with the details of the more difficult mapping. The Plynlimon management were therefore quite unaware that immediately under the 12 fm level, in the centre of the mine, the lode entered a thick bed of sandstone, in which it would prove unproductive. This rock was not only a barren host, but very hard, and expensive to drive through, and the lode in it consisted of a rib of calcite, 4 to 24 inches wide, with spots only of lead, zinc, and copper minerals. Nevertheless through it they toiled, often delayed by flooding when frost or drought stopped the pumping wheel, in constant hope of a valuable discovery, from May 1871 until they reached ore at last, much further east than expected, late in 1875.

In the meantime, however, not only was the 12 east opening good ore, but a further run, beyond the old end, had been encountered in the adit east. These discoveries were a long way from their engine-shaft, and ventilation and access prompted them to sink a new shaft to open this end of the mine. This was started in December 1871, and proceeding by stages, reached the 24 in December 1874, and the 36 in July 1877. No attempt was made to drive the 36 through from engine-shaft, which had been sunk to that depth in April 1872, so, in order to be able to follow down the ore below the 24 east, flat-rods and cables were installed to work pumps in, and haul from, new shaft.

A fine lode had, ultimately, been opened in the far end of the 24 east, well beyond new shaft, the hope of the mine. It would have taken far too long to reach this at greater depth simply by driving from the new shaft bottom, and two suitably spaced winzes, Jones' and Herbert's, were accordingly sunk in the bottom of the 24, and the 36 expedited by driving east and west from the bottom of each, as well as east from new shaft.

While the developments outlined above were going on, more or less regular sales, sometimes as much as 40 tons of galena a month, but usually less, were made. These resulted in a profit of a few hundred pounds in the first part of 1872, and £1,231 in the year to July 1875, but overall the company's capital gradually drained away. This unsatisfactory result was mainly due to the unexpected configuration of the orebody which, so long and satisfactory in the adit and 12 fm. levels, failed below, due to the unexpected change of strata. It was compounded, though, by the remote and elevated situation of the mine, which added to transport costs, deterred labour, and rendered the mine particularly prone to a failure of its sole source of power, water, due to frost in winter and drought in summer. These together could amount to a loss of as much as three months work in a year.

As a result of these difficulties it became necessary to raise more capital, and in June 1876 it was agreed to wind-up the old company, and to form a new one, to be in 12,000 shares of a nominal value of £2 each. Of these 6,000, credited as fully-paid, were to be distributed pro-rata among existing shareholders, and 3,000 offered for subscription, each of which brought with it a free bonus share. It was agreed that unless 2,000 shares were taken the reconstruction would not go ahead, but at first offers for 1,200 only were received. In spite of this, encouraged by the splendid lode opened that summer in the 24 east, the mine struggled on, and in November it proved possible to form the Plynlimon Lead Mining Company (Limited), with the same structure, and to place 2,000 shares by the statutory meeting of the new company in February 1877.

With these additional funds the equipping of new shaft for pumping and winding could be completed, development of the 36 fm level hurried on, and the dam of their reservoir raised, a project long urged by Captain Garland.

All might yet have been well, but the price of galena fell from a high of over £15 per ton in late 1876 to something over £12 in 1877, and to less than £10 in the summer of 1878. The resulting serious decline of income, and the failure to place the remaining 1,000 shares, put their finances in a parlous state, and when a long drought in the summer flooded the mine, and then their dam burst, it was no longer possible to carry on, although the 36 fm. level had not reached the end of the oreground, and little stopping had been done over it.

The Plynlimon Lead Mining Co., in liquidation, held the mine until 1883, no doubt in hope of better times that didn't come. It then passed into the possession of Mr. William Thomas, of Mid Wales Villa, Llanidloes. He sank a winze 12 fms. below the 36 east of New Shaft, the ends of which were reported to show a solid rib of galena from 4 to 7 inches wide, and encountered good ore on driving out east and west at the 48. From this working he sold nearly 200 tons of galena between 1887 and 1891. It is expensive and impractical to try to pursue a shoot of ore by means of a winze some distance from the working shaft, but no doubt the cost of driving from the shaft was prohibitive.

It appears from the Lists of Mines that Mr. Thomas died in 1892. At any rate, he was succeeded in the Lists by an Elizabeth Thomas of the same address, presumably his widow. She retained it until 1897, but did little further work there, and since then the mine has remained idle. Total production at the Plynlimon Mine was ca 3270 tons of lead ore (O.T.Jones, 1922).

