# COAL MINING IN STRUCTURALLY COMPLEX GEOLOGICAL SETTINGS – EXAMPLES FROM SOUTH WALES AND SOUTH AMERICA

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## Abstract

Coal mining in areas of compressional thrust faulting can be an attractive proposition. Individual seams or sequences can often be repeated and stripping ratios are improved for attractive opencast mining. The situation in deep mines is not often so rosy. With increased rock and gas pressures, production is often hampered by hazard mitigation practices. The complexity of the structures and the features associated with them bring their own problems from those of correlation in the exploration phase, in the modelling and evaluation of resources, in the practicality of mining, in the quality of product and in safety. The structural features of a former open pit anthracite and deep underground mine in South West Wales are described along with their impacts on exploration, modelling, mining and coal quality. Examples of features from similar structural domains in other parts of the world have been reported. These are presented, along with some thoughts on a possible mechanism for coal mine outbursts.

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## Introduction

Complex structural geology within coal deposits is often the main factor causing difficult and hazardous mining situations. Within the United Kingdom, the most hazardous deep mine conditions are located in the west Wales anthracite belt, in the Gwendraeth Valley close to and north of Llanelli. Although deep mining almost ceased in the late 1980s, opencast mining has continued in the area. Typically, highly faulted and thrusted coal measures have caused not only complex mining operations, but have also resulted in underground mine gas outbursts. The flexibility of opencast mining methods can overcome difficult structural geology, while underground operations are not so lucky, with tragic consequences. During work both in the UK and overseas in the South Americas and Russia, the authors have documented analogue geologic settings from Colombia and make reference to similar problems experienced in underground and open cast mines in the Ukraine and Siberia, where complex geology has caused serious problems to the underground mining methods. Detailed examples are taken from Cynheidre deep mine near Five Roads, Ffos Las Opencast Mine near Trimsaran and El Cerrejón Opencast mine Colombia.

## Location and geological setting

The study area of the Gwendraeth Valley, South Wales is shown in Figure 1 and a detailed Geological model of the South Wales Coalfield is shown in Figure 2. The Gwendraeth Valley is on the western margin of the South Wales Coalfield, north of Llanelli. The El Cerrejón mine is located in the Gurajira Department of northeastern Colombia.

### *Ffos Las Opencast Site and Cynheidre Deep Mine*

The tectonic setting of the broadly synclinal South Wales Coalfield is critical to the understanding of mining hazards and how they can be mitigated. Jones (1991) suggests that the simple broad synclinal nature of the coalfield masks a more complex structural system. Thrusting of Variscan age is largely confined to the mudrock dominated, lower competence Lower and Middle Coal Measures and the central and northern coalfield is dominantly a fore-thrust system. However, along the south-crop a major back-thrust system is developed which in places penetrates the Upper Coal Measures. The south-crop shows features analogous with a mountain front in which pre-existing basement faults have facilitated uplift. The lack of thrusting within the competent, 'Pennant Sandstone'-dominated, Upper Coal Measures, in contrast to the underlying weaker Lower and Middle Coal Measures, suggests they have acted as a passive roof to the thrust system. Geographical variation in the intensity of the deformation can be related to the proximity and buttressing against the Caledonian massif of deformed Lower Palaeozoic rocks to the north of the coalfield. Although broadly analogous with current models of foreland basin development and deformation,

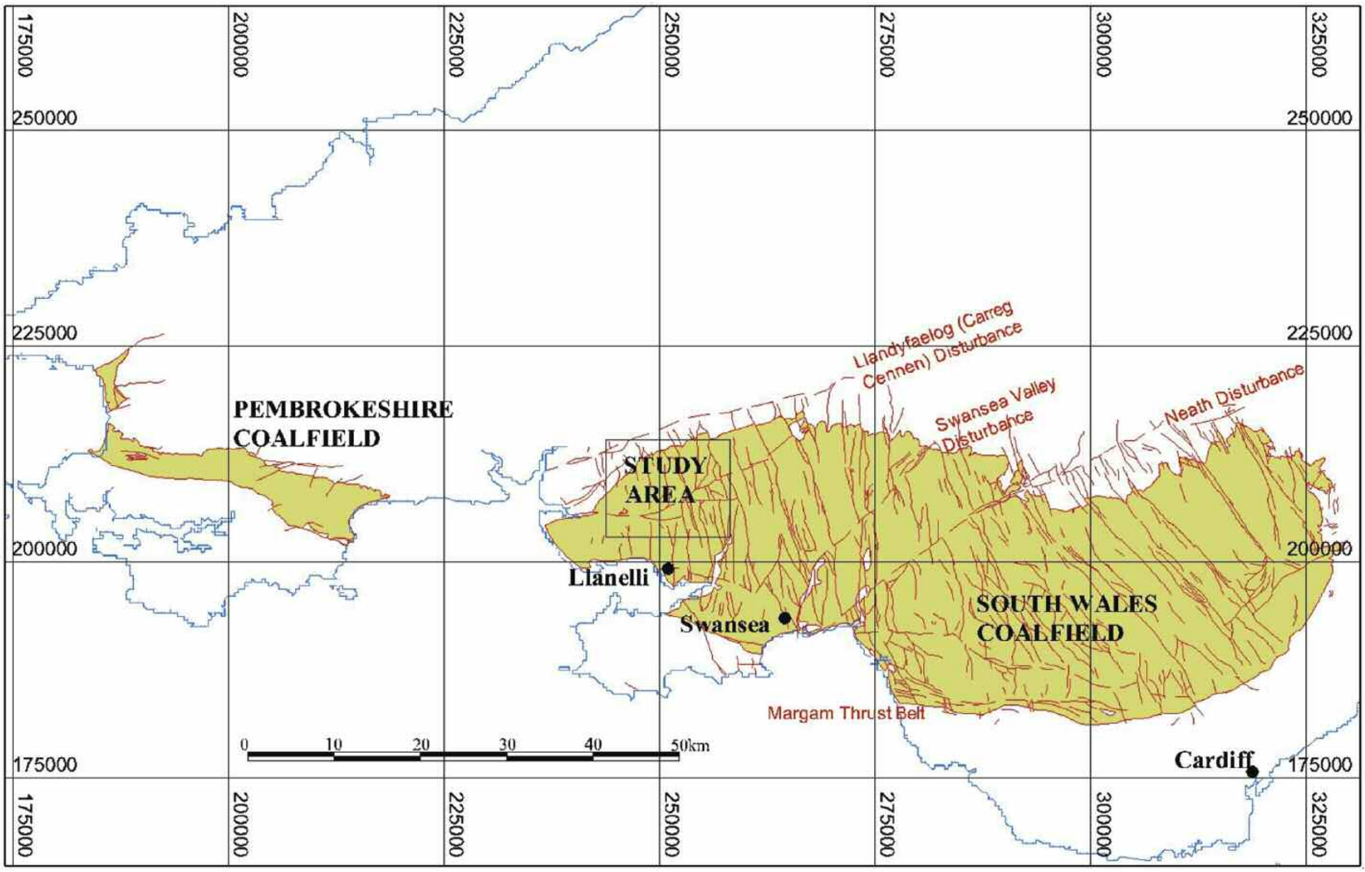


*__Figure 1.__ Location map of the study area around the Gwendraeth Valley, South Wales.*

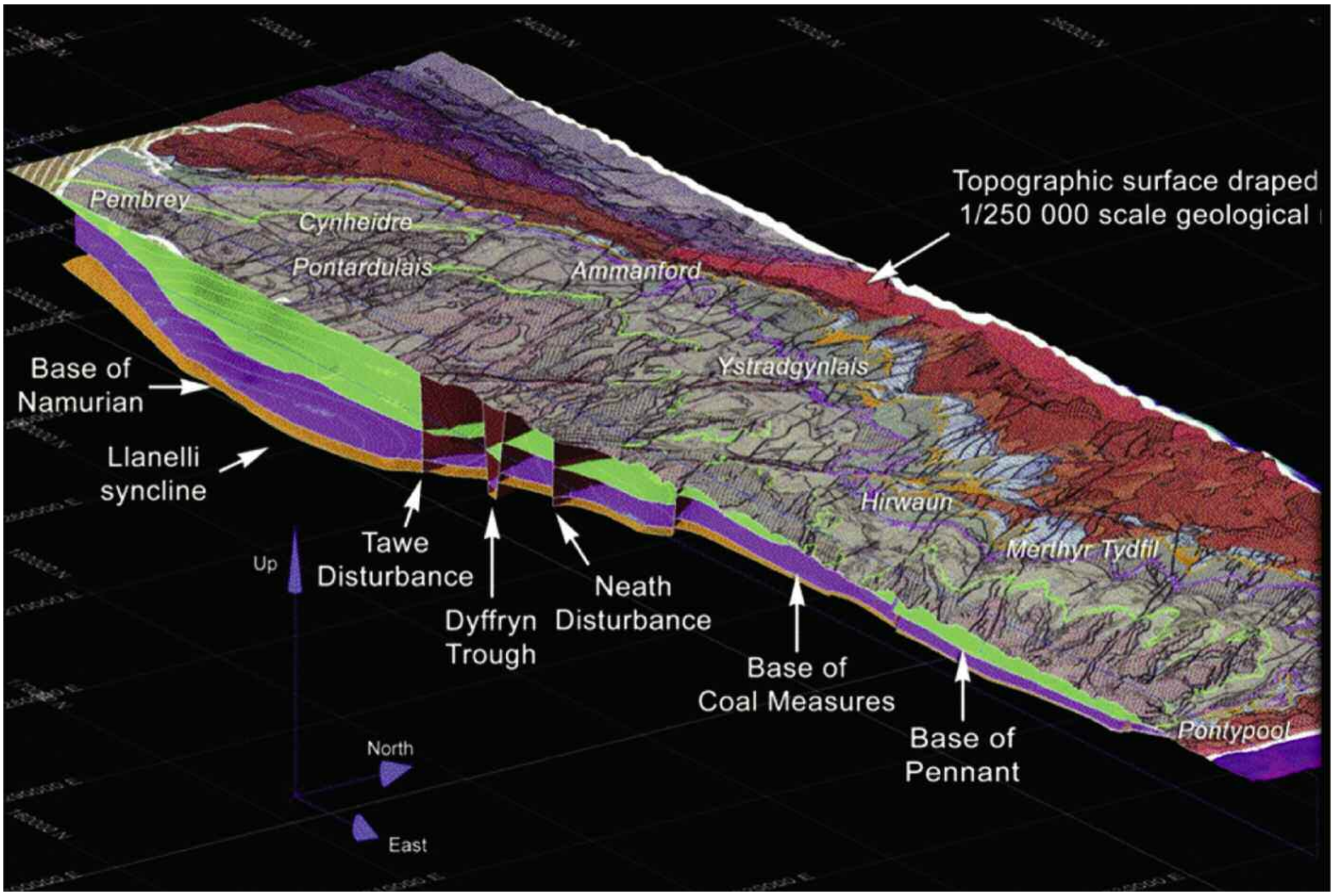


*__Figure 2.__ Vulcan 3-D geological model of the South Wales coalfield, draped with 1:250,000 scale geological map. Oblique W-E cross-section along National Grid 200000 N looking towards north-west. National Grid at 10Km spacing at –3000m elevation. Vertical exaggeration x 2.*

the South Wales coalfield demonstrates the importance of pre-existing massifs and lineaments in determining the precise evolution of an area.

