UNEXPECTED INRUSHES INTO A SMALL MINE

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Abstract

The drowning of 4 miners by an inrush into the Gleision mine on 15th September 2011 was a major shock. The immediate cause was the intersection of flooded old workings by the advancing heading. As a consequence the mine manager (Malcom Fyfield) and the owners (MNS Mining) were prosecuted for manslaughter through gross negligence. After a three month trial in 2014, they were all acquitted. This paper indicates why there was sufficient doubt about the events to secure that acquittal.

The c.0.7m Ynisarwed seam, which dipped steeply (14°) into the hillside, had been worked intermittently since the late 19th Century in a band some 200m wide. A heading had been driven some 300m down dip, from which a heading had been driven along strike some 55m downdip of the old workings. A heading driven up dip from this strike heading intersected the old workings.

The prosecution claimed the old workings had been flooded for years (to a very prominent flood mark) and were known to be flooded. The manager insisted they had been dry when he checked them the day before. The matter at issue was could he be telling the truth? Could the workings have been dry and then flooded overnight?

Of prime importance was the old workings not being a 'bathtub' - at best they were a leaky bathtub. The coal had a thick sandstone roof and a steep dip. The water that came in through the permeable sandstone roof near the outcrop could leak out through that same roof on the downdip side of the workings when there was a drain to remove that water further downdip. A rigorous analysis of the hydrogeological regime was impossible – there were too many unknowns. However, a simplified analysis of the alternating aquifer and aquiclude sequence and mine working voids was possible. This demonstrated that indeed, when the mine workings downdip were being kept dry, there was sufficient flow through the roof to keep the old workings up dip effectively dry. There was a delicate balance between inflow and level of flooding in the workings. Undoubtedly the workings would have been flooded before the downdip strike heading had been driven, but afterwards the heading could act as a drain to the old workings.

Where, then had the water come from? There had been insufficient rainfall to fill the workings up overnight. Inspection of the mine plans and old Ordnance Survey (OS) maps indicated three possible sources that could have caused the overnight flooding. The conclusion (which was supported by other evidence) was that the manger probably did go and check the day before and the accident was due to an unfortunately timed breach of some blockage in the old workings.

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Introduction

A major inrush occurred into the working stall of the Gleision mine at about 9:20am on the morning of Thursday 15th September 2011, as the working stall was being connected to earlier workings of the colliery. Of the seven men underground at the time, four were drowned and three escaped. Two of those who escaped ran up the intake drift ahead of the flood waters and raised the alarm. The last to escape (the manager) emerged some time later (just as the emergency services were arriving) having escaped from the working stall through the breach and up through the old workings, once the initial flood had passed. The manager was immediately rushed to hospital, suffering from the effects of water inhalation and exposure and was consequently unable to give any assistance with the rescue effort. When the alarm was raised a major rescue operation (handicapped by the remote location and difficult access) was set in motion by the Mines Rescue Service (MRS) but the victims were all dead long before they could be reached, indeed probably before the last man had escaped to the surface.

Following completion of the rescue effort on Friday 16th September, the Health and Safety Executive (HSE) undertook an investigation into the mine and the causes of the disaster. This lasted from the 17th September to the 6th October. Inspection was limited to the area of the inrush and the two routes leading from it to the surface. Considerable rehabilitation was required to safely inspect even this small area. Owing to the condition of the mine after the inrush there was no inspection of disused areas of the mine beyond these two passages. Unfortunately, the manager was not fit enough to say what he had done and seen until two days after the investigation had finished and the mine allowed to flood. Consideration of his version of events indicated that important information may have been present in areas of the mine that were not, and now could not, be examined.

The immediate cause of the disaster was that the old workings intersected that morning contained some 1,500m³ of water that rushed through the breach with devastating effect. The HSE alleged that this water had been in the old workings for years and was (or ought to have been) known about. As a consequence the mine manager (Malcom Fyfield) was prosecuted for manslaughter through gross negligence and the owners (MNS Mining) were prosecuted for corporate manslaughter. The case against the owners was based entirely on the actions of their manager, there were no separate allegations against them other than what their manager had done or failed to do.

After a three month trial in 2014, all the defendants were acquitted. The author acted as an expert witness for the mine owners and gave evidence for the defence at the trial. This paper gives the interpretation of events from the defence point of view and indicates why there was sufficient doubt about the prosecution version of events to secure that acquittal.

The Mine

Location

The mine entrance is on a steep wooded hillside forming the south-eastern side of the Tawe valley, between Pontardawe and Ystalyfera, in the western half of the South Wales Coalfield, see Figure 1, and between Swansea and the Brecon Beacons National Park. Surface access to the mine was very poor, at the end of a 2km long, narrow, single carriageway road with very few passing places. This access road severely limited the possible output. The mine worked the No. 2 Rhondda seam (known as the Ynisarwed in this part of the coalfield), which was about 0.7m thick at outcrop and was worked from an adit ('Conveyor Drift') running down dip in a south easterly direction.

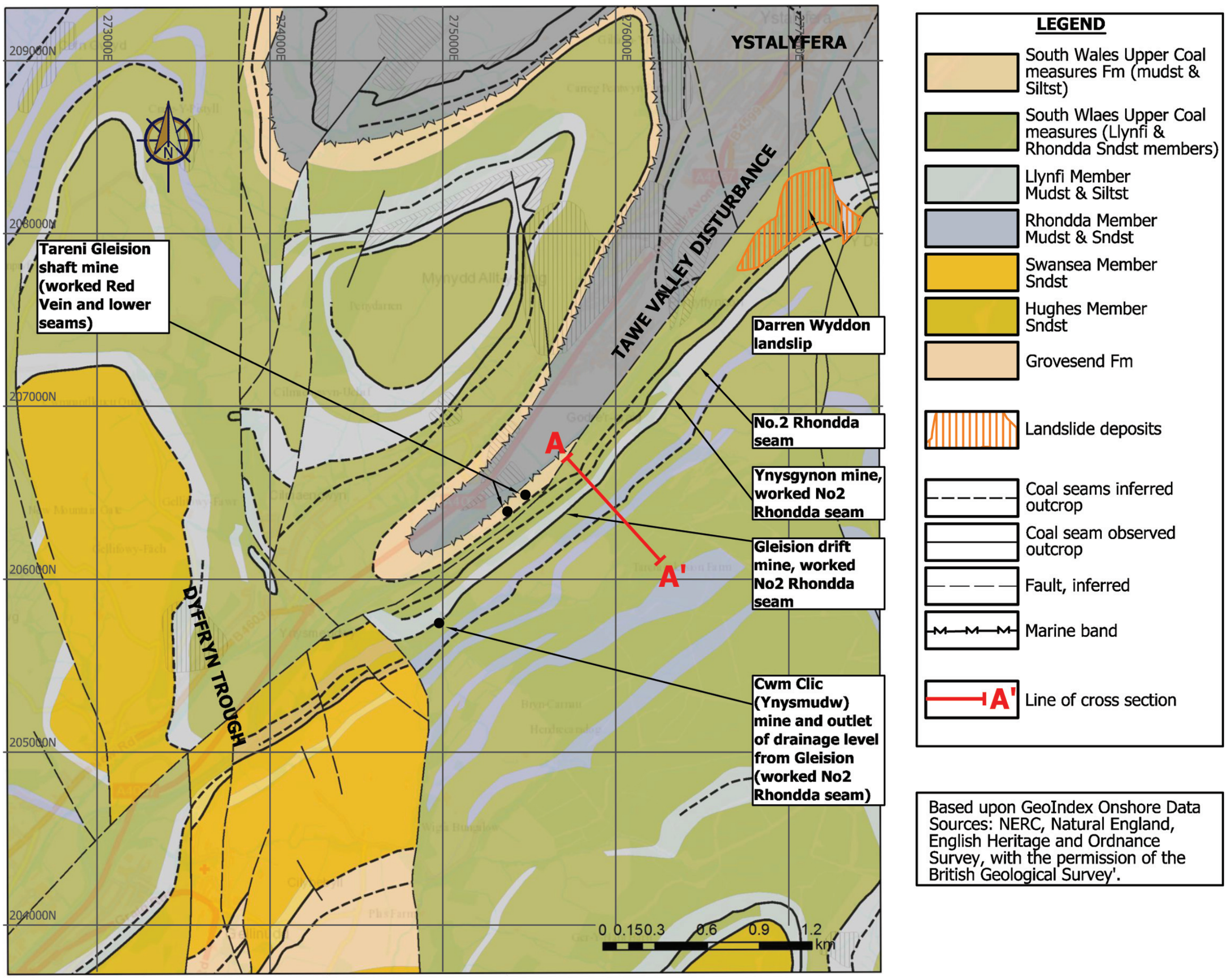

Figure 1. *Extract from BGS 1:50,000 map showing location of Gleision mine and surrounding mines. The line of cross section A- A' is shown, the corresponding cross section is on Figure 2.*

Strata sequence

The No.2 Rhondda seam is one of the coals in the Pennant Sandstone Formation. It forms the base of the Rhondda Member and sits on top of the Llynfi Member, both of which are of Upper Carboniferous Westphalian C age. The Llynfi Member beds are mainly mudstones and sandstones with thin coals and seatearths of varying thickness. Their topmost unit comprises some 1.1m of seatearth forming the floor of the No.2 Rhondda (and the mine). Thick sandstones of the Rhondda Formation form the roof of the mine. Beneath the Llynfi Member are the mudstones and siltstones, coals and seatearths of the Middle and Lower Coal Measures.

Apart from workings in the No.2 Rhondda seam, limited outcrop workings took place in the coal seams and seatearths of the Llynfi Member. More extensive workings took place in the Middle and Lower Coal measures. Near to the top of the Middle Coal Measures and some 240m below the mine is the Red Vein, which was extensively worked. Workings in other seams in the Middle and Lower Coal measures were limited in the immediate area of the Gleision mine, owing to folding and faulting making working difficult.

Geological Structure

The predominant structure is the Tawe Valley Disturbance. Abandonment plans for Tareni Gleision Colliery (worked 1907 to 1941) show that in this part of the valley this is a faulted anticline, downthrowing to the south-east some 55m. Outcrop patterns indicate a substantial 1km sinistral movement as well (Strahan et al, 1907). The mine lies on the eastern side of the disturbance, with the seam dipping at 1 in 4 into the hillside, flattening off as the seam was followed down dip to the east. This is shown by the cross section through the mine in Figure 2.

Minor rolls and disturbances are present in the No.2 Rhondda, and also in the Red Vein, but only amount to throws of a meter or two. As is common in South Wales, the less competent Middle and Lower Coal Measures have suffered much more disturbance.

