Landscape evolution in south-east Wales: Evidence from aquifer geometry and surface topography associated with the Ogof Draenen cave system

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Abstract:
The evolution of the Ogof Draenen cave system, in south-east Wales, has been profoundly influenced by the geometry of the karst aquifer and its relationship with changes in the surface topography. Using data from within the cave combined with a model of the aquifer geometry based on outcrop data, we have estimated the location and elevation of putative sinks and risings for the system by extrapolating from surveyed conduits in the cave. These data have enabled us to assess the scale and pattern of scarp retreat and valley incision in the valleys of the Usk, Clydach and Lwyd, that together have influenced the development of the cave. From this we can construct a relative chronology for cave development and landscape evolution in the region. Our data show that scarp retreat rates along the west flank of the Usk valley have varied by more than an order of magnitude, which we interpret as the result of locally enhanced erosion in glacial cirques repeatedly occupied and enlarged during successive glacial cycles. This process would have played a key role in breaching the aquiclude, created by the eastward overstep of the Marros Group clastics onto the Cwmyniscoy Mudstone, and thereby allowed the development of major conduits draining further south. In the tributary valleys incision rates were substantially greater in the Clydach valley than in the Lwyd valley, which we attribute to glacial erosion predominating in the north-east-facing Clydach valley and fluvial erosion being dominant in the south-facing Lwyd valley. There is evidence from within Ogof Draenen for a series of southward-draining conduits graded to a succession of palaeoresurgences, each with a vertical separation of 4-5 m, in the upper reaches of the Lwyd valley. We interpret these conduits as an underground proxy for a fluvial terrace staircase and suggest a direct link with glacial-interglacial cycles of surface aggradation and incision in the Lwyd valley. Fluvial incision rates for broadly analogous settings elsewhere suggest perhaps a million years has elapsed since these resurgences were active and implies a significantly greater age for the oldest conduits in Ogof Draenen.

Keywords:
Valley incision; scarp retreat; karst aquifer; glacial cirques; fluvial terraces

Ogof Draenen is a major cave system in south-east Wales (Fig. 1) that was discovered only in 1994 yet, with approximately 70 km of passages already explored (Fig. 2) and many more to be discovered beyond the current limits, it is destined to become the longest cave in the UK. Its discovery and exploration opened up a new archive potentially recording aspects of the region's geomorphological history spanning many hundreds of thousands of years. Many visits by us to different parts of the underground system and to surface features, and the compilation by others of a detailed survey of Ogof Draenen (Fig. 2), have enabled us to build up an internally consistent sequence of events within this complex cave system. Many questions remain to be answered, particularly concerning conduits beyond the current explored limits of the system. However, new discoveries have tended to confirm our initial hypotheses, as outlined in Simms et al. (1996) and Waltham et al. (1997), and we consider that our overall model for the development of the system (Farrant and Simms, 2011) is unlikely to be radically altered by future discoveries.

Detailed interpretation of the development of the Ogof Draenen cave system itself is discussed in Farrant and Simms (2011) and builds on earlier work (Simms et al., 1996; Waltham et al., 1997). In these we have necessarily linked interpretation of the cave to the surface topography in terms of the locations of putative sinks and resurgences, but in this paper we address more specifically the development of the surface topography in relation to the already documented history of the cave system, and to the outcrop and subcrop geometry of the aquifer that has so strongly influenced its development.