The structure of the main productive Coal Measures within the anthracite zone in the western part of the South Wales coalfield was re-examined using data from operational opencast coal sites and British Coal deep mines data by Frodsham and Gayer (1997). They observed that Variscan thrusts and/or folds and bed-parallel shear structures are present within all of the sites studied. They noted that the complex disturbance zone at Ffos Las combines both E-W-trending folds and more variably oriented thrusts which together shorten the coal bearing strata by up to 2 km. They interpret this to be the major Variscan frontal thrust ramp in the extreme west of the coalfield. They further note that the Variscan compressional structures within South Wales Coalfield are not consistent with a simple thin-skinned thrust system.

The strain induced by deep-seated Variscan thrusts was distributed throughout much of the coal-bearing sequence by easy-slip deformation along weak, incompetent horizons or bedding planes rather than being localised along a single regional detachment, and additional thrusts present around the northern margin of the coal basin appear to have formed as isolated autochthonous structures. The inherent weakness of coal seams across South Wales is attributed to the presence of greatly increased fluid pressures, which would have been generated both by the maturing coal and by the influx of fluids along deep-seated disturbance zones (Figure 3).

The most extensively mined seams are located within the Westphalian A and B, notably the Big Vein and the Pumpquart seams (Figure 4). The most extensive workings in the Gwendraeth valley occur in the Big Vein and the Pumpquart seams. (Figures 5 and 6) The structure is dominated by thrusts, which locally disturb the coal at low angles and underground often are associated with coal gas outbursts. Figure 7 shows a cross section across an area of the Ffos Las Opencast site. The major mining hazards in the Gwendraeth Valley are associated with the thrusts.

### *El Cerrejón Open Pit Mine*

The Carbones del Cerrejón mine is located in the Gurajira Department of northeastern Colombia. It is the largest coal mine in Latin America with coal is produced from the Central Member of the Cerrejón Formation, a 900-1100 m thick Triassic to mid-Miocene repetitive sequence of banded siltstone, shale, lesser sandstone, thin carbonates with numerous coal seams distributed throughout and along the stratigraphic sequence. Although lacking in distinctive marker beds the Cerrejón Formation has been divided into three Members on the basis of the distribution and thickness of the coal seams with the productive Central Member containing up to 60 coal seams with an average thickness of 3.8 metres. There are around 40 economically recoverable seams, and current production is centred on those ranging from 700mm to 10m thick. The coal mined is low-ash, low-sulphur, non-caking bituminous coal that is suitable for power station fuel and for pulverised fuel injection (PFI) in steel-making.

Deposition within the César-Rancheria basin which hosts the Cerrejón Formation is considered to have begun in the Tertiary whilst the continents of North and South America separated and developed into a back-arc setting that, with accretion of the Western Cordillera in late Maastrichtian to early Eocene, created a pre-Andean foreland basin in which the coal beds formed, with deposition terminated by early to mid-Eocene deformation. Accretion of the Western Cordillera in the

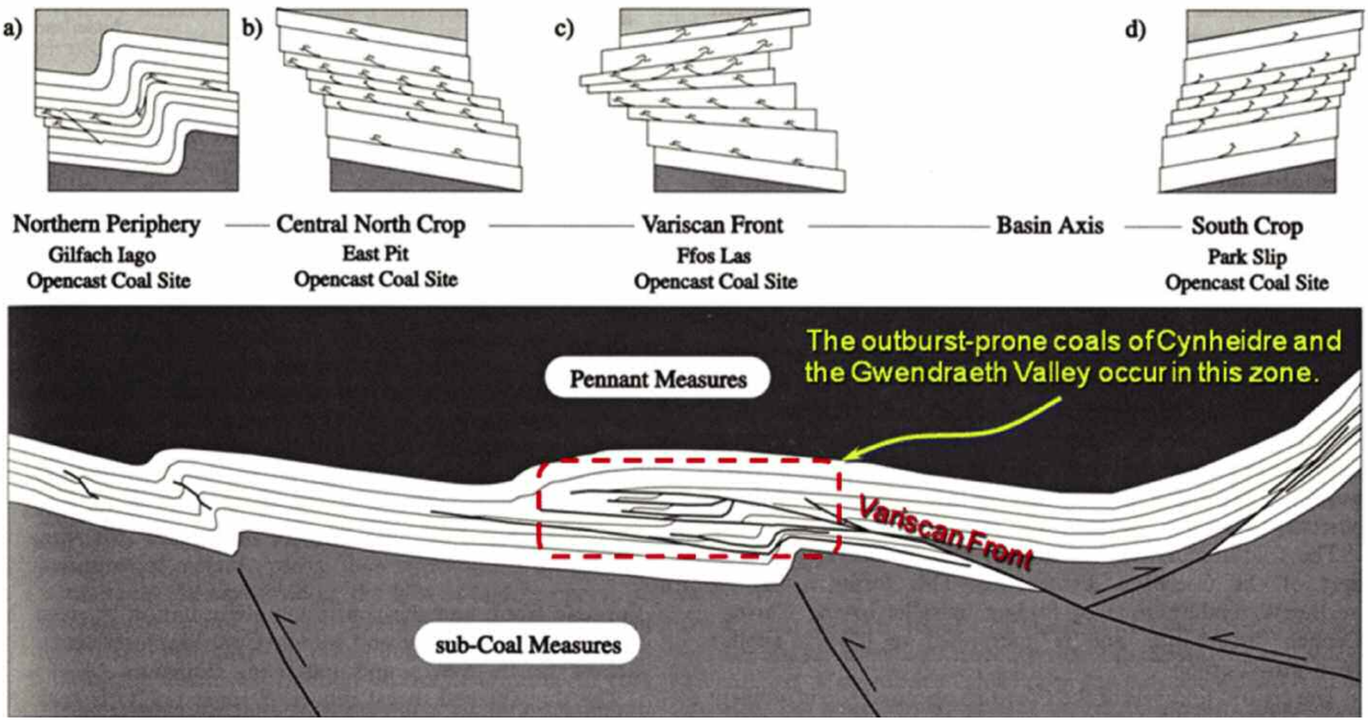


***Figure 3.*** *Schematic structural section of South Wales coalfield showing most intense thrusts and detachments occurring within the lower productive Coal Measures in the vicinity of the Variscan front (adapted from Frodsham and Gayer, 1997).*

late Maastrichtian to early Eocene created a pre-Andean foreland basin in which a coal-rich alluvial plain, coastal plain and estuarine sediments accumulated. Sedimentation was only terminated by early to mid-Eocene deformation. The major principal stress direction across this part of the South American plate was in a northwest – southeast direction leading to a dominant northwest tectonic transport direction. A cross section is shown across the mining lease (Figure 8). The compressional regime, although much younger in age than that described in the Gwendraeth Valley, shows almost identical structural complexity.

The basin is bounded by the east west striking Oca Fault to the north, by the crystalline basement of the Sierra Nevada de Santa Marta massif to the northwest, by the Mesozoic sediments of the Perija Mountains to the southeast and by a system of large faults to the west. The typical regional structure of the basin is of SE and NW dipping thrust sheets which are broken up by E-W and NW-SE striking steeply dipping strike-slip/normal and reverse faults. Broad open folds occur between the large thrust faults. Strata within the César-Rancheria basin have an average dip of about 15° to the southeast. Thrusts have produced repetition of the coal bearing strata at the Cerrejón mine and seams are typically affected by small displacement of less than 10 metres. The geological complexity is considered to be moderate.

## MINING HAZARDS

Although underground mining has ceased, the records, information and knowledge from the Gwendraeth Valley are important in the understanding of the causes of outbursts and their management (Jackson, 1984;