Ore location and extents from records in the Mining Journal

With the exception of the West Bank Trial adit and the first few metres of the discovery adit (still open), all directly observed (as opposed to projected) subsurface data has been

derived from the Mining Journal, see Figures 4 - 8. The following are the principal conclusions.

- There was a practically continuous run of oreground in the adit, about 180 metres long and averaging at least one ton / fathom. This seems to have extended only about 20 - 25 metres above the adit.
- This ore appears to have persisted to the 12 fathom level, and there to have extended perhaps 50 metres further east. Definite information is, however, lacking west of New Shaft, and mineralisation here may have been weaker than above.
- The 24 fathom level east of Engine Shaft went through a great length of extremely hard ground in which the lode carried little galena and evidence from the cross-cut north from the 12 fathom indicates this to be a massive sandstone. Eastwards, worthwhile ore came in at about 70 metres east of New Shaft and continued for about 110 metres.

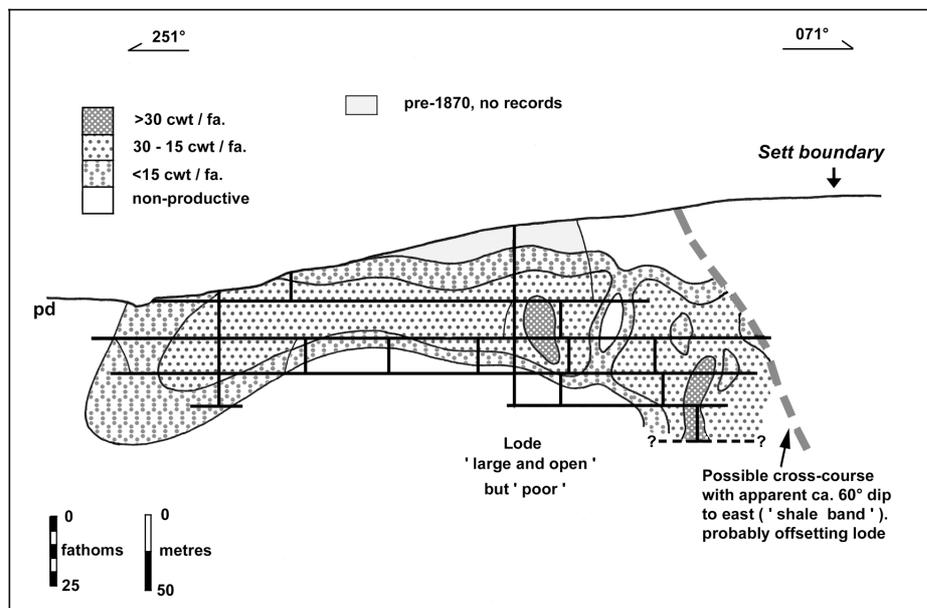


Figure 4: Cross-section of the Plynlimon Mine in the plane of the Main Lode, illustrating an interpretation (smoothed) of the productivity of the lode in cwt / fathom. Note that the best values very broadly lie in an anticlinal zone and that within this there appear to be shoots of greater and lesser value. The zone lies close to but above the top of the massive sandstone (see Figure 6). *pd* is the present-day erosion surface.

- The 36 fathom level was discontinued only a few metres east of Engine Shaft and west of New Shaft and we interpret this as defining the extent of very poor lode quality in the massive sandstone (Figure 6). It was driven east of New Shaft to develop a good ore shoot seen in the easternmost winze below the 24 fathom level. This good ground came in ca 110 metres east of New Shaft, and then continued as far as the level was driven, not so far as the 24. A winze sunk under this level to a 48 fathom level about 1890 showed a rib of galena 4 to 7 inches wide according to a report by Captain John Roberts of Nantgarw dated 18/9/1895. The extent of the 48 fathom level to east and west of the winze is not known but might have been as much as 90 metres based on ore volume produced, assuming no stoping. There does not seem to have been any significant change in ore grade with depth, at least in the best shoots, when away from the massive sandstones (whether this is true for areas with sandstones in both footwall and hanging wall but less so for sandstone in the footwall only is not clear). Figure 4 is a necessarily smoothed attempt to depict ore grade distribution.
- The eastern ends of the adit, 12 and 24 fathom levels were all given up on reaching a band of 'shale', which seems to have been dipping east (in the plane of section) at

between 11 and 15 metres at each deeper level. The proximity of the sett boundary discouraged further exploration in this direction. This band is best interpreted as a non-mineralised fault; such clay-filled 'slides' are not uncommon in mid-Wales (Smyth, 1848, p 665).