Geological and hydrological setting

The detailed stratigraphy and lithology of the geological succession associated with the landscape of this region has been described in greater detail elsewhere (Barclay, 1989; Farrant and Simms, 2011), as has the hydrogeology (Maurice and Guildford, 2011). Hence these aspects are only summarized here, augmented by additional points that are particularly salient to this paper. The basic lithostratigraphy of the region (Fig. 3) comprises a limestone-dominated succession up to about 150 m thick, of Dinantian (Lower Carboniferous) age, underlain by thick Devonian fluvial clastics of 'Old Red Sandstone' facies, capped by the Quartz Conglomerate Group, and overlain by similarly thick fluvial clastics of Namurian and Westphalian (Upper Carboniferous) age, with the Marros Group at the base overlain by the South Wales Coal Measures Group above. Within the limestone succession there are three main carbonate aquifers, the Dowlais Limestone Formation and Clydach Valley Subgroup within the Pembroke Limestone Group, and the Castell Coch Limestone Formation at the base of the underlying Avon Group. These are separated by two significant aquicludes; the Llanelly Formation in the Pembroke Limestone Group, and the Cwmyniscoy Mudstone Formation at the top of the Avon Group. The Llanelly Formation is about 20 m thick in the Clydach valley and includes both mudstones and limestones. The 4-5 m thick Gilwern Clay Member at the top is a major aquiclude while the somewhat thinner Clydach Halt Member at the base, and the thinly interbedded limestones and mudstones of the succeeding Cheltenham Limestone Member, also form a significant component of this hydrological barrier between the Dowlais Limestone Formation and Clydach Valley Subgroup. Another minor aquiclude or aquitard, the Darren Ddu Member, occurs at the top of the Coed Ffyddlwn Formation in the upper part of the Clydach Valley Subgroup. Although this member is composed predominantly of micritic limestones (Barclay, 1989), it does includes decimetre-scale hard green mudstones which, judging from observations made within the cave, have hindered the downward movement of water from the Gilwern Oolite Formation into lower parts of the Clydach Valley Subgroup aquifer. Six formations are recognized within the Clydach Valley Subgroup (Fig. 3). Each has exerted its own lithological influence on passage morphology and configuration but in terms of the overall development of the systems the main distinction is between the Gilwern Oolite Formation, at the top of the subgroup and above the Darren Ddu Member aquiclude, and those formations below it. In terms of the sequence of development of the cave, the older passages commonly lie within the Gilwern Oolite Formation while passages formed during later periods of development are located almost entirely in the Clydach Valley Subgroup below the Darren Ddu Member.

Although the limestone succession reaches a maximum thickness of about 150 m in the north-west of the region covered by this paper (Fig. 4), it thins dramatically eastwards. Thickness variations of individual members within the sequence are well documented (Barclay, 1989) but the main factor causing this eastward diminution in thickness of the limestone is the overstep by the Marros Group clastics which overlie it. Thus the Dowlais Limestone extends only as far as the western side of Gilwern Hill, the Llanelly Formation extends only just a little east of Cwm Llanwenarth, and along the eastern scarp even the entire Clydach Valley Subgroup may be cut out. The Marros Group rests directly on the Cwmyniscoy Mudstone on Blorenge and even lower, on the Castell Coch Limestone, on Mynydd Garnclochdy. Structure contours on the top and base of the Clydach Valley Subgroup indicate that nowhere south of Blorenge did this aquifer extend much more than one km east of the present scarp before it was cut out completely by the Marros Group overstep (Fig. 4). North of Blorenge the line of this overstep is more difficult to ascertain since the limestone outcrop swings around to eventually run east-west along the north scarp of the South Wales Coalfield (Fig. 1). However, a thin remnant of the lower part of the Clydach Valley Subgroup preserved beneath the Marros Group on the summit of Pen Cerrig-calch [SO 217224], about 10 km to the NNW of Blorenge, indicates that the overstep of the Marros Group onto the Cwmyniscoy Mudstone probably lay a little to the east of here and this has helped to constrain the position of the overstep line in Fig. 4. Structure contours on the top of the Clydach Valley Subgroup and top of the Cwmyniscoy Mudstone Formation show a fairly consistent NNW-SSE orientation along much of the 'East Crop' but swing round to almost east-west across Gilwern Hill and into the Clydach valley. The slightly more northerly trend of the lower set of structure contours reflects the effect of the Marros Group overstep on total thickness of the Clydach Valley Subgroup.

Explored passages in Ogof Draenen are developed almost entirely in the various formations of the Clydach Valley Subgroup. Just a few minor passages are developed in the lower part of the Llanelly Formation and none have yet been entered in the Dowlais Limestone Formation, which anyway is confined to the extreme north-west of the region (Fig. 4), or in the Avon Group. The Dowlais Limestone is a major karst aquifer to the north and west of this region (Waltham et al., 1997) and hosts a number of minor caves in the Clydach Gorge and beneath Mynydd Llangattock to the north of the immediate area under consideration. However, we do not consider it to have played a significant role in the development of Ogof Draenen because of its limited extent across the region and particularly because it is separated from the Clydach Valley Subgroup aquifer by the Gilwern Clay (Llanelly Formation) aquiclude. Similarly, we consider that the Cwmyniscoy Mudstone aquiclude effectively defines the lower stratigraphical limit of conduit development within Ogof Draenen except in one or two specific instances where it has been breached by faults.