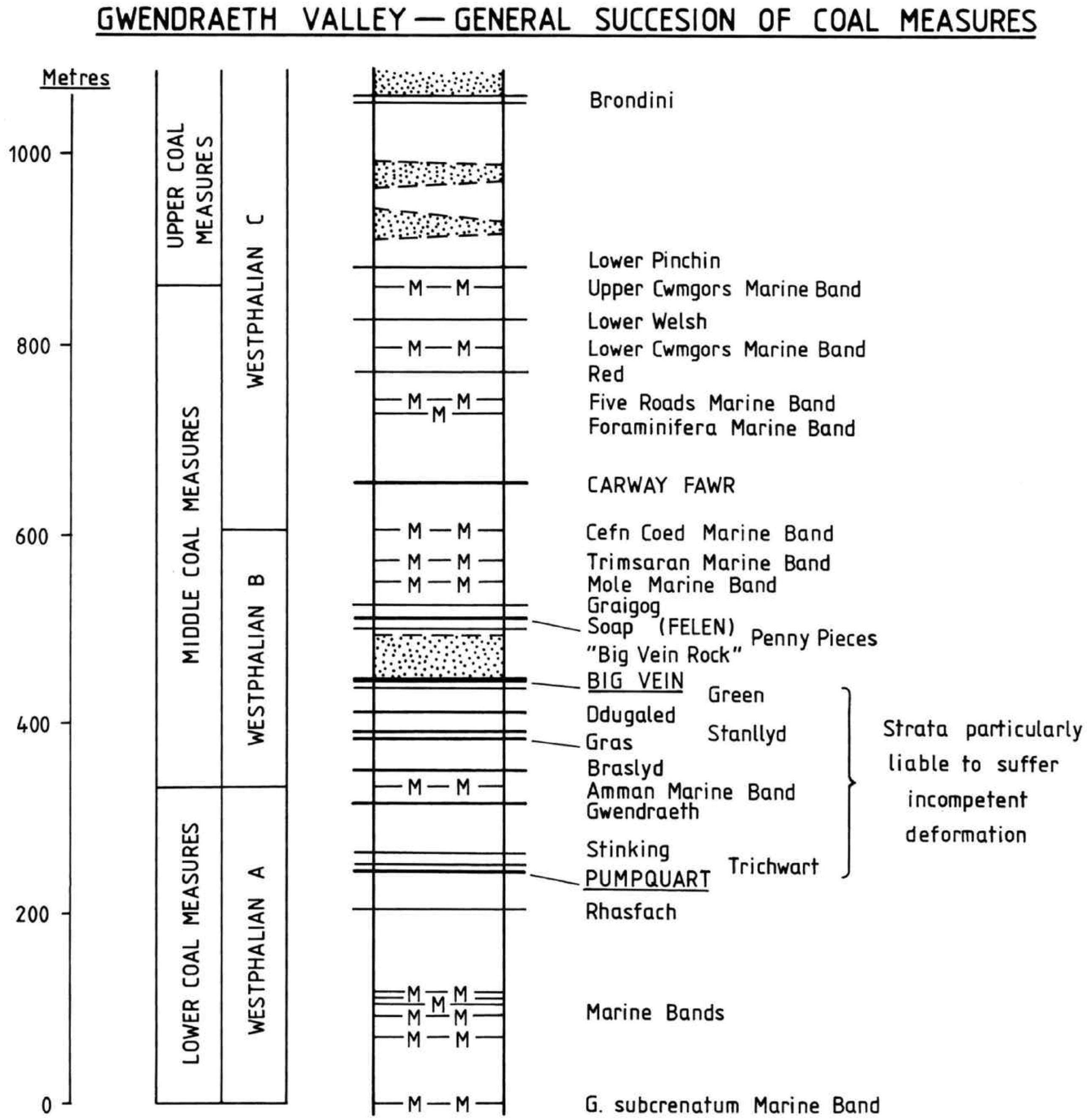


**Figure 4.** *Generalised vertical succession of the Coal Measures in the Gwendraeth Valley, South Wales (after Dumpleton, 1990).*

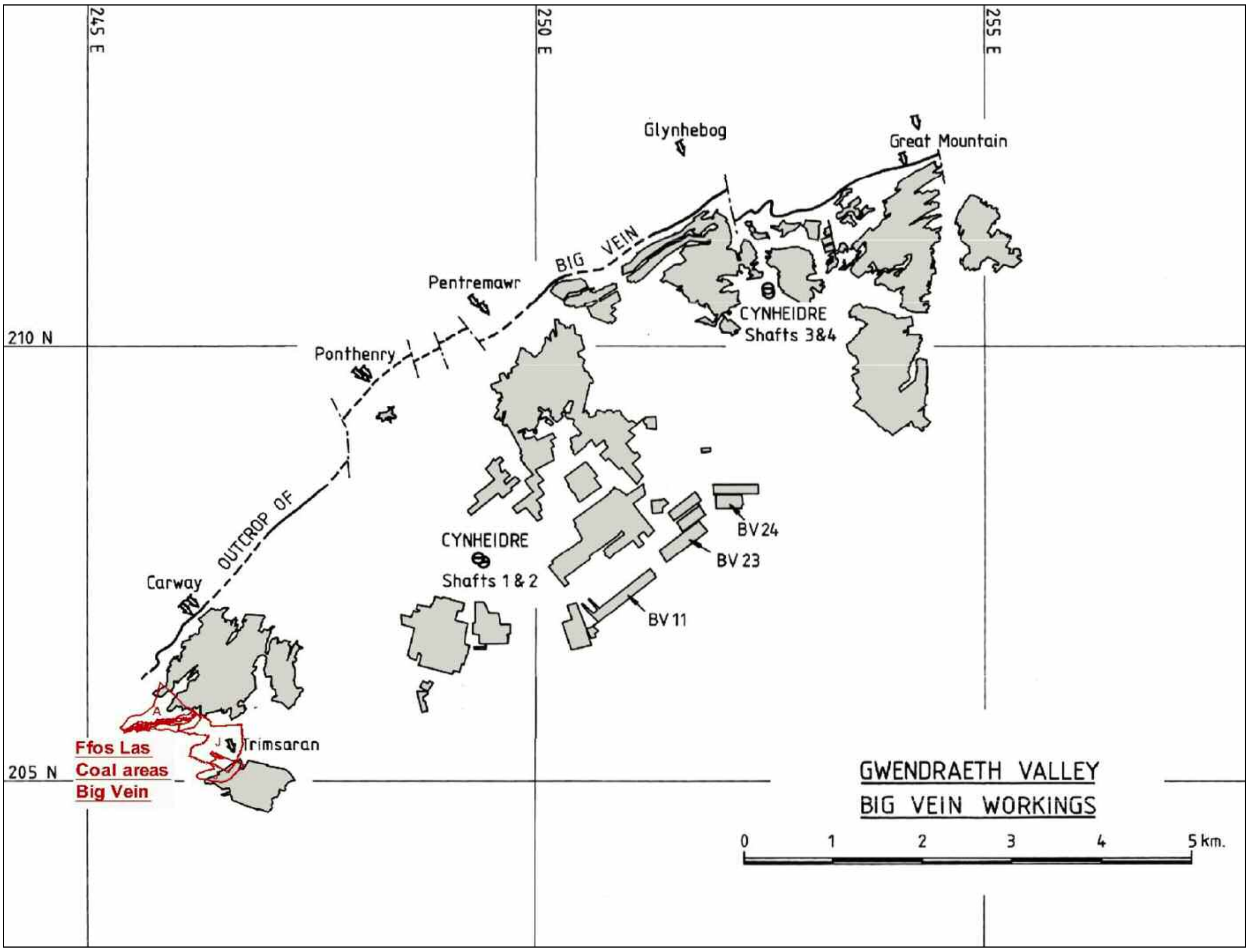


***Figure 5.*** *Underground workings in the Big Vein coal seam (after Dumpleton, 1990).*

Dumpleton, 1990). Further experience gathered from international projects have allowed comparisons to be made and knowledge shared.

Spontaneous outbursts of coal and gas are a major hazard to coal mining in many parts of the world. Typically, up to several hundred tonnes of powdery coal and thousands of cubic metres of either methane, carbon dioxide or mixtures of both are expelled with some force over a period of a few seconds from a heading or working face and fill the surrounding mine roadways for many metres. Mine personnel in the vicinity may be asphyxiated by the dust and gases, buried beneath the outburst material or crushed by mining equipment. Explosions of gases may occur after the outburst, ignited by sparks from damaged equipment. Production will invariably be disrupted for days or even weeks. In the worst cases, the mine may have to be closed (Jackson, 1984).

## Gwendraeth Valley outbursts and Cynheidre Colliery

During the history of underground mining in the Gwendraeth Valley there were nine collieries producing high rank anthracite. From 1913 to 1985 there were 226 outbursts recorded and tragically 27 miners were killed. Figure 9 shows the aftermath of an outburst at Cynheidre Colliery in 1971. Approximately 400 tonnes of coal was pulverised and ejected with 57,000 m3 of firedamp. The gas emission curve (Figure 10) shows that, in addition to the asphyxiation hazard arising from the sudden ejection of methane and coal dust, there is a significant risk of a major explosion, when the gas concentration is waning after the outburst event and passes through the explosive mixture range of 15.5% - 5.5%.

## Factors contributing to outbursts in South Wales

Much work has been done globally into the cause of outbursts, with the major common factors from the list collated from the Gwendraeth Valley and adjacent anthracite belt in South Wales being:

- Geological disturbance. Some type of disturbance (folding, faulting, thrusting or shearing, particularly in the coal seam itself) always appears to be present at or close to the site of an outburst. Dumpleton (1990) noted that undisturbed coal, particularly where the coal bedding could still be observed, appeared not to be outburst-prone.
- Coal rank. In South Wales, outbursts are only known in the highest rank anthracites.