Workings in No.2 Rhondda

In spite of stories of mediaeval workings by the monks of Neath Abbey, the first known period of sustained working in the No.2 Rhondda seam on the south-eastern flanks of the Tawe valley commenced in the 1870s at Cwm Clic (Strahan et al, 1907). These nineteenth century and early twentieth century workings spread north-eastwards along the valley side as far as Tareni Gleision farm in a zone at least 600m long and 200m wide. Numerous small adits and at least one shallow shaft mark the outcrop of the seam in this area. There appear to be no extant plans of any of these workings, despite postdating 1872 and there consequently being a requirement to make abandonment plans. At some time, a drainage level (the Ynysmudw water course) was driven to or from Cwm Clic to drain all these workings. This level has never been surveyed in its entirety,

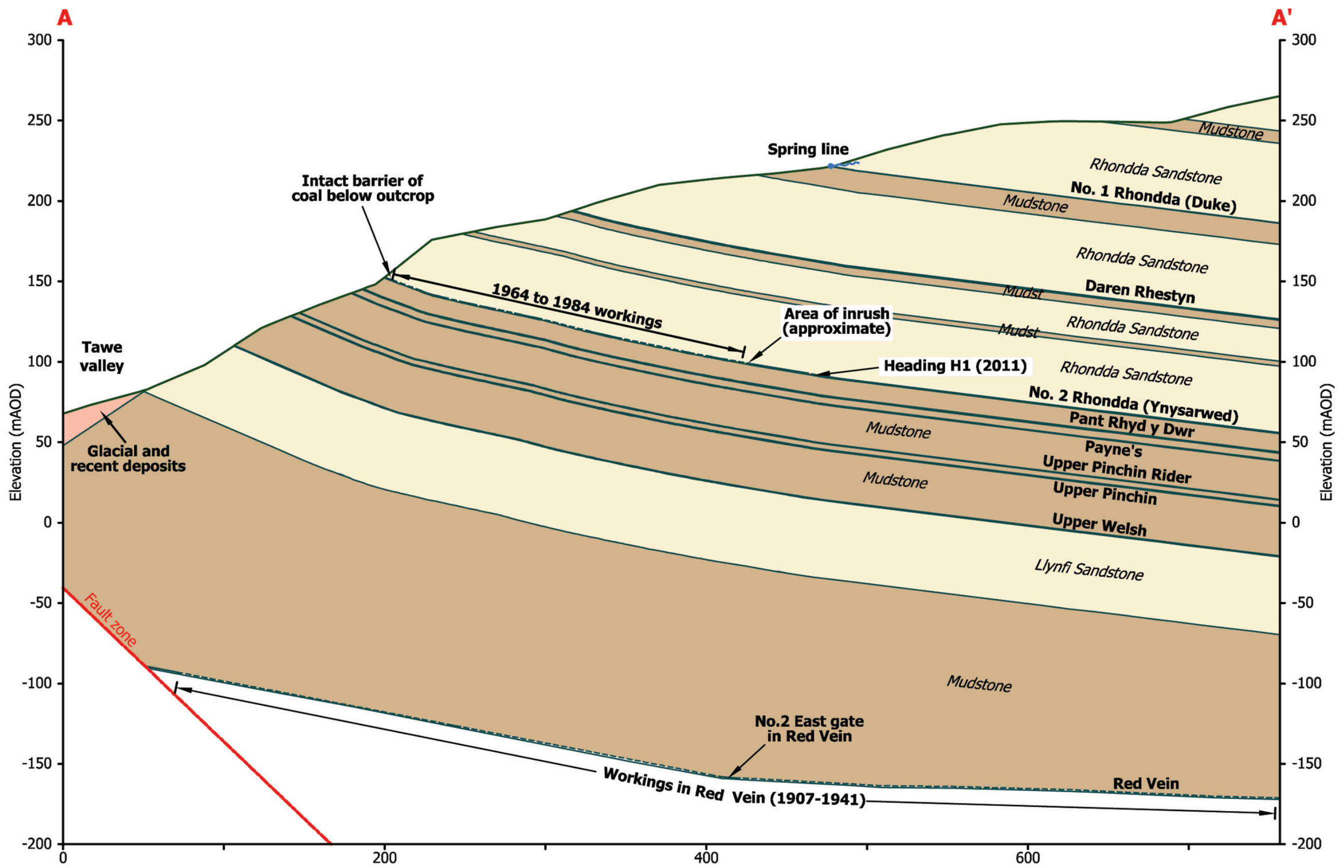

Figure 2. Cross section through the mine at the inrush location showing coal seams and sandstones. The line of cross section is shown on Figure 1.

although used ever since to drain the Gleision collieries. On the north-eastern side of the future Gleision mine area, extensive workings took place in the first three decades of the 20th Century from the Ynysgynon (Cambrian Mercantile) colliery drifts, 1.3km to the north-east of the Tareni Gleision farm.

Following closure of Ynysgynon in 1921, minor scratchings occurred from time to time. The second period of sustained working in the No.2 Rhondda commenced in 1957 with the Gleision No.1 private licensed mine (Old Gleision), 220m south-west of the Gleision mine adit. It closed due to lack of reserves, after intersecting uncharted old workings in 1959 (which included the Ynysmudw water course).

Working the main Gleision mine (strictly Gleision No.2 mine) started with the sinking of the Conveyor Drift in 1962. The layout is shown on Figure 3. In the first 22 years, workings extended from the surface to some 200m down dip, on either side of the Conveyor Drift. The mine intersected the eastern end of the Ynysmudw water course and used it for drainage. Working from the Conveyor Drift ceased about 1984, the last working being from a heading known as Top Road which branched off to the north of the Conveyor Drift (see Figure 3). It was these 1984 workings that were intersected in the inrush incident.

In 1984, a new adit (the 'Rail Drift') was sunk to access the northern end of the mine. Numerous connections were made between the two drifts, for air, emergency access and drainage. The mine worked continuously until October 1997, when it closed briefly, to reopen the next year under new ownership (S & T Fuels Ltd). Until 2000, S & T Fuels continued working north-eastwards from the Rail Drift until reaching the limit of the licence area (the 'Far eastern workings'). Ultimately, the workings extended some 650m north-east from the Conveyor Drift mouth.

Between 2000 and 2003, an area to the south-east of the Rail Drift was worked ('Eastern workings', shown on Figure 3). This working area was accessed by a branch off of the Rail Drift at 124mAOD, running down dip, initially through old workings, for a distance of 262m to a level of 90mAOD. The position of this working was apparently dictated by the need to leave protection pillars for the electricity poles and pylons at the ground surface.

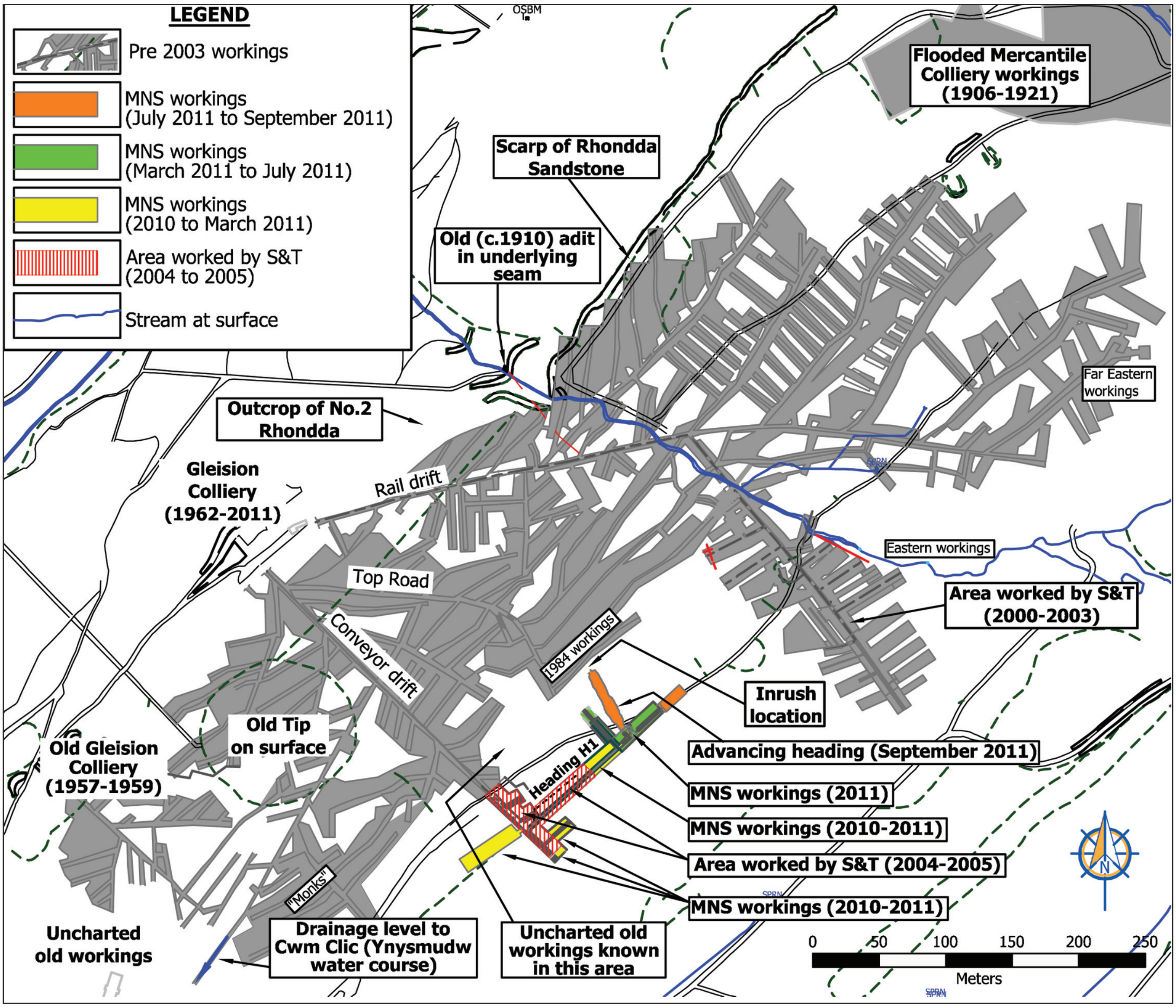

Figure 3. Mine plan showing working areas in the mine and inrush location.

In 2004, the working area was transferred to the bottom of the Conveyor Drift and this heading was extended down dip some 60 to 70m. In early 2005, a heading, H1, was started, running north-east back towards the Eastern workings and about 50m down dip of the 1984 workings. This had reached a length of about 50m when S & T Fuels became bankrupt. The mine was mothballed and allowed to flood up to the Ynysmudw drainage adit level.

A company called Coal Direct Ltd (which included one of the main creditors of S & T Fuels) bought the mine in 2008. They extracted very little coal (about 100t) and themselves became insolvent in 2009. The last owners, MNS Mining (set up by a major creditor of Coal Direct), took over in 2010. Working restarted and almost immediately had to be stopped due to planning difficulties. When these were resolved with the issue of a new planning consent, work restarted in September 2010.

The MNS Mining workings all took place from the Conveyor Drift. H1 was driven north-eastwards to an ultimate length of some 150m by September 2011. Several other headings off of the Conveyor Drift and H1 were also dug, as can be seen on Figure 3. The last was the inrush stall, heading northwards from H1 to the 1984 workings.

During the trial, evidence was given indicating the presence of uncharted workings in the area between the 1984 workings and the Conveyor Drift. Exactly when these were worked and who by was never established.

Working method

The Gleision mine was worked by the pillar and stall method. Design appears to have been done empirically by individual managers on site. For many years narrow headings c.2m wide and 1.6m high were driven in the coal and underlying mudstone, which were subsequently widened out by removing the coal on either side. The roof was supported by timber pit props. The mudstone from the floor was disposed of underground by packing in worked out areas beside the roadways. Latterly, the headings were apparently worked forward at full width, instead of by a narrow heading being widened out.

During earlier working periods, stall widths were variable and shown on the mine plan to range from 5-15m, although 10-12m was most common. During the MNS working period, stalls were 10-12m wide until Mr Fyfield took over in July 2011, when the width was narrowed to 8-9m. Coal was brought down by blasting. With the 10-12m wide stalls, blasting was generally once a day at the end of a shift. The narrower stalls used by Mr Fyfield required smaller blasts and two per day were often necessary, with one taking place midshift.

Pillars of intact coal were (or should have been) left between adjacent stalls to support the roof. During the MNS working period, the limited length of pillars formed appear to have been a minimum of 5m wide. During the later years of S&T Fuels ownership, pillar widths were very variable, from 2-15m and they were sometimes removed altogether. In earlier years (1970s and 1980s) there were large areas left with no, or very small, pillars to support the roof. If the roof subsided where roadways needed to be kept open, this would have to be done by digging out the floor of the heading as the sandstone roof was far too strong to excavate easily. The mine plan gives the impression of a somewhat chaotic operation, with headings and pillars in many areas not following a particularly logical pattern.

Reliability of the mine plans

During the investigations, it became apparent that there were a number of errors and inconsistencies on the plans. These took a number of forms:

Transcription errors

The original Gleision mine plan was drawn up in 1962 on paper using imperial units, onto which quarterly surveys were added. A new metric plan also on paper was drawn up in December 1993 (although the old plan was not discontinued until April 1994). In transcribing the data from one plan to another, much detail (in terms of levels, seam thicknesses and faults) was lost. Locations of workings were also not always accurately transcribed. In January 2000, this paper plan was in turn superseded by an electronic version maintained as an AutoCAD drawing file, with paper copies produced for record keeping and use by the colliery. The earlier plan was digitised by the surveyor, but this digitisation again resulted in loss of some data, in particular an area of working undertaken in 1994 and 1997 between the 1984 workings and the Far eastern workings.