The autogenic catchment for the aquifer is very small as the Clydach Valley Subgroup forms only a relatively narrow outcrop along the steep western scarp of the Usk valley, along the steep flanks and in the floor of the Clydach valley, and in the floor of the Lwyd valley (Fig. 4). Consequently, recharge throughout the cave’s history has been predominantly allogenic, derived largely from streams flowing from the outcrop of the Marros Group clastics to the west. Preliminary analysis of sediments within the cave indicate that all are derived from the Carboniferous succession, and particularly from the overlying Marros and South Wales Coal Measures groups. No clasts have yet been found that can be attributed to any of the ‘Old Red Sandstone’ facies that outcrop stratigraphically below the aquifer to the east.

Modelling erosion rates and patterns

Previous work (Simms et al., 1996; Waltham et al., 1997) has established that the three valleys, of the rivers Usk, Clydach and Lwyd, have together had a profound influence on the hydrological and geomorphological evolution of the cave system. Much information on the changing landscape across the region has been obtained from analysis of data from conduits within Ogof Draenen, but much can also be deduced from an analysis of the potential interplay between geology, aquifer geometry and surface topography. We have constructed models for the aquifer geometry using outcrop elevations for the top and base of the Clydach Valley Subgroup and have used these data to draw up structure contours from which we can infer the former extent of the aquifer at various stages during the evolution of the region’s landscape. We have also modeled the progressive unroofing of the aquifer in the floor of the Lwyd valley to ascertain how this correlates with known conduits within the cave. The results of these analyses, described here, are in good agreement with those already deduced from Ogof Draenen itself (Simms et al., 1996; Waltham et al., 1997; Farrant and Simms, 2011). Furthermore, they help to constrain surface locations of putative sinks and resurgences beyond the currently explored, or preserved, limits of the cave system, while also highlighting the extent and pattern of valley incision and scarp retreat throughout the history of Ogof

Draenen. In the following sections we address each of the three valleys in turn.

The Clydach valley

Palaeohydrological data from within Ogof Draenen indicate that the Clydach valley has played a major role during two separate, and contrasting, phases in the cave's development (Simms et al., 1996; Waltham et al., 1997; Farrant and Simms, 2011). During the cave's early history it was a focus for major sinks draining into the 'Megadrive System', represented by the Bolder Land-Megadrive conduit and its southward continuation in Elliptic Passage and beyond (Fig. 2). This role continued, perhaps to a declining extent, with a series of conduits (Luck of the Draw through to Strawberry Passage; Fig. 2) that subsequently captured flow southwards to a succession of resurgences in Cwm Afon (Fig. 8). In a subsequent phase the Clydach valley became instead the location of a resurgence fed by northwards drainage, from sinks along the western flank of the Usk valley and in the head of the Lwyd valley (Farrant and Simms, 2011). The altitude of the main phreatic trunk conduits for these 'subsystems' within Ogof Draenen provides an approximation for the elevation of their sinks and resurgences in the Clydach valley. There are sound reasons, discussed below, for assuming that the Megadrive sink was located on the Gilwern Oolite Formation at the top of the Clydach Valley Subgroup. We also assume that the resurgence for the northward draining 'subsystem', focused on Gilwern Passage (Fig. 2), was at the base of the Clydach Valley Subgroup, perched on the Cwmyniscoy Mudstone aquiclude.

To constrain possible locations for these sinks and resurgences we have constructed structure contours for two hydrologically important stratigraphic horizons – the top of the Clydach Valley Subgroup and the top of the Cwmyniscoy Mudstone Formation in the underlying Avon Group – which effectively form the upper and lower limits of significant conduit development within Ogof Draenen (Figs. 4 and 5). Based on outcrop data from Mynydd Llangattock to the north of the Clydach valley, and Gilwern Hill and Blorenge to the south, we have projected these structure contours across the intervening gap where the limestone has long since been removed by incision and scarp retreat (Fig. 5). We have also tentatively estimated the elevation of the top of the Dowlais Limestone where the structure contours on the top of the Clydach Valley Subgroup cross the mid-line of the Clydach valley but, because of the rapid eastward diminution in thickness of the Dowlais Limestone, the latter are only an approximation.