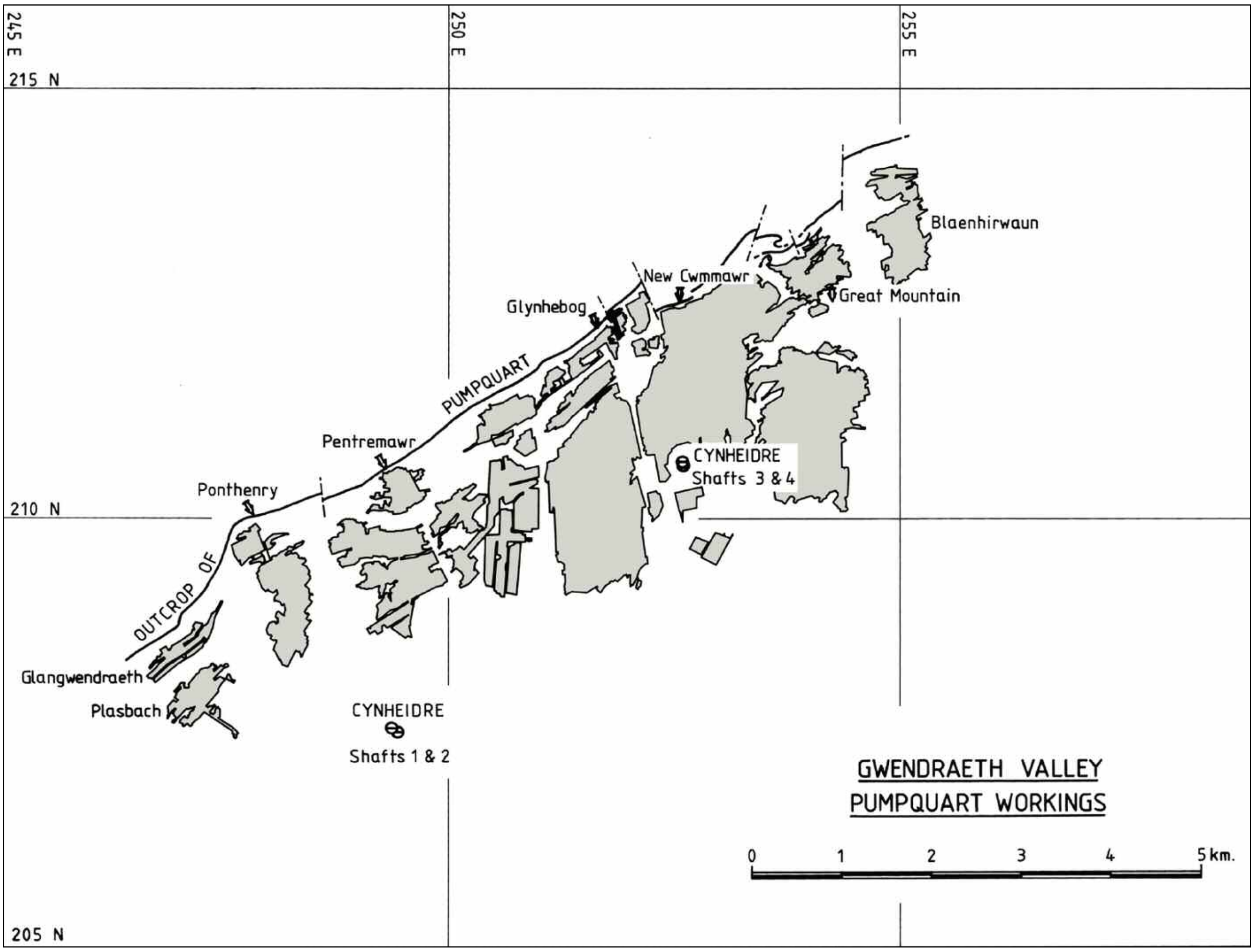


***Figure 6.*** *Underground workings in the Pumpquart coal seam (after Dumpleton, 1990).*

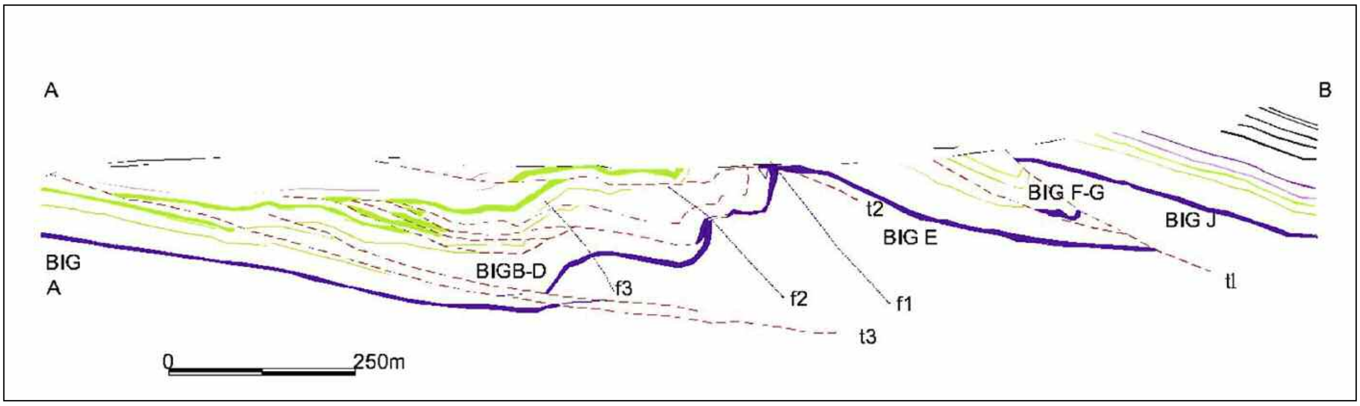


***Figure 7.*** *Cross-section across Ffos Las opencast site illustrating thrusted disturbance of the Big Vein coal seam.*

- Depth of working. There appears to be a threshold depth of working (approx. 200 m - 600 m) below which outbursts start to occur (Dumpleton, 1990).
- Presence of gas. No methane = no outbursts. The Pembrokeshire coalfield, although containing intensely disturbed, high-rank anthracites, has relatively low methane concentrations and no outbursts were ever recorded from the mine workings.
- Stratigraphic control. No outbursts recorded from above the stratigraphic horizon of the Big Vein.
- Mining layout and induced stresses. Some outbursts are deliberately induced, e.g. by shot-firing between production shifts.
- Rate of coal extraction. Rapid coal extraction (e.g. by modern mechanised longwall methods) may not allow time for the coal to degas passively and an outburst may occur if a pre-existing outburst-prone zone is present.

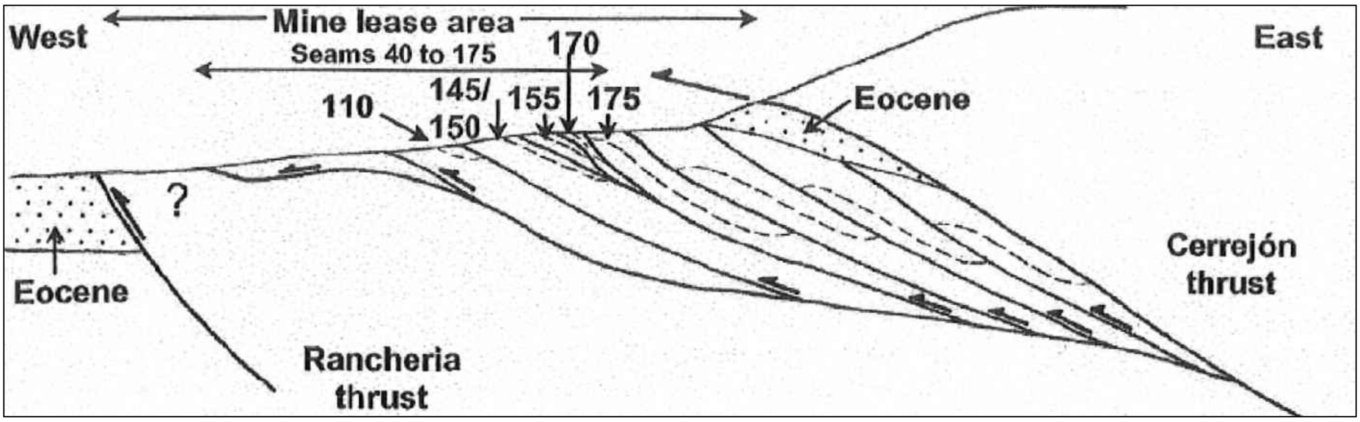


***Figure 8.*** *Diagrammatic cross-section across the El Cerrejón mine lease, Colombia.*

In the Gwendraeth Valley area, variability in the confined stresses controlled by break-back thrusting is a factor contributing to the presence of outburst zones. At Ffos Las opencast site, the Big Vein coal seam is overlain by a significant sandstone horizon, the Big Vein Rock. Although at Ffos Las opencast site, the Big Vein Rock was highly disturbed, at the nearby Cynheidre Colliery the sandstone was generally very strong and competent and appears to have exerted a stratigraphic control on the upward propagation of thrusts. Consequently, many (often small-scale) compressional features such thrusts and folds appear as incompetent deformation structures in the stratigraphic zone below the Big Vein Rock, particularly in the weak mud-rocks and the coal seams themselves (Archer, 1968). The Big Vein Rock also has a locally low gas permeability, limiting gas migration and dispersal.

It would therefore appear that the Big Vein Rock acts as a barrier 'locking in' the confining stresses and gas pressures in the relatively incompetent and low-permeability strata below, awaiting mining operations to disturb the equilibrium, relieving the excess pressures and releasing the gas in an outburst. From observations of outburst sites in collieries in the Gwendraeth Valley, it is fairly certain that disturbed, highly sheared coal has to be present; outbursts do not appear to have occurred where the coal is strong and intact.

In the South Wales coalfield, outbursts only occur in the highest rank anthracites. These coals possess a pseudo-graphite macro-molecular structure, with intra-molecular space capable of sorbing excess methane under the lithostatic pressures and geothermal gradients associated with rapid and deep coal basin burial, diagenesis and resultant rapid increase in coal rank. This sorption is further enhanced by the increase of surface area available in a zone of highly sheared coal. When mine workings encounter such a zone, the pressure is relieved and the gas can desorb rapidly, in extreme cases resulting in an outburst. The already sheared coal is in a powdered, friable state and becomes fluidised by the rapidly desorbing gas, ejecting it into the mine opening (Figure 9). Thus, outburst zones can be seen as true geological phenomena: patches of mechanically degraded, highly sheared coal, resulting from the Variscan deformation,'lying in wait' for the unwary miner.

Elsewhere in the South Wales coalfield, e.g. along the south crop, areas of intense deformation are present, but outbursts do not occur; the coal rank is not high enough to generate the pseudo-graphite structure and gas sorption/desorption capabilities. In the geographically and geologically separate Pembrokeshire coalfield, the coals are the highest rank anthracites in South Wales, and the Variscan disturbances and sheared coal zones are intense. However very little gas was encountered; indeed naked light illumination was permitted in some of the mines, and no outbursts were ever recorded. This is thought to be due to the shallow nature of the Pembrokeshire coalfield; post-Variscan uplift has allowed just about all the gases to escape.