Omissions

Detailed surveys were only made of the headings that were open at the time of quarterly survey. This was a consequence of the working method, whereby panels once worked out often became inaccessible. Consequently, actual coal face positions were often just assessed from information provided by the manager at the time and could be 6m out. Further problems arose due to the lack of a survey at the time of closure of the mine in 2005 at the end of S & T workings, at any time during the Coal Direct ownership or at the start of MNS operations. As noted above, workings of unknown date were discovered in the area between the Conveyor Drift and the 1984 workings, but never surveyed.

Error in surveying

The inrush occurred shortly before the next quarterly survey was due. Consequently, it having been started after the previous quarterly survey, the inrush stall had not been surveyed. The HSE commissioned a survey of the Conveyor Drift, connecting heading H1, the inrush stall and the Top Road. Whilst there was agreement between the mine survey and the HSE survey in terms of the position (but not level) of the Top Road, there was a significant difference (8m) in plan position (but not level) between the two surveys regarding the location of the base of the Conveyor Drift. There was insufficient data to resolve which survey was correct.

These inconsistencies made it very difficult to establish how much water was actually involved in the inrush.

Water Management In The Mine

Gleision was a wet mine. Water pumped amounted to over 10t for every tonne of coal mined - and could reach 66t per tonne of coal mined. This is large even for South Wales, where on average, 8t of water was pumped for every tonne of coal (Robins et al, 2008). Most of the water entered through cracks (open joints) in the sandstone roof.

Water entering the eastern side of the Conveyor Drift above 105mAOD (i.e. any water coming into the drift from the old workings to the north-east) was transferred across to the western side of the drift by the 'Black Pipe' – a 254mm diameter pipe installed across the floor of the drift for this purpose. This pipe transferred the water by gravity to the workings on the western side of the drift and was installed in about 2005. Although it was an important factor in the mine water drainage system, the position and level of this pipe was never surveyed, either by the mine's own surveyor before the incident or the HSE's surveyors afterwards. To stop water having passed through the pipe flowing down dip to the mine sump from the western workings, the Black Pipe was extended by a 70m long 154mm diameter pipe. Whilst the reduced diameter reduced the capacity of this drainage system, the prevention of down dip flow lead to an overall improvement. Only water entering the Conveyor Drift down dip of the Black pipe (and any that escaped entering the pipe) ran down to the sump at the base of the Conveyor Drift marked on Figure 4, where pump 1 was located.

During all of the MNS period, dewatering was primarily by a submersible pump located in the sump of the Conveyor Drift (Pump 1 on Figure 4). This had a capacity of 1,100m³/day and pumped up to the level of the 'Monks workings' (actually workings of 1970s vintage), at c.105mAOD (the location of the Black Pipe shown on Figure 4), some 30m above the sump. In wet weather, this pump had to work for 24 hours a day. There was another pump in the Monks workings (Pump 2 on Figure 4) at a level of c.95mAOD pumping water up to the Ynysmudw water course at a level of c.108m AOD. When MNS took over, these were the only two pumps in the mine. MNS added a further two pumps in the Conveyor Drift, one by the Black Pipe (Pump 3 on Figure 4) and one at the junction of the Conveyor Drift with the connection to the Ynysmudw water course (at about 120mAOD; Pump 4 on Figure 4). Pump 3, by the Black Pipe, was to lift water from the Black Pipe level (the

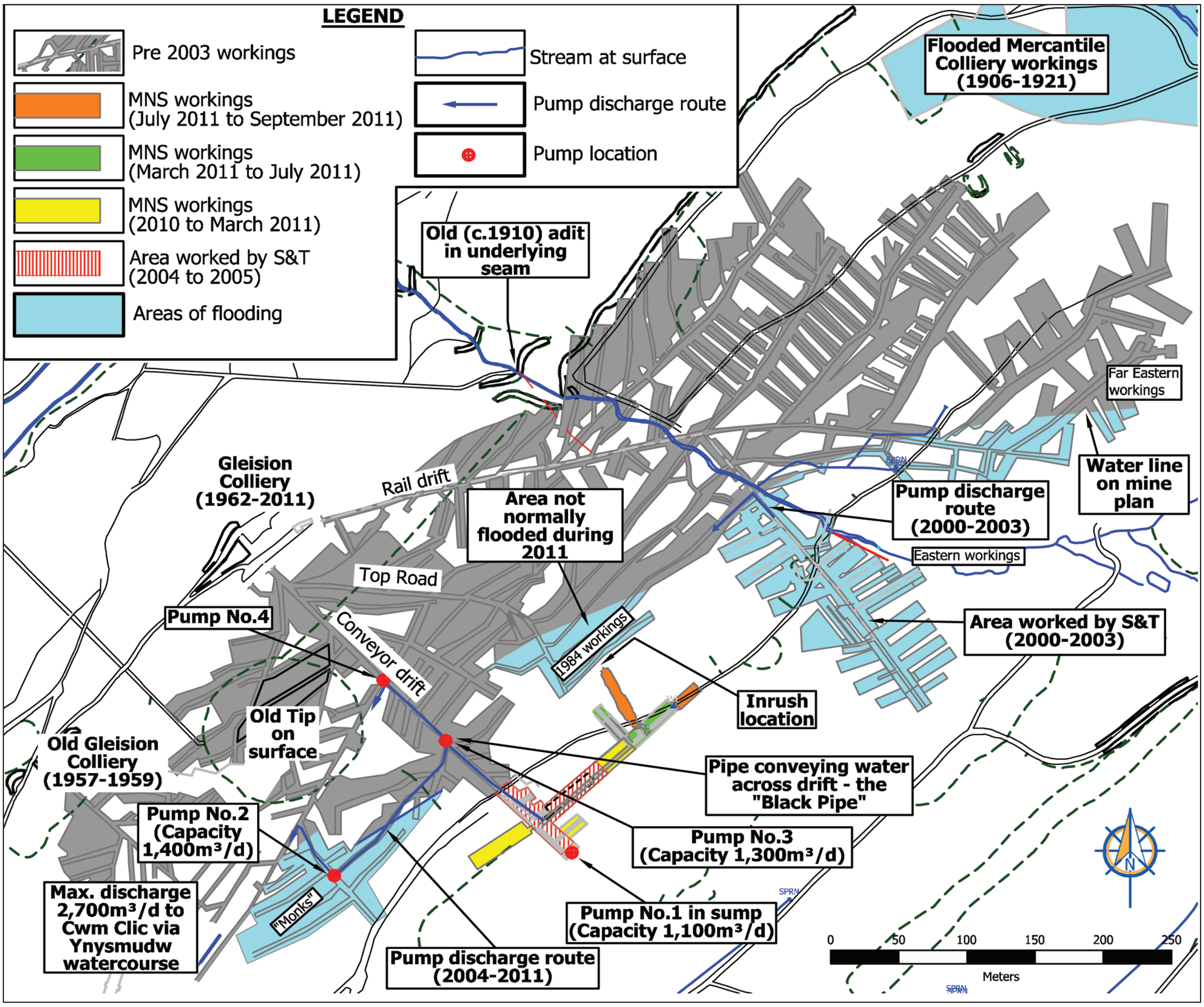

Figure 4. *Pump locations and capacities in 2011 just before the incident.*

outfall of Pump 1) to the connection with the Ynysmudw water course when the pump in the Monks workings (Pump 2) could not cope with the water flow. The pump (4) at the intersection with the water course could pump to surface if the water course became choked. The locations of these pumps are shown on Figure 4. All pumps were of the same type (BS2125 submersible). Capacities varied slightly due to the differing heads they had to pump against.

Although direct measurements were never made, the discharge rate to Cwm Clic could reach 2,700m^3/day when all pumps were working. Of this, 1,100m^3/day came from the sump at the base of the Conveyor Drift and 1,600m^3/day from the rest of the mine, even though the catchment area of the latter was far more than 1.5 times that of the mine sump.

Events Preceeding The Inrush

Before the last manager took over in July 2011, the plan had been to advance heading H1 to a total length of about 250m and intersect the old eastern workings of 2000-2003. This would enable a good ventilation circuit to be formed. However, by August 2011, the 150m length of H1 was proving difficult to ventilate with the equipment available. Consequently, the manager decided to drive a cross heading up to the old 1984 workings to provide a shorter ventilation circuit within the capacity of the equipment.

This stall was driven about 10m east of an earlier up dip heading, aiming towards a point some 25m north-east of the bottom end of the Top Road. The manager maintains that during the advancement of this stall he twice went around to the 1984 workings via the Top Road and found them dry.

According to his account, on the 14th September 2011 the manager again went around to the 1984 workings via the Top Road and found them effectively dry, with small amounts of water ponding along the coal face. At the same time, advance boring from the stall intersected the old workings, some 6m closer than expected. A small amount of water came out (described as being 'like a tap half on') entirely consistent with the managers observations.

The Inrush

The incident occurred mid shift at about 9:20am on 15th September 2011, shortly after a blast intended to form the connection. A detailed plan of the area is shown in Figure 5. At the time of the blast, there were four miners (including the manager) in the lower end of the inrush stall (about 40m from the blast), two in Heading H1 near the entrance to the inrush stall (about 56m from the blast) and one at the junction of H1 with the Conveyor Drift (about 140m from the blast, measured along the workings). From the statements of the survivors, it appears that the quantity of water that was encountered was completely unexpected by any of the people in the mine at the time. Whether or not it was reasonable to expect those workings to be nearly dry is another matter.

There was a delay of about 15 to 20 seconds between the blast and the water entering from the old workings. The noise of the inrushing water was said to be 'like a jet engine', so must have been flowing under considerable pressure. Two miners neither of whom were in the inrush stall at the time (one was in the Conveyor Drift at the junction with heading H1 and the other stationed on H1 at the entrance to the inrush stall) escaped up the Conveyor Drift by running as fast as they could. Sometime later the manager escaped from the working area in the inrush stall after the flood had subsided, through the breach that had just been made and out via the old workings. Although his escape seems quite incredible, there can be no doubt that the manager was in the inrush stall and escaped through the breach and the old workings - there was no other way he could have got to the surface after the incident.

Four miners (including the shotfirer) were drowned, three in the inrush stall and one in heading H1. Their bodies were recovered over the next two days by a major rescue operation but they appear to have died shortly after the event, before any rescue effort could possibly have reached them and indeed probably before the survivors reached the surface.

Although comparison was often made with the Lofthouse disaster of 1973, the inrush was actually much more comparable to that at Cynheidre Colliery in 1973. In both Gleision and Cynheidre (and unlike Lofthouse) the intersected workings were known about and deliberatley intersected for operational reasons. In both cases, those workings were flooded when they were believed to be dry. The main difference was that at Cynheidre, the belief that the workings were dry relied on a calculation of water volume which, although based on reasonable assumptions, turned out to be erroneous (Davies, 1982); whereas at Gleision the belief was, according to the manager, made on the basis of direct inspection the day before.

The Issue In The Case

To be guilty of manslaughter through gross negligence it was necessary for the prosecution to demonstrate that not only had mistakes been made, but that there had been a blatant disregard by the manager for the safety of the persons affected. This was made clear by the judge in his summing up to the jury. He told the jury that even if there had been breaches in carrying out duties set out in the Mines Regulations (1979), this did not necessarily amount to negligence. Gross Negligence Manslaughter required the acts of commission or omission to be extreme or that the defendants had deliberately taken risks which they knew (or ought to have known) gave a very significant chance that someone would be killed.

The crucial issue was whether or not the manager had examined the old workings the previous day and found them effectively dry before breaking into them. If the prosecution's allegations were true, the manager could not have carried out this inspection, as the site would have been under 9m of water.