- None of the post-1870 development west of Engine Shaft found enough galena to work, but there seems to have been no difficulty in following the lode. The 12 fathom level, that driven furthest west, was reported as showing much blende and pyrite near the face.
- The lode often contains large quantities of blende and pyrite (minor chalcopyrite is also mentioned) but no reliable distribution for these minerals is possible as reporting was not quantitative.
- The dip-slip component of throw on the lode is not totally clear owing to subjectivities in distinguishing areas in which sandstone is present in both walls of the lode from those where sandstones lie in the footwall only, also we cannot exclude complications due to possible strike slip affecting interpretation of the cross-section in Figure 5. The estimate from this cross-section of ca 12 metres of throw is comparable within error to the ca 20 - 30 metres plus or minus 10 metres deduced from the surface mapping.
- Cross-courses throwing the lode small distances are recorded east of New Shaft but exact displacements are not known, The adit evidently went off on a branch about 50 metres east of New Shaft, but was afterwards found by cross-cutting north, see Figure 3.

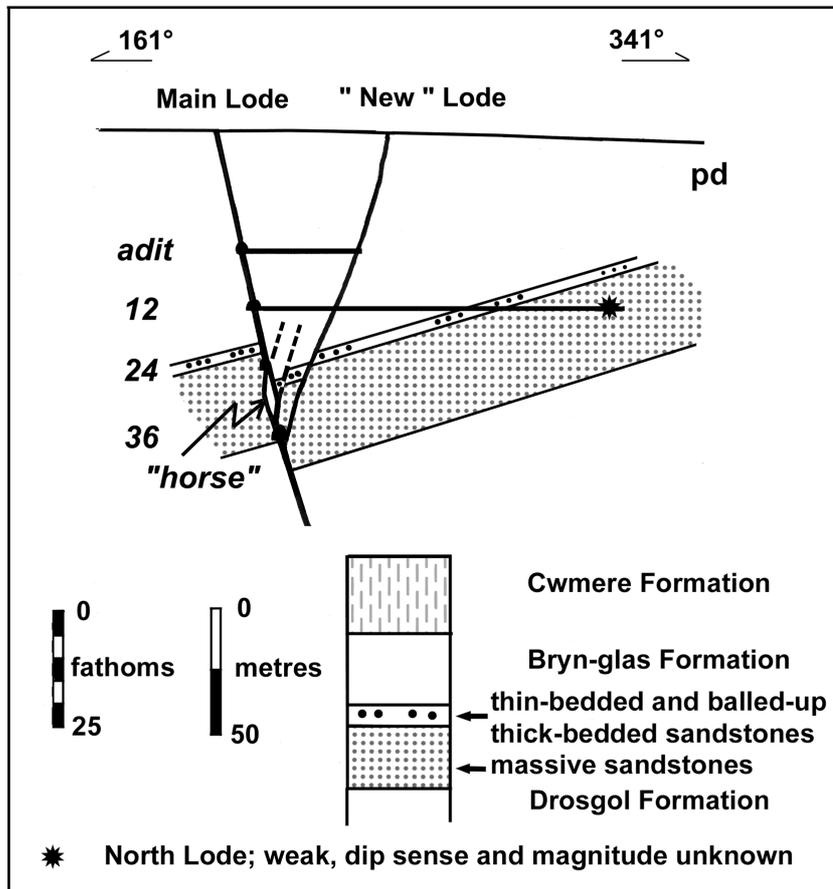


Figure 5: Cross-section of the Plynlimon Mine in the plane of the northern crosscuts to the New and the North Lodes constructed entirely from data in the MJ. This section constrains the thickness of the massive sandstone to be about 35 metres. The MJ is quite specific on the dips of the Main and the New Lodes (1877, p 475 & 502). pd is the present day erosion surface.

- The Engine Shaft was vertical and hit the lode at about the 36 fathom level. This would indicate local steepening from the dip seen at surface hereabouts which would predict intersection at about 22 fathoms. As the shaft is offset to the north from the Main Lode outcrop (Figure 3) this indicates a northerly dip to the Lode and most references in the MJ to its 'underlie' support this (eg 1875, p 499; 1876, p 523; 1877, p 447).
- The New Shaft seems to have followed the lode, although probably not from surface; it is recorded as hitting the footwall at 4 fathoms below the 24 (MJ, 1875, p 1250 & 1307).
- The MJ is often surprisingly specific concerning the geology in local instances; for example it gives the sense of dip of the massive sandstones (1877, pp 243, 727; 1872, p 359) and the occurrence of a 'horse' of killas in the lode (1876, p 1319).