The Megadrive sinks

The most northerly fragment of the Megadrive conduit is a shattered and gravel-choked passage remnant exposed in a quarry high in the Gilwern Oolite at an elevation of about 390 m on the north-east flank of Gilwern Hill (Fig. 5; Simms, 1998; Farrant and Simms, 2011). The abundance of gravels through more than 2 km of the northern part of the Megadrive System suggests that it was a fairly open sink at or near the top of the Gilwern Oolite, with clasts derived from the Twrch Sandstone, at the base of the Marros Group, being swept into the sink and along the passages during major flood events. A simple projection north-west from the Megadrive-Bolder Land conduit, through the gravel-choked passage remnant mentioned above, intercepts the axis of the Clydach valley (the present river) close to the 430 m structure contour. However, because of the westward swing of the strike across Gilwern Hill and the Clydach valley we suggest that the putative Megadrive sink (S1b on Fig. 5) lay closer to the 400 m structure contour, probably at an elevation of about 400-410 m above present O.D. Today the valley floor beneath this point lies at an altitude of just 120 m (Fig. 6), implying subsequent incision of about 290 m in this part of the Clydach valley. It is conceivable that the sink was actually located at a similar altitude on the Dowlais Limestone but we do not favour this scenario for several reasons. Firstly, any drainage from sinks in the Dowlais Limestone would have to traverse the Llanelly Formation to reach the known conduits in the Gilwern Oolite. The Llanelly Formation is dominated by lithologies which either present a barrier to downward movement of water, as in the Gilwern Clay and Clydach Halt members (Fig. 3), or are not conducive to the development of large open conduits capable of transmitting large volumes of gravel into the system, as is the case with the thin limestone and mudstone interbeds of the Cheltenham Limestone Member. Limited drainage from the Dowlais Limestone through the Llanelly Formation and into the Clydach Valley Subgroup below is documented in some of the Llangattock caves (Smart and Gardner, 1989) but the Gilwern Clay, which constitutes the main aquiclude element of the Llanelly Formation, is more than twice as thick in the Clydach valley as on Llangattock (Barclay, 1989), thereby significantly reducing the probability of hydrological continuity between the Dowlais Limestone and Clydach Valley Subgroup here. Secondly, any sink at 410 m on the Dowlais Limestone would have to be located significantly west of the projected continuation of the known conduits (S1b on Fig. 5), which would also place it west of the Nant Dyer Fault. The eastward downthrow on this fault juxtaposes Marros Group clastics against Dowlais Limestone (Figs. 5 and 6) and hence would have formed an additional barrier to drainage from the Dowlais Limestone into the Gilwern Oolite.

It is clear from the pattern of drainage rerouting and reversal in Ogof Draenen (Simms et al., 1996; Waltham et al., 1997; Farrant and Simms, 2011) that the Clydach valley has been the focus of very considerable incision and scarp retreat during the history of Ogof Draenen. We consider it likely that the precursor of the Clydach valley was a north-facing glacial cirque that developed between the Llangattock escarpment to the west and Gilwern Hill to the east. Part of this cirque is perhaps still evident in the south-eastward curvature of the southern end of the Llangattock scarp (Fig. 5), but the cirque’s steep back wall has long since been breached by the River Clydach. During the early development of Ogof Draenen much of the flow was perhaps captured down-dip where it crossed the limestone outcrop rather than continuing down the scarp as a surface river. Through time the profile of the Clydach valley has become progressively less steep as the surface river has incised into the back wall of the cirque and the scarp-forming units (Quartz Conglomerate Group to Marros Group) have retreated down-dip to their present position (Fig. 6). In the case of the top of the Gilwern Oolite, this now lies about 2.4 km to the south-west of the putative Megadrive sink and at an altitude of 220 m (Figs. 6 and 7).

The Gilwern Passage resurgence

The evidence from within Ogof Draenen for a major northward-draining phase, towards a resurgence in the Clydach valley, is unequivocal (Hunt and Simms, 1995; Simms et al., 1996; Waltham et al., 1997; Farrant and Simms, 2011). Phreatic conduit elevations in the downstream parts of the system suggest a resurgence altitude of about 310 m and a position at or near the base of the Clydach Valley Subgroup. The northern part of Gilwern Passage (Fig. 2), the main trunk conduit for this phase of devlopment, maintains a constant elevation yet has a slightly more gentle westwards curvature than the structure contours, indicating that it is descending stratigraphically. A projection of this curvature beyond the current preserved limit of the passage is consistent with a resurgence altitude of about 310 m (R3 on Fig. 5). This lies very close to the projected northward continuation of the Nant Dyer Fault which, by juxtaposing the Cwmyniscoy Mudstone to the west against the lower part of the Clydach Valley Subgroup (Fig. 6), may have prevented the progressive down-dip migration of the resurgence that would otherwise have been associated with continuing incision in the Clydach valley. This may explain why, in contrast to the succession of resurgences that developed in Cwm Afon (discussed below), the northward draining phase of Ogof Draenen’s history appears to be represented by just a single, large, main drain. Today the valley floor below this putative resurgence location lies about 180 m lower, at an altitude of about 130 m, and the base of the Clydach Valley Subgroup has retreated south-westwards by about 1.5 km to where it is now at an altitude of about 200 m (Figs. 6 and 7).