Basically, two conditions needed to be met for the manager to be telling the truth:

1. That the old workings could have been dry the day before.
2. That sufficient water could have entered them overnight.

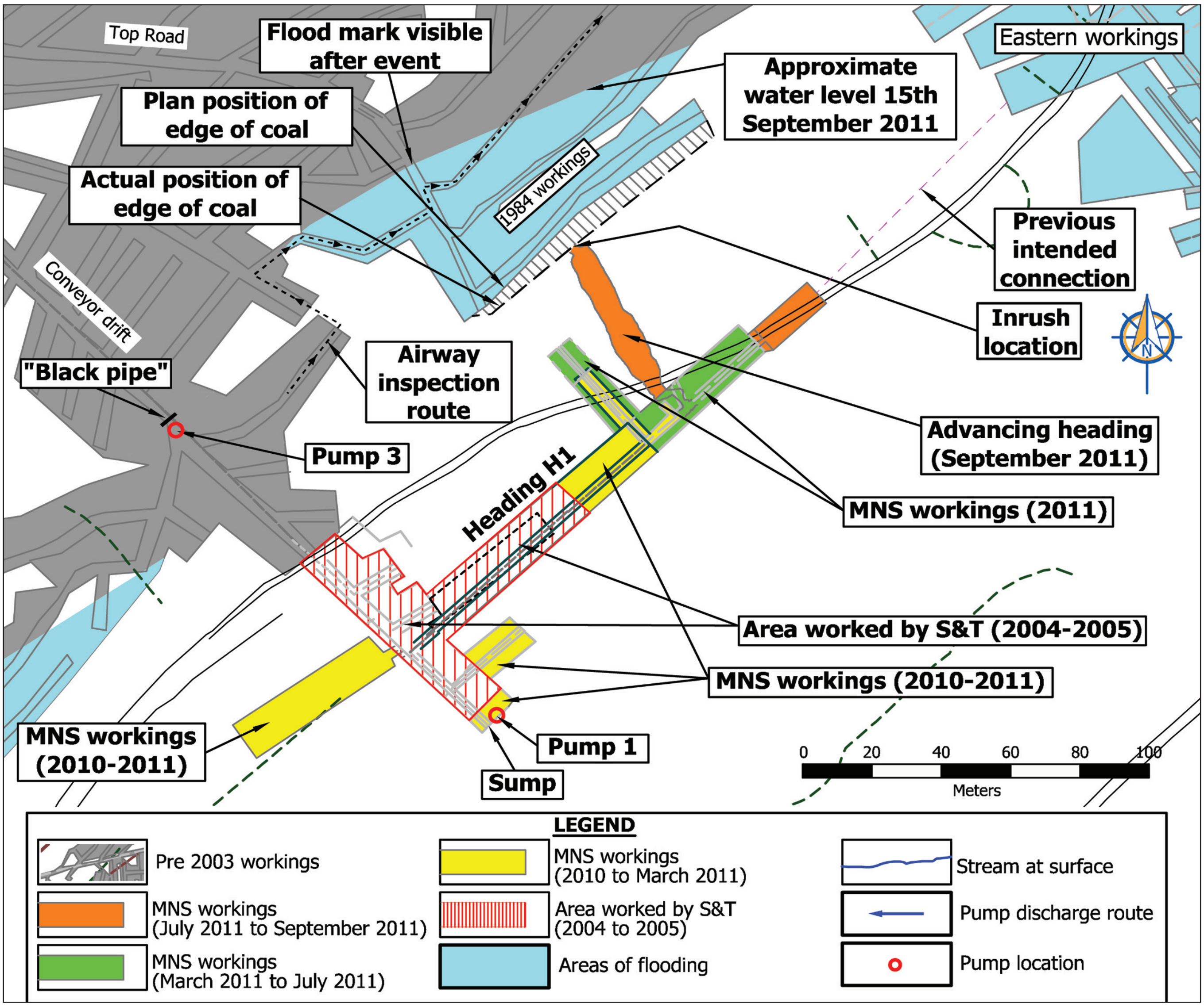

Figure 5. *A more detailed plan of the area of the inrush, showing the location of the workings, the presumed area of flooding on 15th September 2011 and the inspection route employed by previous manager to inspect the airway.*

Could The Workings Have Been Dry The Day Before?

The wet condition of the old 1984 workings and the presence of a fresh flood mark showed that undoubtedly, on the morning of the 15th September the old workings had been flooded. Many old marks indicated that at some time in the past, water had been repeatedly up to this level. But the flood of 15th September also produced a flood mark in heading H1, indicating such marks could be produced with a very short period of flooding.

According to the mine plan, the 1984 workings formed a pocket in which water would be expected to accumulate. For them to be dry, this water would need to be able to escape by another route than the headings shown on the mine plan (although uncharted old workings were known to exist, which could have intersected the 1984 workings). The roof consisted of a jointed sandstone, in theory, it was possible the water could have flowed through the sandstone to the workings further down dip. Whether this was possible in sufficient quantity to drain the old workings was a matter which needed to be investigated.

Hydrogeological Situation Of The Mine

Hydrogeology before mining

The rock types present; sandstone, siltstone, mudstone and coal, have low primary permeability, i.e. there is little ability for water to flow between the rock granules, which are tightly bound or cemented together. Water flow relies on secondary permeability, with water flowing through the discontinuities (bedding and joints). Whilst mudstones and shales have a higher discontinuity frequency, sandstones usually have a far higher permeability as the joints, whilst less frequent, are usually more open and persistent.

The effect of this on the alternating sandstone and mudstone rock mass forming the hillside around Gleision Colliery was to form a series of aquifers (permeable) and aquicludes (impermeable). Water flowed through and was stored in the sandstones and not in the mudstones and shales. A series of perched water tables resulted, with spring lines at the line of intersection between sandstone and underlying mudstone/shale (see Figure 2). This is a widespread situation in the South Wales coalfield (and elsewhere, such as the Cotswolds and

Pennines, where similar alternating aquifers and aquicludes occur). The coal seams, although more permeable than the mudstones, are too thin to have much effect on the overall system. However, any seam, such as the No.2 Rhondda at Gleision Colliery, that is worked beneath a thick sandstone roof is likely to be wet.

Stress relief (the site was on the side of a deep glaciated valley) will have permitted the spreading and opening of the joints. Weathering processes increase the number and openness of the discontinuities, thus increasing the permeability and porosity of the rock mass near to the ground surface. Tree roots penetrate and open up joints, increasing permeability. Softening of mudstones and seatearths can lead to spreading under the load of overlying sandstones on steep hillsides, giving rise to more opening of joints in the sandstones (and large scale failure, as has happened at Y Darren Wyddon, on the flanks of Varteg Hill, 2.2km north-east of Gleision, see Figure 1). The superficial cover of broken rock forming the colluvial debris cover is even more permeable and porous. Thus, in the undisturbed state of the ground, most ground water is contained in and flows through the outermost part of the rock mass.

Faults may or may not act as water flow paths, depending on the nature of the fracture. If clay filled, a fault may form a barrier, if full of broken rock it may form a preferential flow path. The water transmission potential of a fault may differ along its length, depending on the rock types traversed. As rock near a major fault is more broken than elsewhere, permeability and water flow may be higher near major faults. Unfortunately, the available mine plans do not state whether the faults were water bearing or not.

Hydrogeology after mining

Mining has caused several severe changes to the hydrogeological regime in the South Wales (and other) coalfields (Gray, 1969; Booth, 2002 and Robins et al, 2008). These are both direct and indirect. The voids left in the coal seams lead to a major increase in permeability and porosity in the parts of the seams concerned. At the depths of working at Gleision (less than 200m), this occurs even when the workings collapse, as the broken rock is usually (though not always) much more permeable and porous than the previously intact rock mass. The quantity of water that can be stored in the old mine workings and the speed at which it may flow are much greater than in undisturbed strata. Where the roof drops, part of the void is transmitted up into the roof strata, with consequent increase in permeability and porosity in those units (Whittaker and Reddish, 1989).

Whilst the workings substantially increase the transmissivity of the affected area, they do not do so in a uniform manner, as large parts of the workings are backfilled by waste and this waste is variably compacted by the weight of the super-incumbent strata. The amount of compression will also depend on the extent of extraction and how much coal is left to support the roof. The older working areas of Gleision, up dip of the breach point were heavily extracted, so considerable compression is likely. (The manager, in his description of his examination of the area and in his escape, indicates that he saw the roof sagging towards the floor.) Little information is available on how much compression has taken place at Gleision. However, the MRS drove a short access tunnel to the breach point through the goaf which appears to have exposed both roof and floor. This tunnel was mainly 0.4m high (it also exposed an apparently partially crushed pit prop). The coal nearby was c.0.6m thick, indicating a settlement of some 0.2m, or one third of the void thickness some 3-6m from the edge (ribside) of the workings, where the roof was still supported by the intact coal to some extent. Given the depth (c.112m), full closure is unlikely within 20m of the ribside (Whittaker and Reddish, 1996). Hence, further into the 1983/84 workings, the settlement may have been greater – it is unlikely to have been less.

Mine workings have other serious effects on the overlying strata, due to the subsidence and stress relaxation that occurs following mining. Over the ribside zones of wide workings, the overlying strata are subject to opening up of the joints and bedding planes. This greatly increases permeability. (A water feeder shown on the Gleision mine plan in the sandstone roof of the sump to the Conveyor Drift is probably a result of intersecting a joint opened by subsidence above the Big Vein workings – it lies close to the area where fissuring might be expected from these workings.)

These strains can breach aquicludes and significantly alter the water flow regime – elsewhere in South Wales streams are known to be truncated by fissuring of the aquicludes permitting the headwaters to sink down to lower levels (Gray, 1969). The sinking of the roof into the mining void also causes delamination and opening up of the bedding, leaving hidden voids that can be well above the mine roof (Whittaker and Reddish, 1996).

The Tareni Colliery Red Vein abandonment plans show that about 360m below the Gleision Colliery workings a road through the worked out area of Red Vein coal (a gate road) traversed the area of the incident in Gleision Colliery. The gate road would be supported by packs on either side in order to keep it open. Such roads frequently give rise to humps in the subsidence profile and consequent tensile strains (Anon, 1975). A note on one of the abandonment plans shows that this particular gate road remained open in 1950, long (c.25 years) after it was needed for access to the workings and 9 years after the seam was abandoned.

Computation using the NCB Subsidence Engineers handbook (Anon, 1975) shows that the tensile strain could be between 1 and 2mm/m, sufficient to cause significant opening (1-10mm) of joints spaced 1-10m apart. The precise location of this zone of opened joints is uncertain, because of a number of factors:

- The exact position of the gate road is uncertain, due to survey errors in the Red Vein.
- The dip of the Red Vein at this point is not well defined, and the location of the tensile zone can be displaced down dip from the plan position by a distance related to the dip of the seam.
- Subsidence prediction is an inexact science. There is an expected 10% error even with modern rectangular panels, old irregularly shaped panels can give rise to a greater error in prediction.

Another impact of the increased permeability in tensile strain zones is that of increased weathering and softening of the mudstone strata. Although the mudstones still remain relatively impermeable, the increased water flow is sufficient to cause significant softening over a period of 60 years (this was demonstrated to be the cause of the Bolsover landslide in 1991, some 60 years after the hillside had been undermined (Cobb et al, 2000)). The significance of this is that the mudstone floor in the tensile strain zone area noted above may have become weaker than elsewhere in the mine, giving rise to increased penetration by the pit props and coal pillars and consequent lowering of the mine roof. There were reports of some pit props at Gleision having sunk into the floor.

Hydrogeology of inrush stall area

The hydrogeology of the mine area is complex and impossible to elucidate precisely with the information available. As water was continuously entering the old 1984 workings by flow down dip, for them to be dry, the water must have been escaping by some route (specifically through the sandstone roof) at a rate faster than it entered. Until 2005, there would be no sink down dip for the water to flow to, so no major flow through the roof was to be expected and the 1984 workings would remain flooded.

Briefly in 2005, and continuously from 2010, the advance of heading H1 made a significant change to the hydrogeological regime, in that a void that was kept dry (and therefore acted as a drain), was advanced some 50m to the south of the old workings. (There was also at least one cross heading driven even closer, to within at least 37m of the old workings.) The sandstone beam that capped and connected both was not impermeable, but capable of transmitting water (water was often noted dripping in from the roof).

Whilst the old workings were described as a bath tub by the prosecution, this was not a correct analogy – bathtubs do not have one permeable side, as was the case at Gleision. A bucket with a hole in it would have been a better analogy. The sandstone roof at the lower end of the workings was 9m below the watermark. When water is poured in the open, uphill end, it will leak out through the permeable fabric (specifically, the sandstone roof). The water level will depend on the rate of inflow compared to the rate it can leak out. There is abundant evidence that water came in through the sandstone roof of the mine, so there is no reason to believe the roof was not capable of transmitting water in the other direction, given the necessary pressure differential. The rate of outflow varies according to the head of water, the water level in the relevant area of the mine will consequently depend on the balance of the rate of inflow with the rate of outflow.