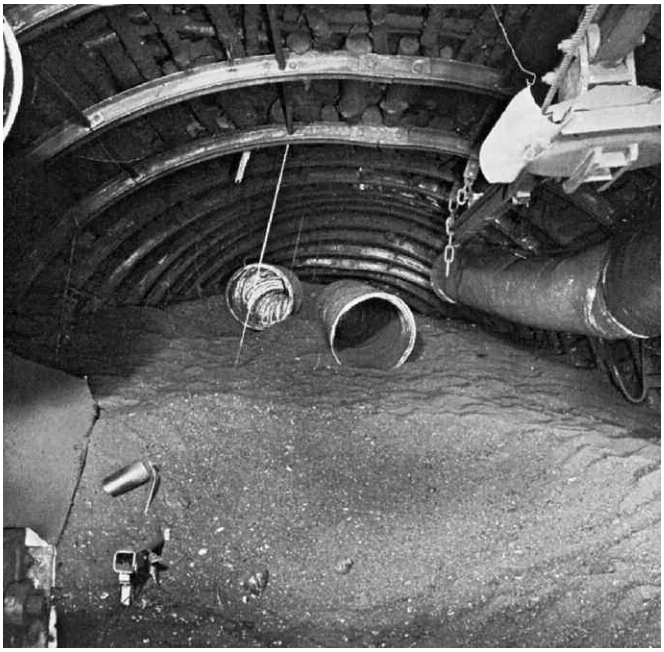

***Figure 9.*** *Aftermath of the fatal outburst at Cynheidre Colliery on 6th April 1971. The main intake drivage is completely filled with the outburst debris (mainly finely powdered coal) for a distance of 30 m from the origin of the outburst. Photo taken from Marshall (1971).*

Figure 11 shows diagrammatically thrust duplex structures encountered at Cynheidre Colliery in the floor strata below the Big Vein. A *décollement* along the base of the Big Vein Rock forms the near-horizontal duplex roof thrust. The thrust duplexes bring sandstone wedges into the working section, resulting in higher incidence of frictional sparking from coal cutting machinery and therefore a high risk of ignition of any methane which may be present. In an outburst situation, this could have catastrophic results.

Two major methods were developed to try and predict the likelihood of outbursts at Cynheidre Coliery: (a) micro-seismic monitoring from surface geophones, and (b) coal seam fracture analysis and mapping, based on direct underground observation. A surface geophone network was linked to the mining control room at Cynheidre and enabled micro-seismic activity due to shot-firing, ground movement and outbursts to be recorded (Styles *et al.*, 1988). Outburst and outburst precursive activity was identified by a recognisable pattern of emergent and decaying micro-seismic events, interpreted as harmonic tremor generated by gas migration through strata with associated propagation of fractures. Based on monitoring prior to an actual recorded outburst, an intensity of 80 precursive events per hour was deemed to be the threshold at which a warning alarm was generated. At 100 precursive events per hour, production was halted until the intensity returned to sub-threshold levels. The areal spread of surface geophones enabled the locations of the micro-seismic events to be deduced with reasonable accuracy, although higher resolution of the location of potential outburst zones was provided by the fracture mapping method developed by Dumpleton (1990). The micro-seismic monitoring system worked well up until colliery closure in 1989. Similar systems are installed in the collieries of the Donbas and Lenin-Kuznetsk basins of Ukraine and Russia.

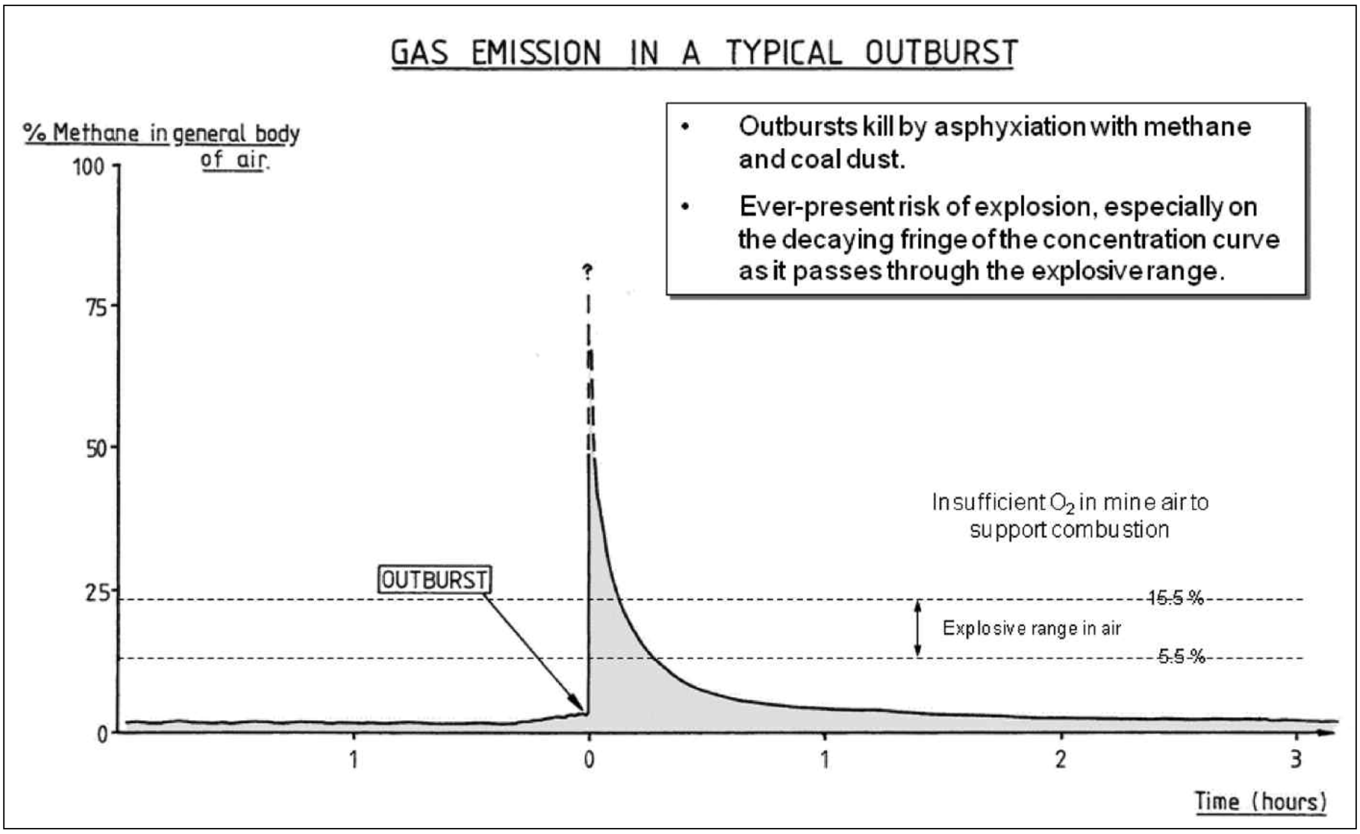


***Figure 10.*** *Time and gas emission profile of a typical Gwendraeth Valley outburst (after Dumpleton, 1990).*

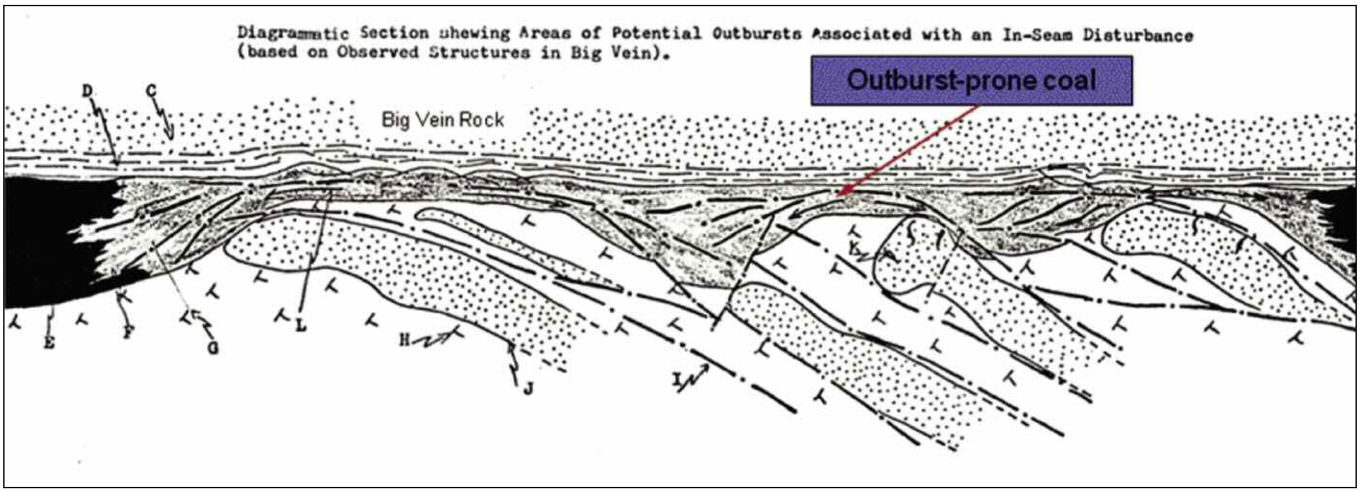


***Figure 11.*** *Diagrammatic longwall face section showing in-seam disturbances leading to potential outburst conditions at Cynheidre Colliery (after Godden,1983. Unpublished PhD Thesis, University of Wales, Cardiff).*

A coal fracture intensity index as an indicator of outburst-prone coal was developed at Cynheidre in the mid-1980s by Dumpleton (1990). Systematic recording and mapping of the coal seam fracture intensity was carried out in development drivages and longwall face exposures. Figure 12 illustrates the method of determining the Fracture Index which could be carried out using simple equipment (a 1 metre-long wood measuring lath).

Based on observations at, and in the vicinity of, an actual outburst site on a longwall face (BV24), a fracture index of >20 was deemed to indicate outburst-prone coal. Weekly mapping was carried out at a sample spacing of 10-15 m, both along the coal face and at a similar distance of face advance. The method successfully enabled the location of high risk zones to be identified, corroborated by the occurrences of two further induced outbursts on the BV24 face. Similar mapping on the adjacent BV23 face identified a further high risk zone, in which a spontaneous (or possibly shearer-induced) outburst occurred (Figure 13).

Developed in parallel with the Fracture Index, a coal Bedding Code Index was developed. This consisted of a qualitative assessment of the state and persistence of bedding planes in the coal seam (Figure 14). Increased fracturing progressively destroys the visible coal bedding, with the complete absence of bedding deemed to indicate outburst-prone coal. The advantage of the Bedding Code Index was that observations could be readily made by non-specialist colliery personnel, on a daily basis if necessary, thus providing extra data in between visits by the mine geologist. The correlation between Fracture Index and Bedding Code mapping was found to be good (Figure 15).