The Usk valley

The Usk valley dominates the landscape to the east of the region under consideration. It is a very much larger feature to which the other two valleys are tributaries and almost certainly is much older than the development of any of the large conduits in Ogof Draenen. In contrast to the Clydach and Lwyd valleys, where we consider that glacial and/or fluvial incision has directly influenced the development of Ogof Draenen through controlling sink and resurgence locations, incision of the Usk probably has exerted very little influence on the cave's development other than indirectly through its role in determining regional base levels for the tributary streams. Instead it is scarp retreat on the western flank of the Usk valley that has been critical to the initiation and development of discrete conduits in Ogof Draenen.

Structure contours drawn on the top and base of the Clydach Valley Subgroup indicate that along much of the western scarp of the Usk valley, from Blorenge southwards to Pontypool, the Clydach Valley Subgroup never extended much more than about 1 km east of its present limit (Fig. 4) as a direct consequence of the Marros Group overstep. When the scarp lay east of this line, overstep of the Marros Group onto the Cwmyniscoy Mudstone aquiclude would have created a confined aquifer in the Clydach Valley Subgroup to the west. Relatively short sink to resurgence conduits at this time probably developed only north of Blorenge, where the limestone was unroofed somewhat earlier, although hypogenic spelaeogensis (Klimchouk, 2000), perhaps with the creation of maze caves, may perhaps have been initiated further south in the confined part of the aquifer. Longer conduits draining further to the south-east could not develop until the Marros Group overstep had retreated westwards a sufficient distance to unroof at least a small area of the Clydach Valley Subgroup south of Blorenge. If the War of the Worlds conduit (Fig. 2) does represent a very early high level phreatic passage (Farrant and Simms, 2011) then it may possibly represent the earliest major conduit development, perhaps draining to a resurgence in the Cwm-mawr area just to the south of Blorenge (R1a on Fig. 5) where the scarp today lies at its greatest distance west of the Marros Group overstep. Further south the aquifer remained confined until a second outlet point was created about 3 km to the south-south-east where a minor valley descends the scarp at Cwm y Nant. This valley intercepts a major north-south fault, which we have named the Cwm y Nant Fault (Fig. 4), with a downthrow to the west. We estimate that this throw is sufficient to juxtapose the lower part of the Clydach Valley Subgroup, in which the explored limit of the Megadrive conduits are developed, against the Castell Coch Limestone Formation. This would effectively bypass the intervening Cwmyniscoy Mudstone aquiclude and would have allowed the establishment of a resurgence in Cwm y Nant at the base of the Avon Group.

The elevation of the base of the Avon Group at Cwm y Nant today, about 360 m, is little different from that estimated for the original Megadrive resurgence (R1b on Fig. 7) at about 370 m. This suggests that in the Cwm y Nant region the scarp has retreated little more than 50 m westwards since the resurgence was active. In contrast, there is clear evidence that further north the scarp has retreated westwards by a much greater distance. Beneath Gilwern Hill and the south-west slopes of Cwm Llanwenarth, the explored Megadrive system conduits are at elevations of from 360 m to more than 380 m yet the base of the Clydach Valley Subgroup today extends no higher than 360 m on the north-east flank of Gilwern Hill and descends as low as 300 m in the south-west corner of Cwm Llanwenarth (Fig. 5). Clearly at the time that these were active phreatic conduits the scarp must have extended further east to elevate the base of the aquifer above the level of the resurgence, to at least 370 m and perhaps close to the initial elevation of the sink at about 410 m. Assuming an average dip of about 8^{o} (Barclay, 1989) and a minimum elevation of 400 m for the base of the aquifer across Gilwern Hill and Cwm Llanwenarth (corresponding to the 400 m structure contour for the Cwmyniscoy Mudstone on Figs. 4 and 5) then by simple trigonometry we can calculate the minimum former eastwards extent of the scarp. This suggests that when the Megadrive conduit was active the scarp extended at least 400 m to the north and 270 m to the north-east of Gilwern Hill, and at least 670 m to the north across Cwm Llanwenarth, which is in striking contrast to the minimal scarp retreat in the Cwm y Nant region. Numerous cirques have been recognized along this scarp, particularly on the north and north-eastern facing sections (Lewis and Thomas, 2005; Thomas and Humpage, 2007) and we attribute much of the observed variation in scarp retreat to the local development of glacial cirques along the western scarp of the Usk valley and their subsequent enlargement during successive glacial cycles.