Hydrogeological Analysis

Model

Analysis of the hydrogeological regime is made difficult by the lack of site specific data. Little information of use to such an analysis was ever gathered during the mine's life, nor was much, if any, gathered during the investigation after the disaster. No permeability measurements were made, no joint spacings and openings measured. Neither were measurements of flow rates undertaken, only a few visual estimates of flow of uncertain accuracy. All that could be done was to use typical figures and test them against the maximum amount of water that entered the mine which could at least be estimated by the maximum pumping rates available.

In mining affected Pennant sandstones, a wide range of permeabilities have been observed (Booth, 2002). At Aberfan, permeabilities of $1x10^{-3}$m/s were measured (Gray, 1969). This is a somewhat extreme value. From the transmissivity data in Jones et al (2000), for Pennant Sandstones in South Wales, a figure of $1x10^{-5}$m/s is more likely.

A model was set up and analysed using the ground water finite element module of Rocscience's Slide 6.0 program. The model comprises an alternating series of zones of high (1x10-5m/s) and low (1x10-11m/s) permeability, representing the sandstone aquifers and mudstone aquicludes respectively, with the workings modelled as zones of very high permeability (1m/s). It can only be considered an approximation of the real situation. It is also only a 2D, not a 3D, simulation. There is insufficient information on geometry and permeability available to model the true situation. It can however be used to demonstrate that with a set of parameters that are justifiable, the 1984 workings could have been dry in the conditions prevailing in early September 2011.

Finite element analysis

Figures 6 to 9 show the results of the finite element analysis on the simplified cross section through the old workings and heading H1.

The model was run for varying inflow rates from the ground surface, in terms of mm/day and also for various permeability values around the assumed figures. Apart from loss to springs emerging at the ground surface at the base of the sandstone units, outflow is via heading H1, which is kept dry continuously, as would be the case with the pumping that was undertaken in the mine. In reality, there would also be loss down dip to springs on the other side of the mountain, but this has not been included as it would be much smaller than the discharge routes included. It can be seen that the level of flooding in the old workings is very dependent on the inflow rate. At the lower rates of 3 and 6mm/day, the workings are nearly dry – the situation as described by the manager. At high rates of 24mm/day, flood levels could reach 104mAOD (still some 4-5m below the approximate height of the pre inrush flood mark). The high inflow rates reflect the 3 dimensional nature of the flow regime - the length of the catchment along strike over which water would flow down to the flooded workings is probably 2-3 times the length along strike of the old workings that would feed water into the sandstone roof. Consequently, an inflow rate of 6mm/day in the model would represent a daily infiltration of 2-3mm/day, and 24mm/day represent 8-12mm/day. Actual rainfall would be significantly higher than the infiltration figures, as not all rainfall would penetrate to the rock – there would be

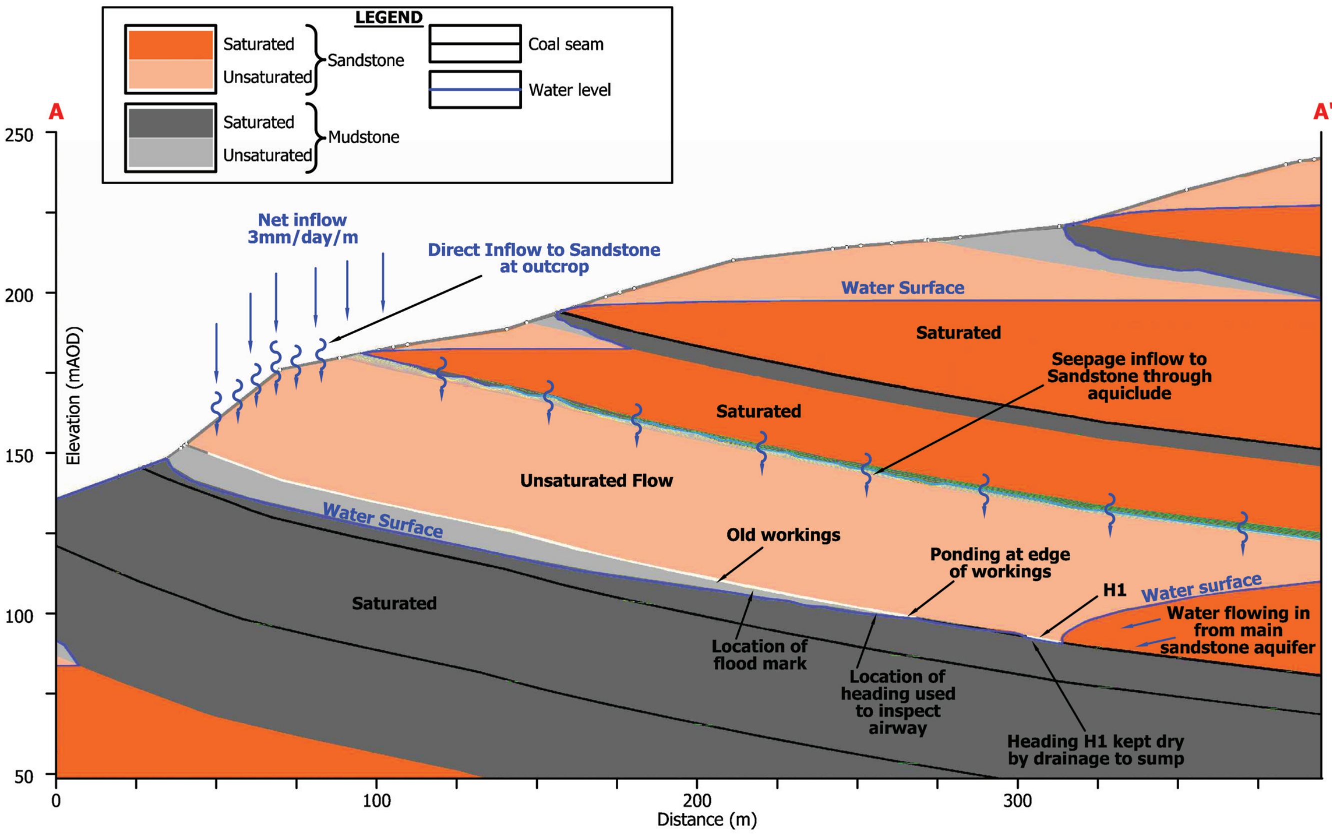

Figure 6. *Cross section showing negligible flooding of old workings with a net inflow of 3mm/day/m of outcrop, and an approximate pumping rate of 650m³/day.*

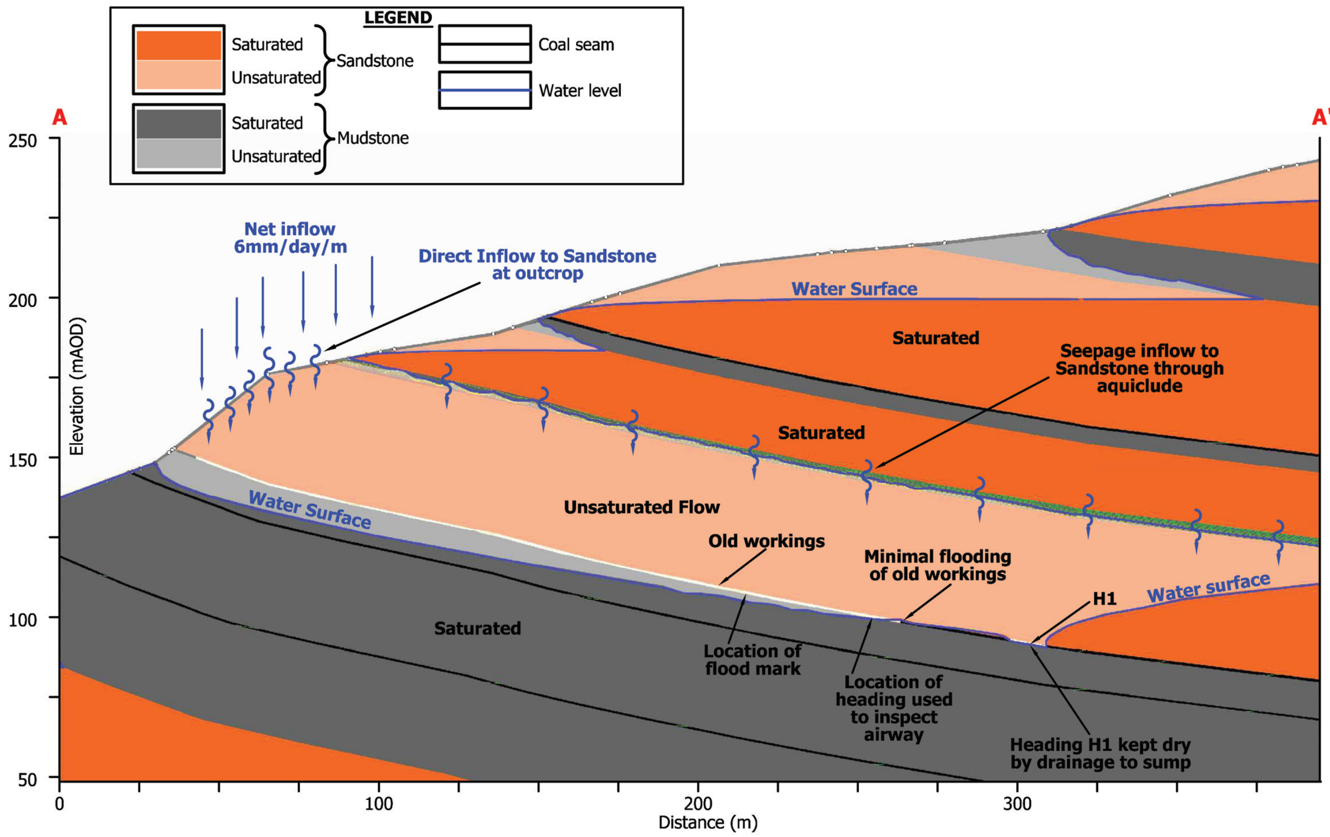

Figure 7. *Cross section showing minimal flooding (to c98mAOD) of old workings with a net inflow of 6mm/day/m of outcrop, and an approximate pumping rate of 690m³/day.*

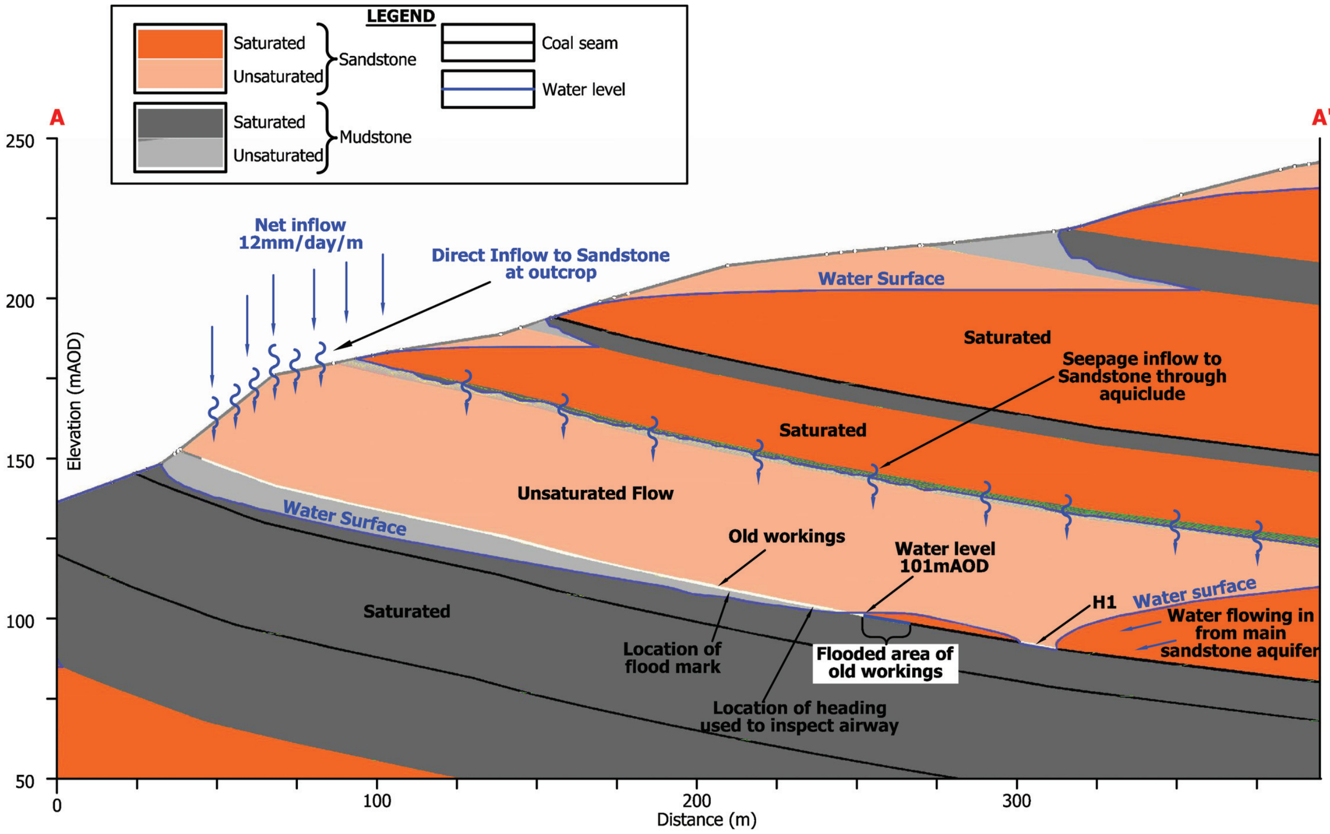

Figure 8. Cross section showing flooding (to c101mAOD) of old workings with a net inflow of 12mm/day/m of outcrop, and an approximate pumping rate of 750m³/day.