Prediction of subsurface structure and ore location from surface geology

Prediction of abundant lithological control at surface onto the plane of the lode utilises structural data on the strike and plunge of fold axes derived from standard stereographic techniques. In the area of the Plynlimon Mine most folds plunge at about 15° towards ca 190°. Bedding dips are corrected for obliquity with reference to the planes of section (Figures 5 - 8). Projection distances for the major lithological boundaries are necessarily considerable (ca 500 metres for the top of the massive sandstones at outcrop around Pen Lluest y Garn to the NNE and ca 700 metres for the base of the Cwmere Formation in the synclinal closure to the SSW). This results in a potential error in the plane of section of ca 9 metres for every 1° of estimation error over 500 metres projection. Despite this the projected positions of folds in the massive sandstone fit quite well with the evidence from the MJ (Figure 6). The projection errors, together with lack of marker horizons in the Bryn-glas Formation, mean that no reliable estimate of any strike-slip on the lode can be made. The poorly / non-bedded nature of the mass-flow silty mudstones of the Bryn Glas Formation, which contains sporadic occurrences of rafted sediment inclusions not lying in the plane of bedding, means that the extensive areas of outcrop of this lithology close to the mine are of little use in structural analysis. The dip-slip on the lode can be crudely estimated as the difference between the apparent thickness of the Bryn-glas Formation in the plane of the lode as constructed from projections in the hanging wall and the footwall, and the true thickness of the Formation where non faulted. Assuming the fairly well constrained thickness estimate at Nantiago is applicable at Plynlimon, this gives an estimate of about 20 - 30 metres of northerly dip-slip with errors of at least 10 metres either way.

The only present-day surface geological control on the lode is in the mouth of the discovery adit at SN 79428565 where it strikes ca 071° and dips ca 73° to the north. This observation is consistent with the MJ and contrary to the statement by O.T.Jones (1922, p 91) that the lode dips to the south. The adit is blocked by a fall ca 10 metres from its mouth just beyond a flooded air shaft. The adit level would appear accessible from the air shaft at SN 79698575 and from New Shaft at SN 79838580 using SRT. Lack of lode exposure on nearby hillsides prohibits any prediction of lode value underground.

Negative surface-accessible control exists in the extensive adit cross-cut just above the road on the west bank of Afon Tarennig (Figure 3) which is still open along its entire length. The date of this trial is not known. If it pre-dates the initial discovery it is not now clear what encouragement led it to be sited here, but a possible target could have been the North Lode reported as once visible in the river ca 150 metres northeast of the Main Lode. If it post-dates the discovery, it is difficult to believe that such an effort, with a drivage of ca 145 metres sited barely 200 metres from the initial discovery, could have missed the Main Lode: possibly it sought the New Lode. The adit portal is, almost within error, directly along strike from the discovery adit and barely 10 metres higher. As there is no damage zone suggestive of lode proximity in rock exposed at the portal, we suspect either that the lode suffers a strike swing (or is offset by a crosscourse) within ca 150

metres of the farthest west workings in the 12 fathom level. It is noted that the lode southwest of the river was very poor in lead, albeit up to ca 0.5 metres wide with plentiful blende and pyrite (MJ, 1875, p 915-1307). A far more conclusive trial would have been to drive WNW from a location ca 100 metres to the SSW along contour (to allow space for tipping). There would have been no reason to go further SSW as at this point exposure downstream of SN 79218554 indicates no lode striking ca 070° is present.