At the time of these outbursts on Cynheidre panels BV24 and BV23, great effort was undertaken to apply both Fracture Index and Bedding Code Index mapping coupled with micro-seismic monitoring. The former direct observation method complements the latter remote-sensing method. The authors believe that this is one of the more robust ways to monitor and manage the risk of outbursts, given their often sudden and hazardous nature. The following points were essential to reduce the risks when mining in outburst-prone regions.

**1**. Stringent adherence to the local Outburst Code of Practice:
   - Prohibits heading advance other than by boring and firing in between shifts.
   - Pneumatic picks prohibited for coal-getting (vibration from this type of equipment is thought to possibly increase the risk of triggering an outburst).
   - Limitations on rate of advance of longwall faces (gives time for coal to degas passively).

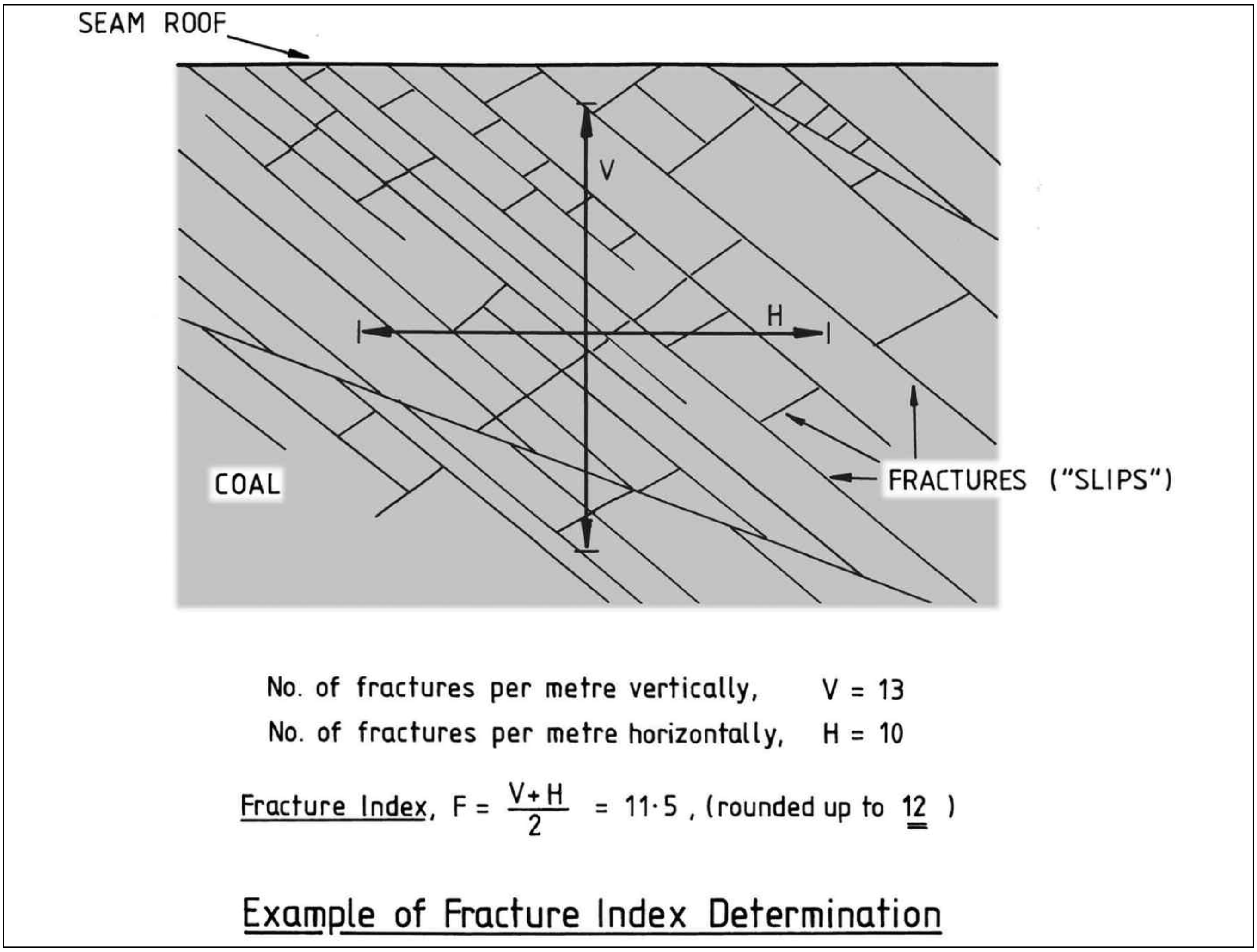


***Figure 12.*** *Fracture mapping index (after Dumpleton, 1990).*

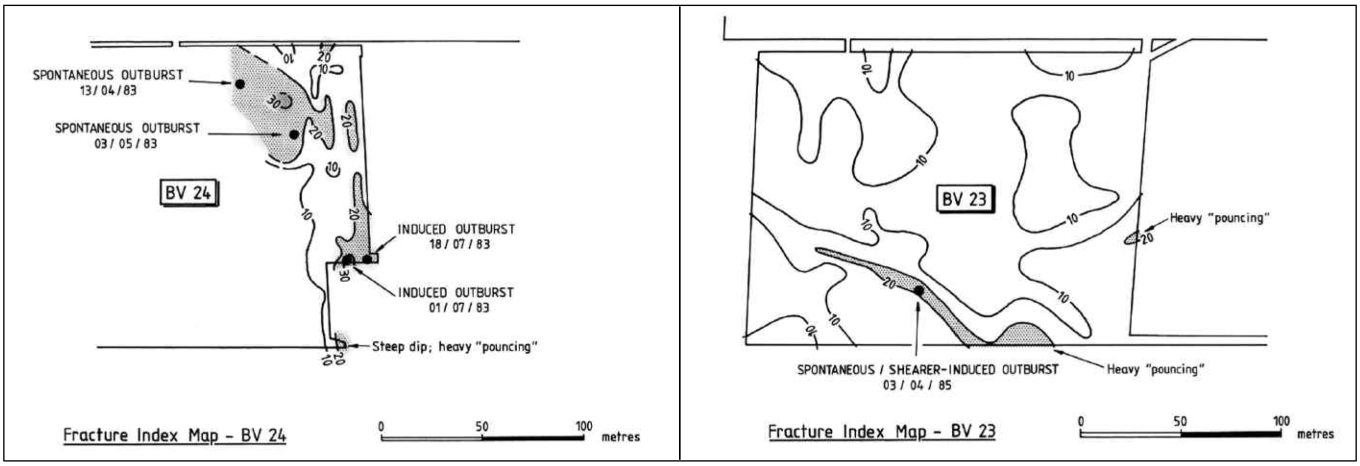


***Figure 13.*** *Plan of Cynheidre BV24 and BV23 longwall panels showing correlation of outbursts and Fracture Index mapping; grey shaded areas indicate FI >20 (after Dumpleton, 1990).*

**2**. Provision of airline breathing stations along coal faces, headings and return airways:
- Additional oyxgen self-rescuers provided for men working in blind headings.

**3**. Pulse-infusion Firing (PIF) on longwall faces and headings:
- Systematic water-pressurised shot-firing prior to machine-getting of coal on longwall faces. Hydro fracturing of coal increases the efficiency of passive coal degassing, thus releasing more excess methane in a controlled and safe manner.
- Immediately following PIF, increased methane co centrations in the mine atmosphere and increased micro-seismic activity were consistently observed, thus demonstrating the effectiveness of the method.

**4**. Monitoring of state of coal (fracture index/Bedding Code Index)
- Enables potential outburst zones to be identified.

**5**. Micro-seismic monitoring
- Enables early warning of precursive outburst events.
- Production can be halted and men withdrawn to safety if necessary.

## Ffos Las opencast site, South Wales

The Ffos Las opencast coal site, now completed and backfilled, was located in the imbricate belt between converging zones of over-thrusting and folding; the Llannon and Trimsaran Disturbances. The site was essentially up dip and in the same strata as Cynheidre Mine. Structures previously known to occur in the southern Gwendraeth Valley included low angle thrust and lag faults, folds, overfolds, faults and incompetent structures. It has been estimated that some 2 km of compression took place in the Ffos Las area during the Variscan orogeny.

Previous underground and opencast coal workings had taken place to the north of the Llannon Disturbance to the north of Ffos Las or to the south of the Trimsaran Disturbance to the south of Ffos Las but underground working had stopped when entering structurally complex areas. The Ffos Las site thus afforded a rare opportunity to examine borehole data and opencast exposures in such geological conditions (Frodsham and Gayer, 1997).

Exploration drilling of Ffos Las and other parts of the lower Gwendraeth Valley was undertaken during the early 1980s. During the exploration and mine planning phases it was crucial to evolve an accurate method of seam correlation and this was greatly assisted by the adoption of downhole geophysical logging techniques: natural gamma and gamma-gamma (density). All geophysical logging was undertaken in cased holes using two density tools with different sources. Both Long Spaced Density and Bed Resolution Density tools were available. At that time most logs were only recorded in analogue format. As the boreholes were cased, no calliper (or virtual calliper) log was available. A limited amount of coring of non-coal strata was undertaken during exploration drilling. A number of marine bands were present in the upper portion of the measures provided key marker horizons for structural interpretation. The geophysical logging of the standard coal measures strata also revealed a number of readily recognisable features which were valuable in enabling correlation between often faulted and discontinuous coal areas, and in interpreting the geological structure during the prospecting phase of operations (Figure 16).

The lower and upper boundaries of the Westphalian B are marked in South Wales by the Amman Marine Band (*A. vanderbeckei*) and the Cefn Coed Marine Band (*A. aegiranum*) respectively. In addition the Mole Marine Band, the Trimsaran Marine Band, and the intermittently present Graigog Marine Band, are present in upper section of the site stratigraphy in the 100 m or so of strata below the Cefn Coed Marine Band. These thin, dark, shale bands with a rich marine fauna represent widespread marine incursion events and are often characterised by increased sulphides and the presence of uranium salts (uraninite and pitchblende) so that they are usually represented by high gamma peaks on downhole geophysical logs. However, on a number of occasions, the horizon at which the Amman Marine Band would have been expected was intersected in boreholes, but with no high gamma peak evident on the downhole logs. This may indicate a change in the provenance of source material for this marine band compared with marine bands higher in the sequence.