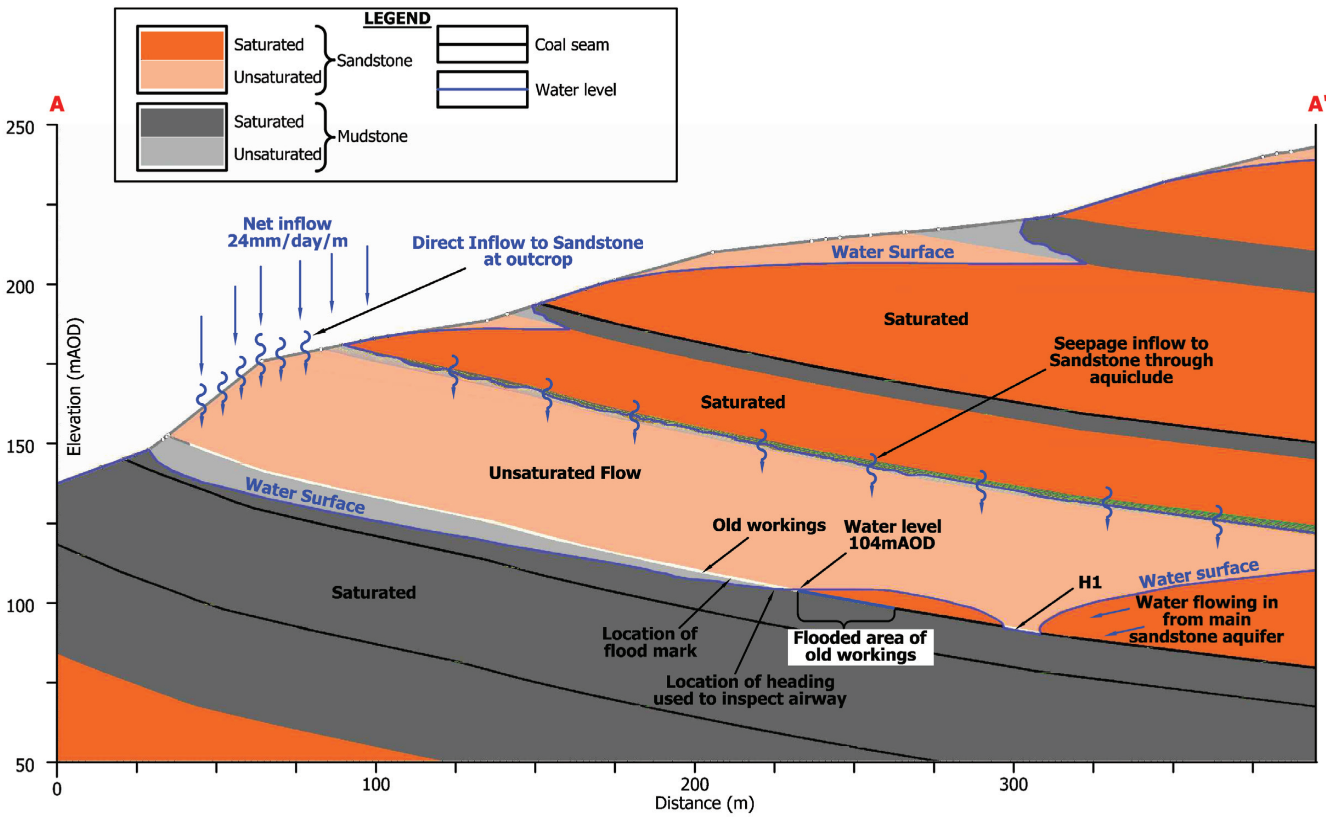

Figure 9. Cross section showing flooding (to c104mAOD) of old workings with a net inflow of 24mm/day/m of outcrop, and an approximate pumping rate of 870m³/day.

significant losses due to evapotranspiration from the vegetation and direct runoff. In South Wales in general, only two thirds of the rainfall will infiltrate (Robins, 2008). As evapotranspiration is much higher in summer than winter, there would be a greater loss in summer than winter (the incident occurred before leaf fall had started, so transpiration losses would still be significant). The rainfall data for the Pontardawe-Ystalyfera-Crynant area, in the first half of September 2011 varied between 0-16mm/day, averaging about 3.5mm/day. Actual infiltration at this time of the year could have been less than 2mm/day.

As a check of the reasonableness of the parameters used, the computed inflow into the combined 205m length of strike heading (Heading H1 and a panel to the west of the Conveyor drift) would have been from 650 to 870m^3/day. This is in accord with the known maximum pumping rate from the sump of 1,100m^3/day. Raising the permeability of the sandstone to 1x10^{-4}m/s gives flow rates an order of magnitude higher, which would have flooded the mine. Lowering the permeability to 1x10^{-6}m/s gives flow rates much lower than observed. It is noticeable that the majority of the water (some 600m^3/day) flows in from the down dip direction and not from the old workings up dip.

Water levels in the mine workings would therefore vary according to the variation in inflow rate. Comparison of flows visible in sundry HSE photographs taken at various dates during the investigations, showed that flow rates down the Top Heading could vary rapidly. The high flows (which appear to be as high as 20l/s) on 21st September 2011 seem to have occurred a day after a period of heavy rain. Low flows on 5th October 2011 were after a period of dryer weather (although it was raining heavily on that day).

This analysis shows that, with drainage via Heading H1, water levels in the old workings could vary substantially depending on the inflow rate. It should be emphasised this is not proof that this did happen (the available data is far too sparse for this). However, it is likely that heading H1 did have such an effect on water levels in the 1983/84 workings. Therefore what the manager said he saw is credible. The influence of H1 would depend on its length adjacent to the old workings, so could be expected to increase from October 2010 to September 2011. Consequently any observations on what the water levels in this area of old workings were before H1 was excavated would not be valid for the situation in September 2011. Further, more extensive workings than shown on the mine plan were indicated by several witnesses to be present in the corner of ground between H1 and the Conveyor drift (see Figure 3). (When these workings were excavated and who by was never established.) These will have increased the effectiveness of the flow path.

Flooding at various times

An estimate of what water levels may have been at various significant times between 2003 and September 2011 is shown on Figures 10 to 13.

When workings were taking place to the east from 1997 to 2003, water was pumped into the old 1984 workings, from whence it decanted into the old drainage sough (Figure 10) of the Ynysmudw watercourse. Water levels in the 1984 workings would consequently have been about the flood mark observed. In 2003, there was no down dip passage into which the water could flow. But, with the advance of the down dip strike heading H1 in 2005, the hydrogeological regime changed. After the driving of H1, the water had somewhere to go, and at least partial drainage of the 1984 workings could have occurred, as shown in Figure 11. When the mine was mothballed in 2005 and allowed to flood, water levels would again have risen to the level of the flood mark observed in the 1984 workings (see Figure 12). From 2010 to 2011, with renewed pumping and driving forward of H1 and at least one crossheading 20-30m updip, drainage of the 1984 workings would again be possible, leading to the situation shown in Figure 13, which is consistent with what the manager claimed to have observed.

Sources Of The Water

Volumes of water involved in the inrush

In order to assess where the water that flooded the old workings may have come from, it is necessary to make an assessment of the actual volumes of water involved. When making these calculations, it is only necessary to consider the worked seam thickness. This is because, although the roadways were excavated to a deeper level (1.6m or so), the waste from these excavations was deposited alongside in the old workings, thus making no overall change in the volume.

In flooded old workings to high water mark

Owing to the lack of level data in the area involved it is very difficult to quantify the actual volume of water that could have been present in the flooded old workings. The actual extent of the workings, the thickness of the seam worked and the amount of compression due to roof subsidence are also unknown - adding to the uncertainty. The author's best estimate (on the basis of such measurements as are available) was 1,560m^3.

In flooded mine after the inrush

Computing the volume of water required to cause the observed flood consequent on the inrush is also complicated. Only the lines of headings were surveyed. The actual extents of coal extraction on either side were not surveyed in detail (seldom being accessible to the surveyors). Although a flood line was observed in H1, its level was not surveyed. Data on the thickness of the coal was also sparse. The author's best estimate was a volume of 1,550m^3 (again on the basis of such measurements as are available). That this is so close to the volume estimated to be available is fortuitous, as the number of assumptions that had to be made to generate both figures are considerable.

What these figures show is that the quantity of water involved is about two thirds of an Olympic swimming pool, significantly smaller than the 2,900m^3 estimated by the prosecution. It is less than a tenth of the quantity involved in the Knockshinnoch disaster, for example, and

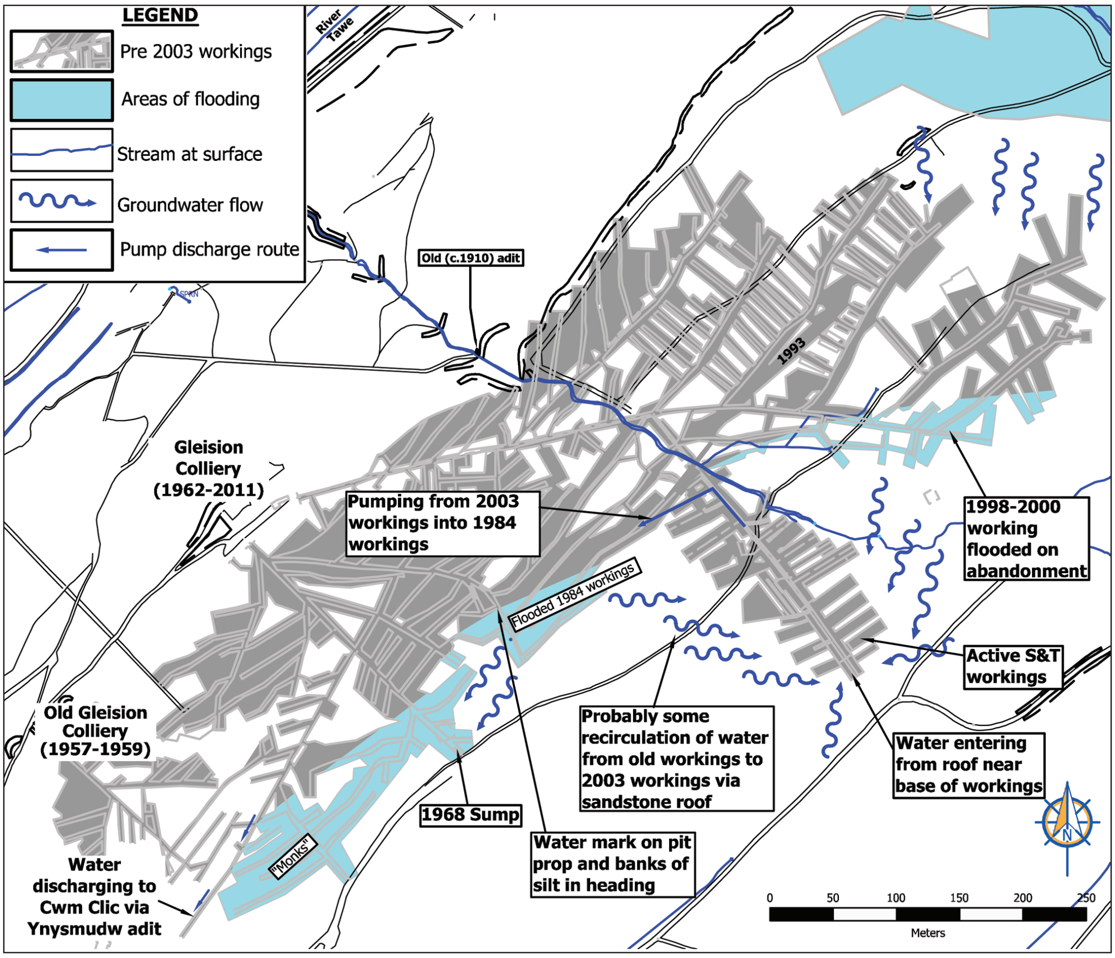

Figure 10. Water conditions in the mine during 2003 showing probable flooded areas and flow.