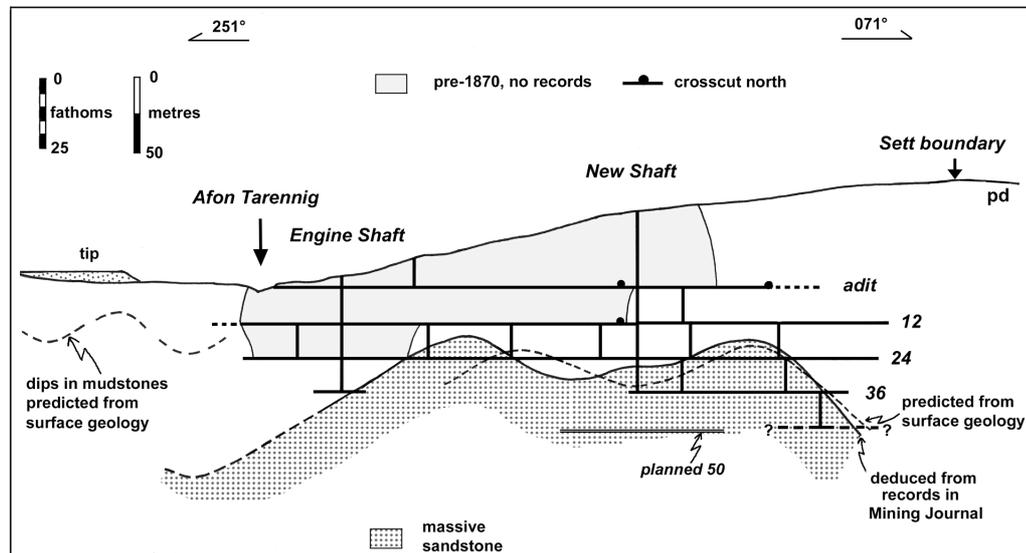


Figure 6: Cross-section of the Plynlimon Mine in the plane of the Main Lode, illustrating the comparison of the position of the top of the massive sandstones in the hanging wall as derived from the MJ, with that derived by the projection of surface geological data. The thickness of these sandstones is not well constrained in the plane of this section. The sandstones are now proven to occur much higher than predicted by O.T.Jones (1922, p 91-92) who thought they might lie at about the 48 fathom level between the shafts. pd is the present-day erosion surface.

East Plynlimon

There is not much data with which to evaluate the failures at East Plynlimon as the operation was curtailed prematurely by the loss of surface facilities in the Wye valley when the Nantiago supply dam burst (MJ, 1871, p 30). The lode in the Wye valley drift was commonly 3-4 feet wide (MJ, 1870, p 990) but in the Nant Cyff crosscut was "small". The former was presumably found in the River Wye but is no longer visible there, the latter also was not found in the current survey. There is no record of the dip of either lode and the surface survey has not determined these dips.

The contact of the soft muddy Cwmere Formation with the harder silty Bryn-glas Formation was recorded during drivage of the Nant Cyff crosscut somewhere between 50 and 62 fathoms (MJ, 1870, p 5) and this fits well with the results of the surface mapping (Figure 7). It is probably coincidental that the position of the lode eventually found in this crosscut lies almost exactly along strike from that at the Plynlimon Mine as the lode at the latter suffered at least one split and a probable offset due to a crosscourse when approaching the East Plynlimon sett boundary. If the lodes at Nant Cyff and the Wye have the same strike, it is doubtful if they are the same fracture. The former is probably best interpreted as the extension of Main Lode at Plynlimon. However, if the latter extends to Nant Cyff it should lie ca 60 -90 metres south of the position of the former there: lack of offset of the top of the Bryn-glas Formation hereabouts in fact suggests it does not extend so far. The Nant Cyff lode was essentially barren. The Wye valley lode

was spotted with galena and contained much iron pyrite ('mundic'); it was locally 4-6 feet wide (MJ, 1870, p 634) and the ratio of galena to pyrite increased with depth (MJ, 1871, p 262).

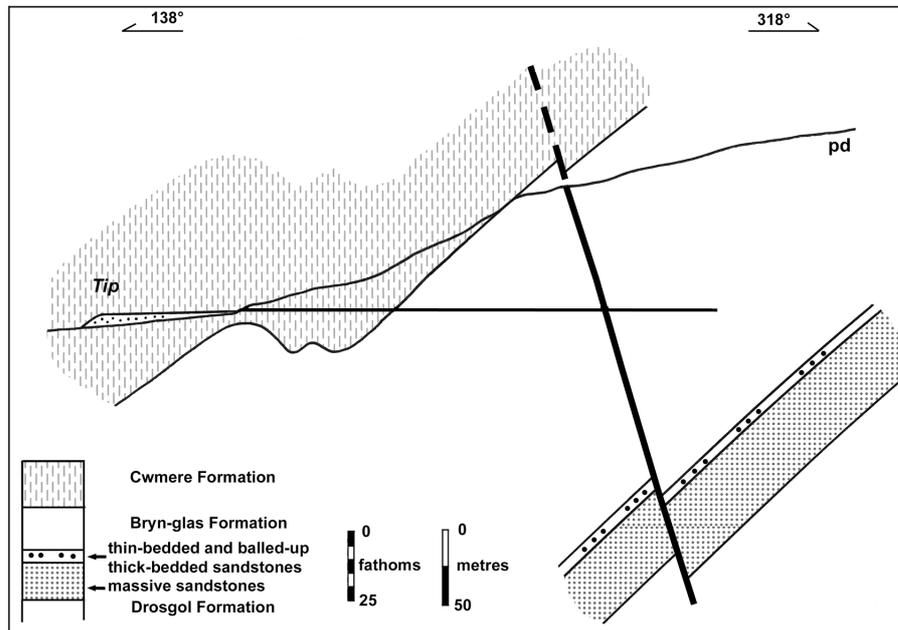


Figure 7: Cross-section of the East Plynilimon Mine in the plane of the Nant Cyff crosscut adit. The dip of the lode is shown as if an extension of the Main Lode at the Plynilimon mine; this is not totally certain, see text. pd is the present-day erosion surface.