Each of the other marine bands present on the site is associated with one or more coals and represented by very characteristic geophysical log profiles. The Cefn Coed Marine Band, for example, is almost always represented by two or three high gamma peaks immediately overlying a thin (<0.2 m thick) coal separated by an interval of some 5 m to the Drap seam, the latter consisting of an upper leaf of around 0.4 m, a parting of approximately 0.5 m and a lower leaf of 0.5 m. The Mole Marine Band appears as a single gamma peak immediately overlying an upper coal of *c*. 0.3 m, a parting of around 0.2 m and a lower leaf of *c*. 0.15 m (Figure 16).

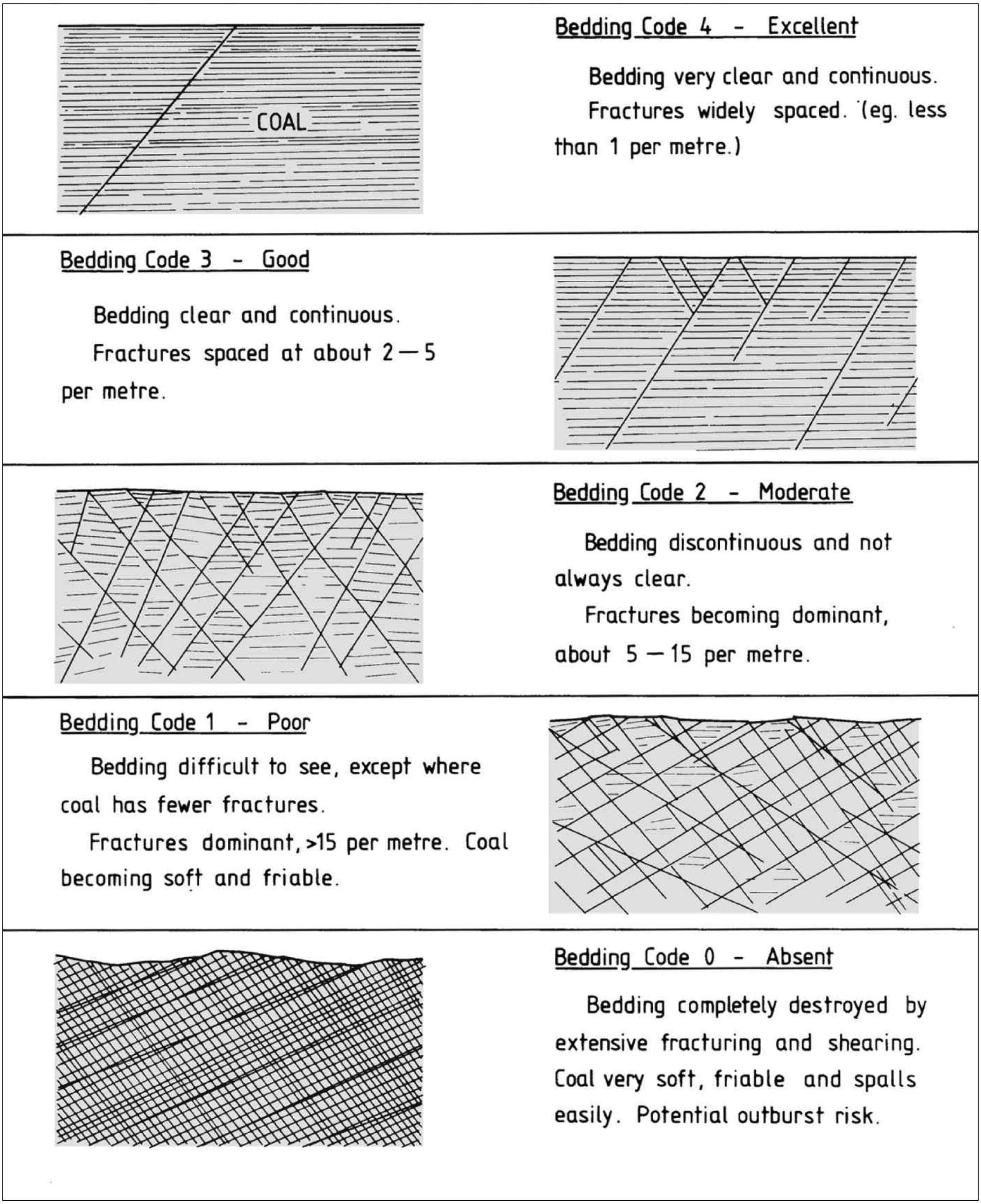


***Figure 14.*** *Coal Bedding Code Index parameters.*

The lower part of the succession contains three seams with characteristic geophysical log profiles as shown below (Figure 17), and in addition, the strata above the Big Vein coal seam also includes the thick and consistent sandstone horizon of the Big Vein Rock, readily identifiable from its low gamma response. Therefore, during exploration drilling it was often possible to identify and assign correlation codes to key horizons on the basis of geophysical log evidence alone, even where the geological structure was at its most complex. The correlation coding was entered into an in-house database using a 5-character convention, where the first one or two characters were used for seam identification, the third character for identification of the structural horizon or thrust slice and the fourth and fifth characters for individual coal leaf identification. For example, the lower leaf of the Soap seam in thrust slice 'J' would be coded 'S0J01'. The code, apart from the 'J', could be entered into the database immediately following interpretation of the geophysical log. It is difficult to imagine how the subsequent interpretation of the geological structure could have been undertaken with any degree of confidence without the advantage of this methodology, particularly as 106 separate coal areas on 12 seams were identified and subsequently worked.

The Ffos Las site produced anthracite coal which was marketed as graded sized products. The presence of disturbed zones of friable coal had a negative impact on the revenues of the site, hence it was important to try to identify these zone in advance.

There was not a great deal of direct evidence from the geophysical logs to enable zones of friable coal or thrust planes to be identified, although significant changes to the physical properties of coal and strata might have been anticipated. Computer modelling of variations in true seam thickness revealed areas of anomalous seam thickening or thinning, possibly indicating where friable coal zones might be expected. These results were consistent with the model of 'break-back thrusting' developed by Frodsham and Gayer (1997).

The presence of two or more thrusts and the competent Big Vein Rock sandstone horizon are seen as key factors in causing the developing foreland propagating thrust system to 'lock up' and thus initiate break-back thrusting. It is suggested that break-back thrusting can provide a model for the development of friable zones and may represent a process by which structurally disturbed zones under confined stress are formed, and which may later be outburst-prone in an underground mining environment.

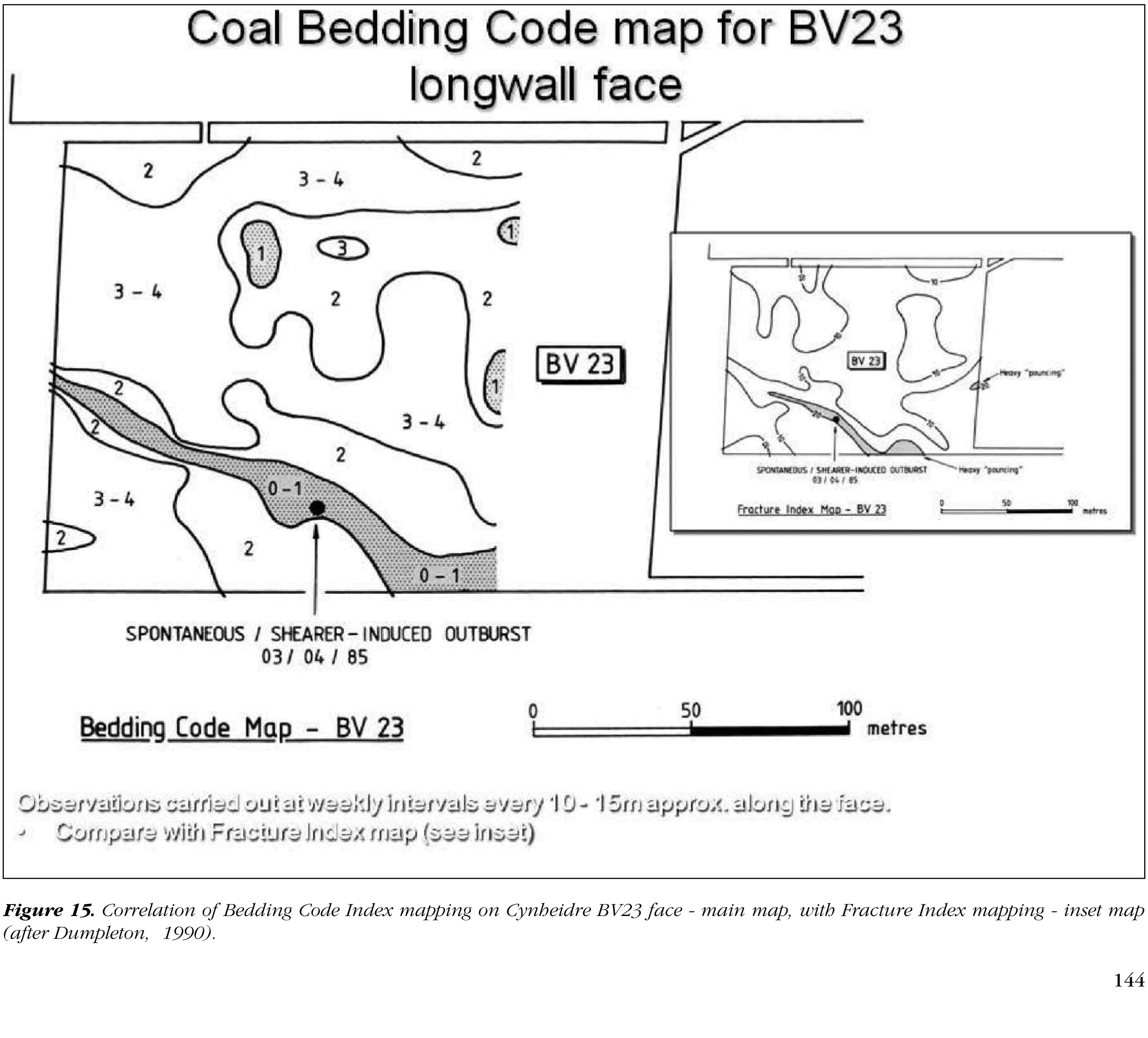


***Figure 15.*** *Correlation of Bedding Code Index mapping on Cynheidre BV23 face - main map, with Fracture Index mapping - inset map (after Dumpleton, 1990).*