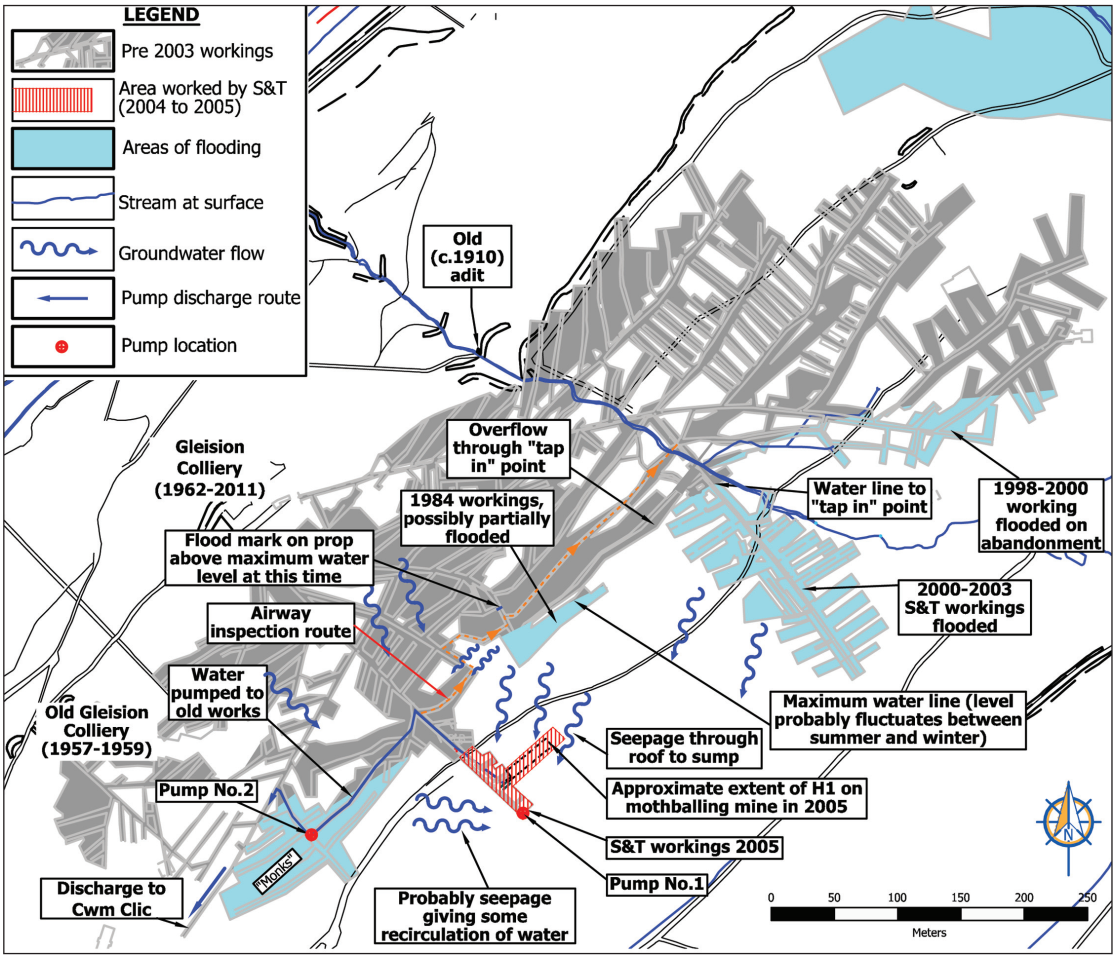

Figure 11. Water conditions in mine, 2004 to 2005.

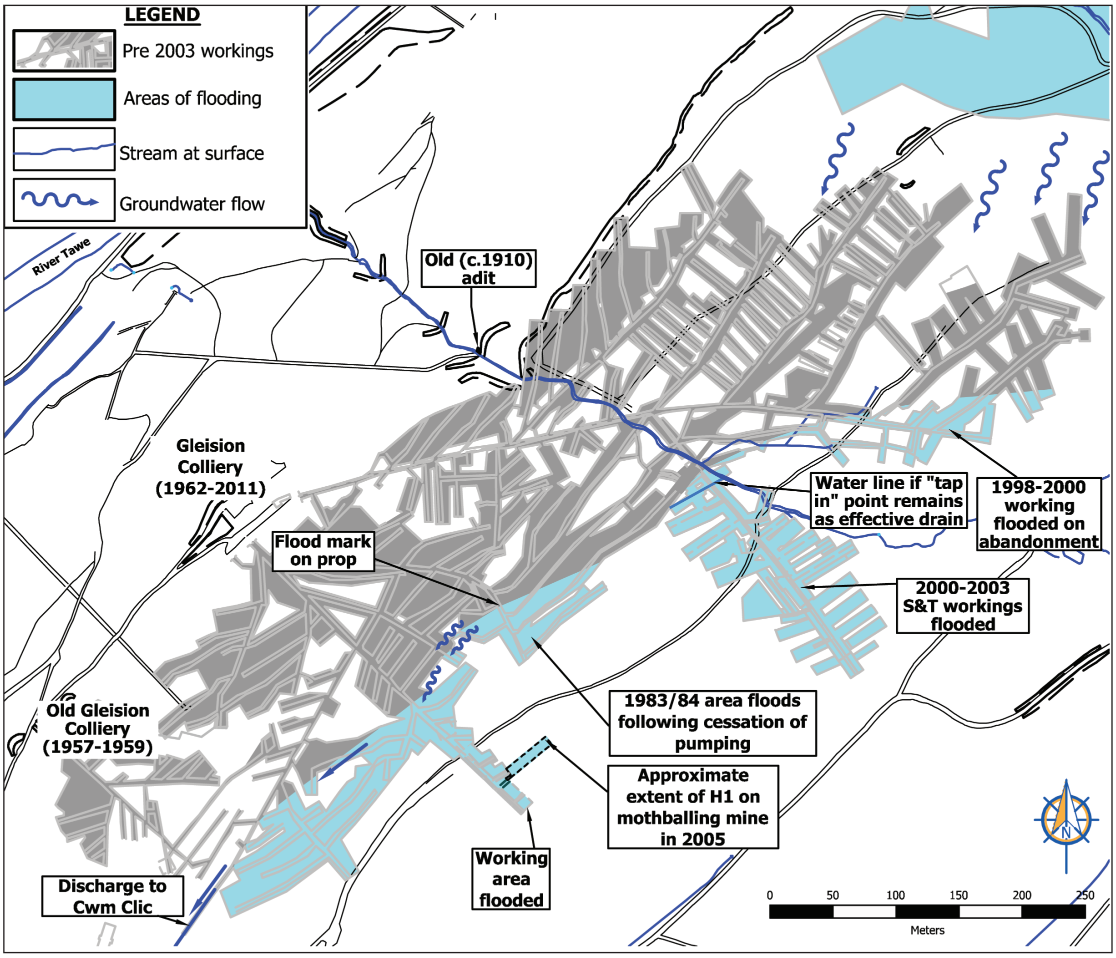

Figure 12. Water conditions on mothballing in 2005 to 2008.

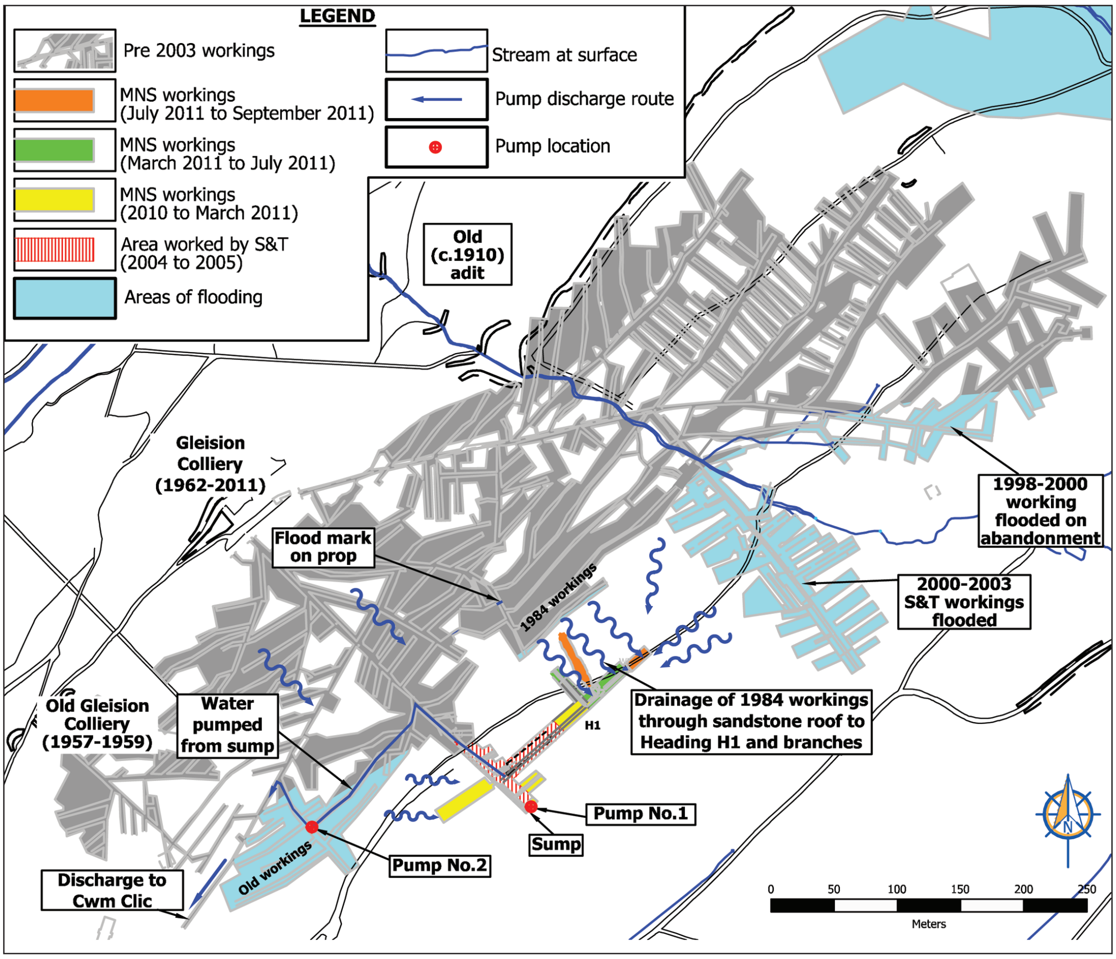

Figure 13. Water conditions August to early September 2011.

less than the 2,3000m³ involved in the Cynheidre inrush. That it had the effect it did was due to the restricted nature of the workings.

Potential sources of water

There are a number of sources that could have discharged the requisite 1,500m³ of water into the old workings in the period between when the manager observed the area on the Wednesday and 9:20am the following morning when the stall breached the old workings. These are considered in detail below.