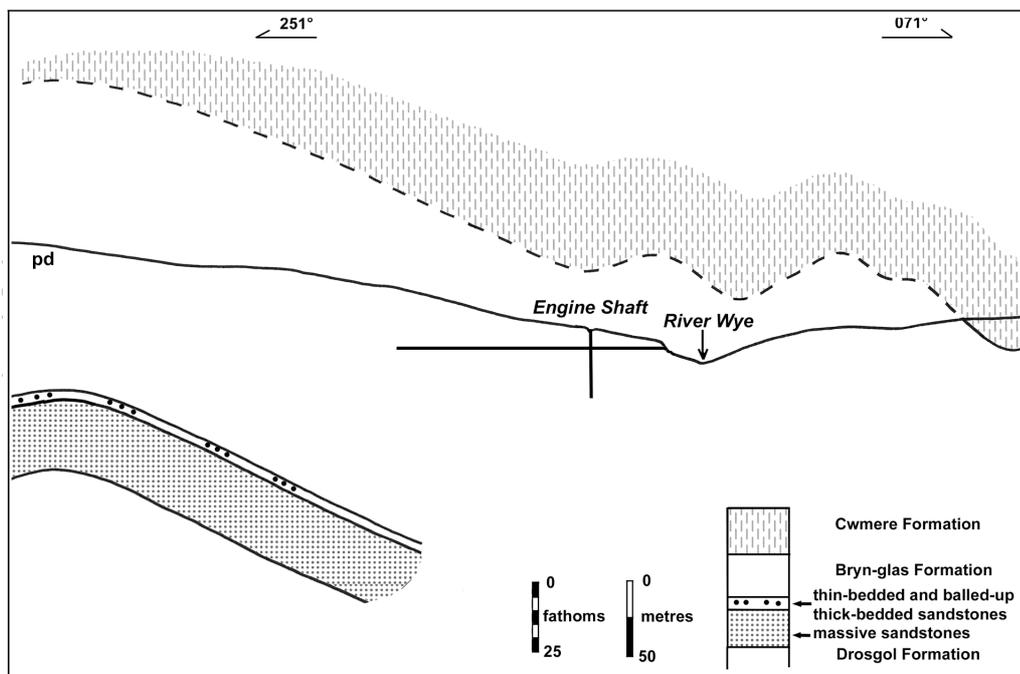


Figure 8: Cross-section of the East Plynilimon Mine in the plane of the Wye Valley drift adit and shaft. pd is the present-day erosion surface.

Our results suggest that it might be said of East Plynlimon, in the words of I.K. Brunel, that, " you have failed..... from that which causes nine-tenths of all failures in this world, from not doing quite enough ". The adit crosscut would have been better sunk for ca 25 fathoms on the " small " lode towards the top of the massive sandstone (see Figure 7) rather than extending along it, and the drift would ideally have been continued for ca 150 fathoms towards the crest of the anticline in the massive sandstone (see Figure 8), at the same time abandoning the shaft which would have needed at least a further 50 fathoms of sinking and dewatering. Such extra effort would have afforded a conclusive evaluation by analogy with the Plynlimon Mine.

Controls on mineralisation

The lodes at Plynlimon and at East Plynlimon cut an essentially identical stratigraphy. At the former mine the ore is concentrated just above the massive sandstones in a zone of limited vertical extent but extensive lateral extent which appears closely to follow the profile of the anticline. Field mapping suggests that the throw on the lode at Plynlimon, albeit poorly constrained, is probably near its maximum amount.