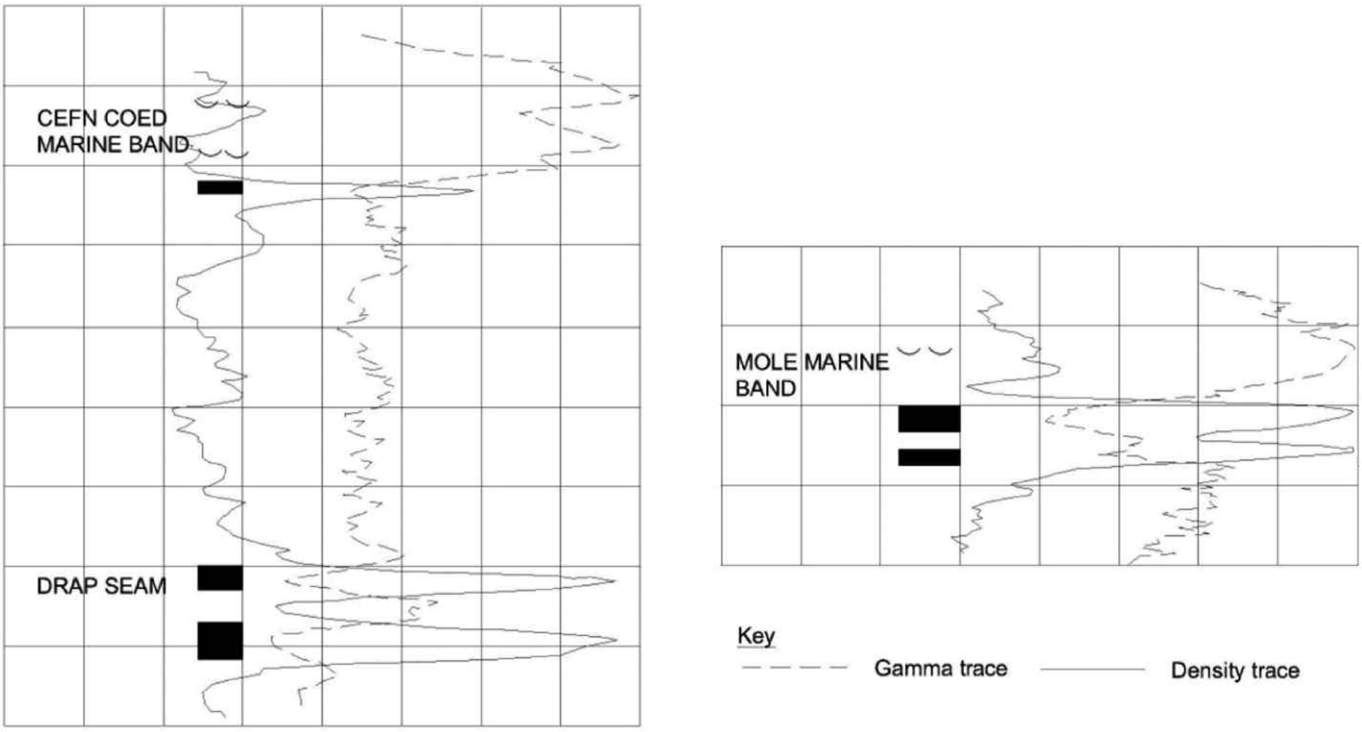


***Figure 16.*** *Illustrative geophysical log profiles of key marine bands and associated thin coals at Ffos Las, South Wales.*

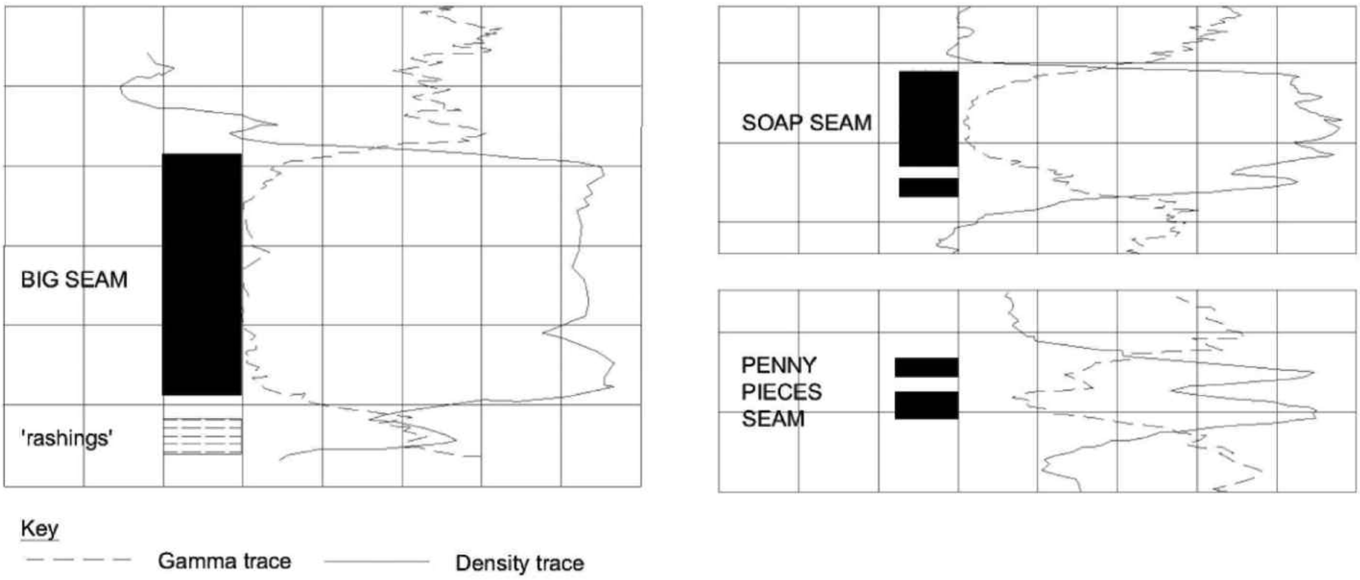


***Figure 17.*** *Illustrative geophysical log profiles of coals from lower part of the succession at Ffos Las, South Wales.*

## Mitigation of mining hazards at Ffos Las

The understanding of structural complexity and the subsequent geological interpretation is a key precursor to resource evaluation and hence developing a life-of-mine plan that can be implemented with minimal risks to the site operational contractors. The flexibility of opencast mining methods helps to plan and recover a much larger part of the resource than the underground method, although seam, and hence product quality, is degraded by the complexity of seam stratigraphy. Clearly, zones of sheared coal result in an inferior product ('duff'). The life-of-mine plan can be devised to minimise the quantity of such inferior product, but nevertheless it can range between 15% and 65%. The smaller product size, particularly after washing the coal, results in lower price returns on the product.

## El Cerrejón, Colombia

Understanding the deformation style and structures that affect the Tertiary Cerrejón Formation was the key to improving seam correlation, resource estimation and geotechnical modelling of the pit-slope (batter) stabilities. The complexity of the deformation may be broadly resolved into three sets of faulting: low-angle thrusts of early Micoene age, steeply dipping thrusts correlated with mid-Miocene Andean deformation, and normal, listric faulting dated between the early Miocene and mid-Miocene Andean deformation.

The age of the Cerrejón Formation is much younger than the European Permo-Carboniferous coal basins. However, the geological complexity is the dominant factor which hinders production and restricts the quality of the saleable product. The coals are bituminous (in contrast to the South Wales high-rank anthracite or coking coals). Low-angle thrusting and higher angle thrusting at differing strike directions can cause a variety of problems.

The high intensity of thrusting results in a number of complications for the opencast mining process. Initially, mine planning is made more complicated because of repetition of seams, which are, in any case, difficult to correlate due to poorly defined geophysical log signatures and the absence of any marker horizons in the inter-burden. Because many of the thrusts run along preferential pathways along the roofs and floors of the coal seams, these become highly sheared and have very low strength, similar to the intra-formational shears found in the South Wales coalfield. Thus, pit planning and mining is heavily constrained by the dip of the strata, which controls the maximum depth to which footwalls can be formed along the coal seam floors before becoming unstable and requiring remedial measures to be undertaken.

Secondly, thrust ramps can lead to the potential for 'daylighting' of coal seams and associated weak horizons in the footwalls, which can have a significant impact on the stability of the slopes. The thrusts are frequently difficult to identify because they can be bed-parallel for significant distances before they ramp up steeply to another seam floor or roof and so may not be revealed until the pit walls are exposed.

Thirdly, normal-sense 'tear' faults that accommodate differential movement between thrust slices can displace the main mining blocks and result in significant complication to the pit layout, as well as potentially having an effect on slope stability, especially when these faults are oblique to the main strike of the coal seams.The accommodation faults also can be difficult to identify during the exploration phase, since they will sometimes show zero displacement at the different ends of the fault. Where thrusting has caused multiple stacking of seams, very variable thicknesses occur, posing problems to tactical production planning. Mitigation of these sorts of problems can only be done with careful geological and geotechnical mapping of the mine as it becomes exposed during production, as correlation from the exploration campaigns cannot pick up all the key structures. Modern techniques such as laser mapping, coupled with the use of 3-D visualisation and mine planning software are today's basic tools allowing the mitigation of the effects of such geological complexity.

In summary, whilst the thrust and ramp structure within the Cerrejón Formation is not as complicated as the much older and more intensively deformed strata at Ffos Las, it shows that similar structural environments occur in very different geological settings, and that solutions to the types of problems encountered in South Wales can be applied in many other parts of the world.

## CONCLUSIONS

Although the 'hey-day' of mining in South Wales is long past, the knowledge and expertise gathered from difficult mining in complex structural terrains has not been forgotten. It can be applied and used to mitigate mining hazards in many other structurally complex parts of the globe. There remains a continual problem in managing outbursts, as demonstrated by recent events in the Ukraine in 2008, where an outburst again claimed lives in the Donbas coal basin near Krasnodon. Careful geological mapping and monitoring are key elements in reducing such mining risks and improving mine safety.

## ACKNOWLEDGEMENTS

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