Potential rainfall inflow over 24 hours

To provide sufficient water would require an inflow rate of some 20l/s. A video taken on 21st September 2011 shows a flow down the Top Road which is of the order of 20l/s (although no flow measurements were ever taken during the investigations). This, however was the day after a rainfall event of 13.6mm in a day. The rainfall the day before the incident was only 0.4mm. It is highly unlikely that the inflow from rainfall would have been high enough to cause the flood.

Collapse of pillars in 2000 to 2003 workings

Expulsion of water from flooded workings due to the collapse of those workings is a possible source of the required volume of water. Collapses of old mine workings years, decades or centuries after working are not uncommon. When one pillar collapses it places more stress on its neighbours, leading them to collapse in turn shortly afterwards, until the collapse zone meets some more substantial pillars or the edge of the workings.

Considering the flooded 2000 to 2003 S&T workings, the stability of many of the pillars are highly suspect, especially in the area shown in Figure14. The author computed the stability of the pillars using the empirical method of Salamon and Munro (1967), with the required adjustments to convert square to rectangular pillars given by Hsiung and Peng (1985) (rectangular pillars are weaker than square pillars of the same cross sectional area). The results showed many pillars with Factors of Safety below 1 (and therefore very likely to fail) and many more with a Factor of Safety less than 1.6 (which may fail eventually). The thick seatearth would also be liable to soften with prolonged exposure to water (Denby et al, 1982) permitting pit props to sink into the floor, removing any support they might give. (It is recorded that the roofs of at least two of the panels in the 2000 to 2003 workings collapsed whilst the pit props were still present, in one case while the equipment was still in the stall.)

Given that the average thickness of the workings in this area is 0.77m, to provide the pulse of 1,600m³ of water required to fill the 1983/84 workings to the flood mark, overnight, would require the collapse of some 2,000m² of roof. The pillars with Factors of Safety below 1 supported some 4,900m² of roof, so collapse of less than half this area would expel the necessary volume of

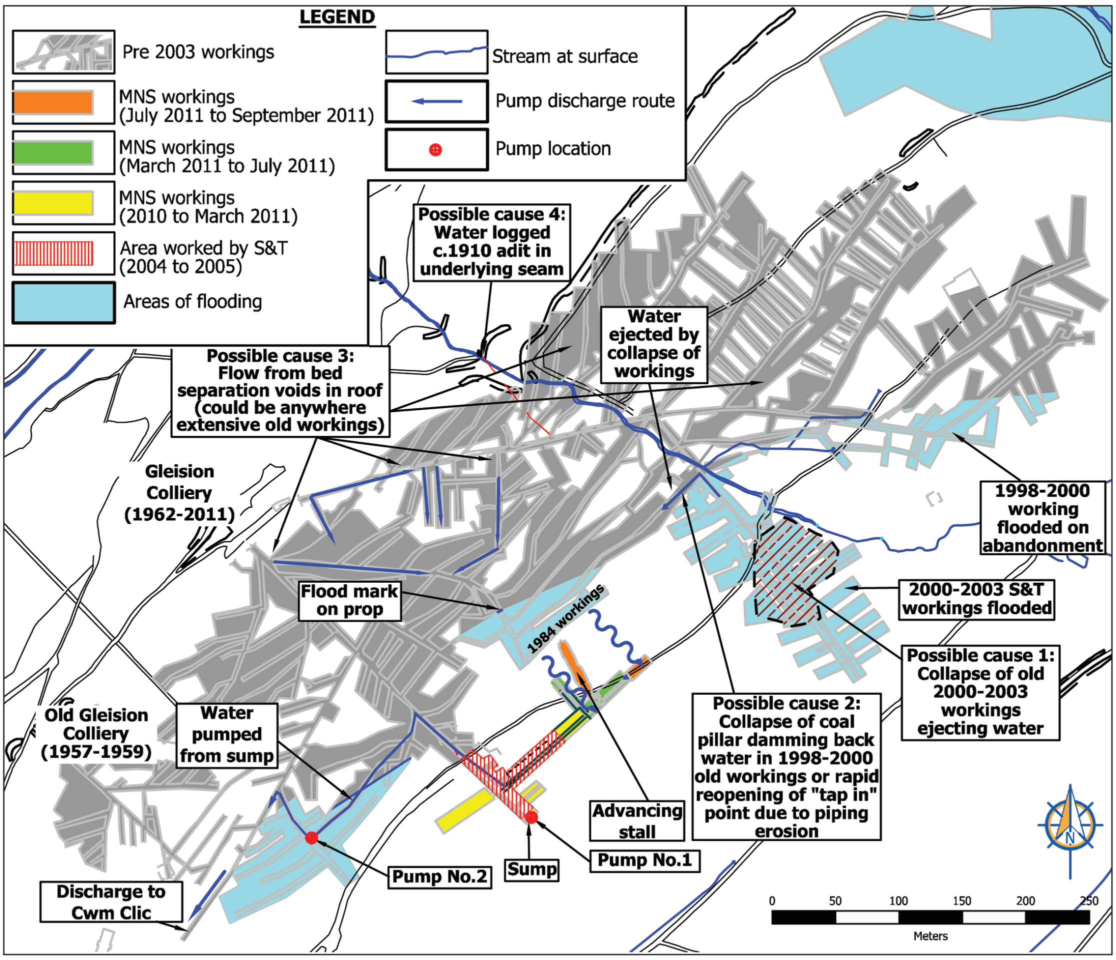

Figure 14. *Water conditions on 15th September 2011 and some possible sources of water to fill the 1984 workings overnight.*

water. The pillars with Factors of Safety between 1 and 1.6 supported a further 1,700m² of roof, with the potential to expel a further 1,300m³ of water.

The route the water would take would have been down the heading used to examine the air way in the years before 2008, into the Top Road below the area of the flood mark.

The collapse of these pillars might cause some movement at the ground surface. However, it would be very small; according to the NCB Subsidence Engineer's Handbook (Anon, 1975), it would be no more than 150mm in the centre of the depression. In a flat, grass field such movement might be noticeable, but on a rough hillside covered in thick brambles, movements of this magnitude would not be visible. (The author looked and the area is impassable due to undergrowth of scrub and brambles and the remains of the clear felling of the trees some years previously.)

Formation or collapse of debris dam in roadway

Small dams of debris were seen in the Top Road before its repair by the MRS, which covered the entire floor of the heading, and similar dams are probable in most of the other disused roadways in the mine. The dams seen in the Top Road, in themselves, would be incapable of holding back sufficient water to cause the flood. Small dams such as these could divert a stream of water into a different route by blocking the floor. Much larger dams than seen in the Top Road (which had been maintained until 2005 as an escape route) are however entirely feasible in the abandoned eastern areas. Collapse of such a dam could easily lead to a flood of the required proportions. No surface expression could be expected.

Water held in subsidence fissures in roof

Undermining of strong strata can lead to the formation of voids in those strata at a considerable height above the workings, by fissuring through the beds and delamination between beds. As noted by Whittaker and Reddish (1989), well-defined fracture lines occur at the edges of the extraction, with prominent bed separation. Whittaker and Reddish note that these bed separations could potentially close at a future date. They specifically note that the major separation 'could act as a temporary reservoir for water percolating from adjacent or overlying strata, and result in later release through interconnecting fractures to the working longwall'. Collapse of the roof of such voids would be one way the water could be expelled into the underlying workings.

The fractures passing up through the strata are narrow at the base and widen upwards. Thus the fractures that would be visible in the roof adjacent to the edge of the working (i.e. what would be visible at Gleision by the breach point) would not be particularly wide. Thus the absence of visible wide fissures in the small part of the Gleision mine roof that was examined by the HSE and police is no proof of the absence of such fractures elsewhere in the mine. Open fissures could certainly be seen 6m from the edge of the workings in the roof of a heading adjacent to the Top road. Indeed, clay appeared to be oozing from these fissures. The mine workings pass beneath a stream, so any extension of a fissure to ground surface in this area could lead to rapid inflow of water from the stream.

It should be emphasised that these voids could be anywhere above the mine workings in the eastern part of the mine. The water expelled from them would flow down to the area of the inrush. Thus the absence of fissures above the breach point is irrelevant. Owing to the widespread extraction of the coal in the pre-1994 parts of the mine, there is abundant scope for such voids to have been present above the roof at Gleision. Had the pillars in the old S&T workings already collapsed, then there would be a potential for such voids high in the roof strata in this area as well. Even assuming the void space was only on average 0.2m high, it would only need an area 90m by 90m to contain enough water. If the expulsion of water was due to further collapse of the roof, then some surface expression might be possible, although the amount would likely to be slight (150mm at most). As noted above, in a flat, grass field such movement might be noticeable, but on a rough steep hillside covered in thick brambles and trees, movements of this magnitude would not be detectable.

Unrecorded underlying mineworkings

There is another potential source of a rapid, unpredictable, influx of water, which is from underlying old mineworkings in the Pant Rhyd y Dwr seam below the No.2 Rhondda workings. A connection could be made by void migration upwards through the predominantly mudstone strata from one seam to another. As shown on Figure 3, there is an old adit which appears to date from about 1910 and from its position appears to be in the Pant Rhyd y Dwr seam, which is some 11m below the No.2 Rhondda. This adit is at about 145mAOD. Because of the strata dip, the mouth of the adit (and hence any potential head of water it would contain) is above the level of the majority of the workings in the No.2 Rhondda. Hence if a connection is established by void migration anywhere below the 145mAOD contour in the Gleision workings, there is a potential for water to flow from the Pant Rhyd y Dwr workings into the Gleision mine. The further down dip this connection is made, the greater the potential volume of water and speed at which it would flow. To establish whether or not such a connection exists would require examination of all potential inflow routes in to the base of the 1983/84 workings. There being no plans of the Pant Rhyd y Dwr workings, it is impossible to calculate how much water might be available. Unlike many of the old adits along the hillside, this adit was served by a tramway (it was probably associated with the sinking of the Tareni Colliery shafts) so a considerable output is at least possible.

Conclusions on alternative sources of water

There are at least three possible sources which could deliver significantly more than the required volume of water to the required place at the required time, viz: collapsing pillars in the S&T workings, collapse of a coal pillar holding back water in the eastern mine, inflow from subsidence induced bedding parallel voids and a possible fourth, connection by void migration from underlying workings. The water normally entering the 1983/84 old workings could drain out through the inclined sandstone roof down to Heading H1, but the influx of this quantity in a few hours would greatly exceed the drainage capacity. Predicting when any of these types of incident would occur, even if much more was known about the geometry and support of the mine than is the case, is not possible. There are far too many unknowns in the properties of the rocks. That such unpredictable incidents can happen was illustrated by the recent (9th/10th January 2016) inrush into the Lea Bailey Gold mine in the Forest of Dean (Needham, 2016)

The prosecution's theory, that the water had been in these workings for years, does not explain why the water level having been at a level of below 105mAOD in 2004/5 and again in 2008 (according to evidence of inspection of the airway shown on Figure 5), should rise by 3m even though drainage was improved by the drivage of Heading H1. That the water arrived due to one (or several) of the causes described above explains this anomaly, by providing a sufficient body of water over a few hours to raise the water level to the observed mark.

Evidence For Water Flows

Owing to the lack of investigation of the relevant areas at the time, the foregoing can only be speculative. However, there was some evidence which emerged indicating an unusual water flow from the east of the mine.

In evidence given for the prosecution, when one of the Mines Rescue teams was exploring down the Top Road looking for survivors, they found it flooded at a point about where the flood mark was subsequently observed.

Water could not have been there 4 hours earlier, as the manager had undoubtedly escaped up this route (there was no other way he could have gone). It can only have arrived after the incident.

This could indicate that a second pulse of water came from the same source as the one causing the overnight flooding. (It also casts doubt on whether the fresh flood mark observed in the Top Road by the HSE actually related to the water level in the Top Road prior to the incident or this flood observed by the Mines Rescue Service.)

Conclusions

The conclusion was that the statement of the manager was credible. He could have been in the old workings the day before and found them dry.

By a very unfortunate coincidence, the water could have arrived overnight from one or more sources.

After a three month trial, the jury took less than 2 hours to find him and the company not guilty.

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