Modern models of fault propagation (see discussion in Cartwright, Mansfield and Trudgill, 1996) suggest that the fault tip line forms an expanding ellipse centred around the point of initial failure which becomes the site of maximum displacement: faults with several apparent sites of maximum displacement result from the amalgamation of initially discrete strands, generally via relay ramps. Ductility contrast being equal, sites of maximum displacement may be expected to generate maxima of fracture-related poroperm and this governs accessibility to mineralising fluids and thus potential economic value. The essence of this situation was presciently expressed by Bick (1977, p 46) as " the lodes of mid-Wales have in some way a tendency to concentrate ore into a single area.....the apparent paradox follows that the only lodes still worth prospecting are those that have never sustained a really productive mine "; a conclusion quite consistent with modern models. Fault propagation involves the release of elastic strain energy and the resultant fracture-related poroperm seems to be greater in regions with strong contrasts in rock ductility independently of throw. This probably explains the greater productivity of the multi-layered Frongoch Formation relative to the rather uniformly muddy Gwestyn Formation (in the terminology of O.T. Jones) and also the concentration of production immediately above the junction of massive sandstones with overlying mudstones that is so evident at Plynlimon. The impression is gained that the massive sandstones stored a large amount of strain energy before fracturing and that this was released almost explosively into the immediately overlying strata, possibly the more so at anticlinal crests which could plausibly have been local sites of maximum pore-fluid pressure gradient just before fracture. Thus, at Plynlimon, all of the above factors affecting economic value seem to have been favourable and their combined effects operated in unison just above the sandstone. Similar conditions appear present at Nantiago and Nant-yr-eira nearby. By contrast at Nantymwyn, 42 km to the south, where similar sandstones are almost four times as thick (James, 2003, p 195, 203-204) the best habitat was in fractures within the sandstones, not in the overlying mudstones (Hall, 1971, p 51-59). Here the available strain energy seems to have been largely dissipated in fracturing the sandstones.

Asperity bifurcation, the smoothing or by-passing of variable-dip segments of the fault plane, is optimally developed in multilayers with strongly contrasting frictional properties such as the Van Formation rather than the Gwestyn Formation. Tip-line bifurcation can in principle occur at any angle to sedimentary fabric, particularly where the growing fault has intrinsic curvature, but is favoured where a fault tip-line advances at different rates along differing sedimentary layering (Childs, Watterson and Walsh, 1996, fig 4). Rejoining of bifurcated tip-lines in relay zones would isolate a central mildly deformed zone between two strongly deformed slip surfaces in a way that is commonly seen in the lodes of mid-

Wales. It seems likely that such relay zones would develop with two principal orientations; bedding-parallel and fault-movement parallel. The latter may account for steeply plunging ore 'shoots' which commonly parallel slickensides, the former (together with asperity bifurcation) may account for 'stratiform' concentrations of ore within the plane of the lode. 'Stratiform' ore concentrations, ie with intra-lode orientation parallel to the dip of wallrock sedimentary layering, are very common in mid-Wales; both in the Frongoch Formation (O.T. Jones, 1922, p 75,79,118 and 151) and the Van Formation (O.T. Jones, 1922, p 54, 91 and 164). Figure 4 suggests that both types of orientation were present in the orebody at Plynlimon.

Synthesis of results

We have found little difficulty in reconciling our two avenues of investigation. Specifically we have found no differences in their separate conclusions beyond those attributable to measurement error and some inevitable subjectivities in the interpretation of the MJ. The broad structure at depth proved calculable from the surface data; albeit becoming refined by use of the MJ. However the geometry of the New Lode, antithetic to the Main lode and joining it via an extensional relay in its the hanging wall, is invisible at surface and has been deduced entirely from the MJ. The structure at the East Plynlimon ventures is also adequately constrained from the surface mapping and the MJ adds little of value. Overall, we have corrected several of the conceptions of structural geology and the layout of the workings that are found in the only previous account, ie that of O.T.Jones (1922), and gained some insights into a possible model for preferential location of ore deposition within the local host stratigraphy.

Some references in the MJ are enigmatic without knowledge of the local geology. Two in particular have now been resolved; namely 'greenstone' (1875, p 111) and 'boulders' (1873, p 227; 1874, p 115). The former might otherwise be misinterpreted as igneous rocks but are in fact sandstones with abundant chlorite in their matrix. The latter are not clasts within conglomerates but rather 'ball and pillow' structures in sandstones that have foundered into less dense lithologies (eg Potter and Pettijohn, 1963, p 148 - 151). A fine example of a 'boulder' may be seen in the Nant yr Eira stream at SN 82638752, where it lies at exactly the same stratigraphic level as the 'boulders' at the Plynlimon mine.

Although the prime purpose of the MJ is to report progress and prospects to shareholders, the geological information therein has in many instances not only proved consistent with the results of the surface survey but the integration of the two sources of data has resulted in a far more reliable interpretation than would have resulted from either source taken in isolation. We recommend a similar re-evaluation approach to other old mine sites wherever practical. Our work deliberately separated the two approaches as a test for internal consistency but in most cases the design of the detailed surface survey would best follow, and be based on, the insights available from the archival record.

Remaining prospects

There is no one model of ore deposition in mid-Wales that commands general support and, even more importantly, has predictive ability that has been put to the test.

If the local model of preferential ore habitat developed above has validity, then the mine at Plynlimon was well situated and lateral extensions downdip may not prove attractive. Prospects in depth, at the anticlinal crest, may be better and it is noteworthy that few mines if any in the Central Wales Orefield ever adequately tested the zone below the ductility contrast at the base of the massive sandstone. The Wye valley drift at East Plynlimon was not a conclusive test; it was well downdip of the anticlinal crest ca 400

metres to the west and its lode may well be prospective where crossing this structure (Figures 1 and 8).

The orebody discovered at the Plynlimon mine in the late 1860s, and explored between then and the mid 1890s, proved to be of considerable horizontal extent, about 400 metres. at the adit and 12 fm. levels, driving east into the hill from the valley floor, but of limited height. It is now clear that it coincides with a favourable horizon for intensified fracture development and / or rapid drop in pressure / temperature. It failed on entering the hard sandstone below, but it also did not extend far above the adit level. Here there is now known to be no change in rock type and it may be that this rather abrupt change is more likely to represent a chemical mass-action effect as change in temperature and pressure would be small over such a short interval. This situation was not appreciated when the mine was first opened, when the study of geology had not penetrated far enough into the mining community for it to be used to guide exploration or plan future mining operations.

At the west end of the mine, development carried out at the various levels down to the 36 failed to discover payable lead values, although the lode seems to have remained strong, and to carry in places considerable quantities of sphalerite.

At the east end, however, the galena oreground appears to have been cut out by a cross-course which dipped down eastward at about 60° in the plane of the lode, and seems to have persisted so far as the workings extend at the 36 fathom level below the adit. It was not followed further because to do so was impractical with the mining methods then available, that is, sinking shafts and driving levels, and the serious fall in the price of lead, and other metals, had anyway made it impossible to raise more capital. Moreover the workings were fast approaching the sett boundary here.

It should be born in mind that compressed air rock drills were still at a primitive stage, and were not in general use, so that levels could only be driven at the rate of about 6 feet a week. An oreshoot only 50 fms. from the shaft was therefore a year away, plus the time taken to sink to another level. But exploration had to proceed from a shaft, as it was only from a shaft that water could be pumped and rock drawn by machine.

The Plynlimon oreshoot is likely to be prospective east of its probable offset by a cross-course (Figure 4) although its location in a monotonous lithology below peat cover is difficult to map. High resolution aerial photography might assist in tracing it, but it is very narrow. However, as it lies in a monotonous lithology, the use of geophysical techniques may be practical. How far the lode might persist is, however, pure speculation, and a ribbon shaped oreshoot, only about 50 metres high, and containing perhaps 8 to 10% lead, is not a very attractive target, although it could be readily followed with modern mining machinery, and we need not today be frequently held up for lack of power. Additional revenue would nowadays also accrue from sales of sphalerite, which is apparently common in the lode. This mineral, then worth perhaps £3 a ton, could not possibly be recovered at a profit from so remote a site in the 19th century.

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David James is a Chartered Geologist and an Honorary Research Fellow in the Department of Earth Sciences, University College of Wales, Cardiff. His interests in mass / heat / fluid flow and associated fracture mechanics in the Central Wales Orefield developed during an international professional career as a geophysicist in hydrocarbon exploration, concurrent with a longstanding private research interest in the sedimentology and tectonics of the Welsh Basin. Email: davidmd.james@virgin.net

George Hall has worked on both history and future prospects of metalliferous mines in the British Isles for more than fifty years. He has written two books based on field and archival research, 'Metal Mines of Southern Wales' and 'The Gold Mines of Merioneth', together with numerous articles on individual mines. He has also been, and is currently, involved in several prospecting ventures. He took a prominent role in the reopening of the Gwynfynydd Gold Mine in 1981. Fax: (44) 1584 877521.

Further Notes:

The mine was visited by a WMS field trip on June 7, 2008. The highlight of this was the identification of a wheelpit for a 30ft wheel at SN7974 8599 found by Geoff Newton; this lies well to NNE of the dam and is thus not shown on Fig 3 of the paper. The pit aligns to azimuth 151° and thus directly to New Shaft. The wheelpit was measured by Geoff Newton and David James and a full description is planned by Geoff for the WMS newsletter.

Geologically, the northward underlie of the main lode argued in the paper was confirmed in two places. Dave Seabourne and David James entered the adit to confirm that the fall beyond the air shaft was effectively terminal and noted a winze near the shaft with clear northern underlie; a range of fabric dips in the lode was noted between 65° and 80°, consistent with those recorded previously closer to the adit portal. At New Shaft Roy Fellows found a vantage point above the south wall to look directly down the shaft; in good light the shaft wall is seen to be vertical and then dip steeply north as the underlie is intersected.