The Lwyd valley

Evidence from within Ogof Draenen shows clear evidence for a shift from the south-east draining Megadrive conduits to a succession of progressively lower conduits draining southwards to putative resurgences in the upper reaches of the Lwyd valley (Farrant and Simms, 2011). We attribute this shift to the initial unroofing in the valley floor of the Clydach Valley Subgroup, here overlain directly by the Marros Group, thereby tapping directly into the down-dip extension of the aquifer which previously had resurged at Cwm y Nant. The relationship between aquifer geometry and the developing landscape is critical to understanding how, and where, this down-dip capture occurred. The Afon Lwyd flows southeastwards at first, obliquely up-dip, but gradually swings round to flow almost due south, obliquely down-dip, towards the Trevethin Fault and Pontnewynydd (Fig. 4). As a result lower strata would have been unroofed first on this gentle bend at Cwm Afon, about 2 km south-east of Blaenavon (Fig. 8), and indeed today this exposes an elongate inlier of the Avon Group surrounding a core of Quartz Conglomerate Group clastics, which we term the Cwm Afon Inlier.

The Cwm Afon resurgences

The highest elevation of the Clydach Valley Subgroup in the Cwm Afon Inlier is at about 360 m, which corresponds closely in altitude to Luck of the Draw (Fig. 2), the highest of the southward draining conduits in Ogof Draenen (Farrant and Simms, 2011). Continuing incision of the Afon Lwyd caused resurgence levels both to fall and to migrate downstream as the area of exposed limestone was extended. The elevation of each of these resurgences (R2a to R2f on Fig. 8) can be deduced from the elevation of conduits in Ogof Draenen and their approximate locations in Cwm Afon can be derived simply from the elevation of the top of the Clydach Valley Subgroup along the valley.

However, the Cwm Afon resurgences represent just the first of two phases of southward drainage into the Lwyd valley, with a second phase, represented by the Beyond A Choke streamway (Fig. 2) in Ogof Draenen, separated from the first by a reversal of drainage northwards to the Clydach valley (Farrant and Simms, 2011). To understand the relationship between these three phases we need to ascertain the relationship between aquifer geometry and the surface topography. To do this we have constructed a long profile of the valley based on present day altitudes at 15 stations along a 7 km stretch of the valley floor. We have then superimposed this profile onto that for the top surface of the Clydach Valley Subgroup along the valley (Fig. 9), lowering it progressively to ascertain significant points at which the limestone becomes exposed. We have assumed, somewhat by necessity, that the long profile of the Afon Lwyd has remained essentially the same since the initial unroofing of the aquifer in Cwm Afon. Admittedly this is a rather bold assumption to make but we consider that it can be justified as a first approximation. Firstly, the Afon Lwyd is effectively a strike-orientated river and so the effects of down-dip retreat of different lithological units on its profile is greatly reduced compared with the River Clydach, which is orientated up-dip. Secondly, what we can deduce from the present river profile does tend to suggest that as a long-term average the profile may have remained relatively unchanged. The present gradient of the river is significantly lower (12 m per km) where it flows across the Quartz Conglomerate Group inlier than where it flows on the limestone to the north-west (38 m per km) or south (24 m per km average). This suggests that prior to unroofing of the Quartz Conglomerate Group the river may have had a more evenly concave profile than it does now. Conversely, the Marros Group clastics which overlie the limestone, and which are of similar lithology to the Quartz Conglomerate Group below, may have exerted a similar influence on erosion in which case the overall gradient may have been less steep on those parts of the valley where the limestone was still to be unroofed. Either scenario will have had some bearing on the development of resurgences in the Lwyd valley, in particular their chronological spacing, but it would not materially have altered the overall sequence that we have deduced using the present-day long profile as a proxy for these earlier profiles. Taken together we consider that these potential variables cancel out. The role of glacial deepening of the valley cannot be dismissed although it is not thought to have been a major erosive factor (Barclay, 1989). The south-facing aspect of much of the Lwyd valley would not have favoured ice accumulation during Younger Dryas-type stadials and the Devensian ice-sheet barely reached this far (Jansson and Glasser, 2008). However, it is probable that an ice-sheet covered the area during several earlier glacial maxima, with likely transitions between erosive warm-based ice and more protective cold-based ice having an effect on valley deepening and widening.

Initially the Lwyd valley would have been floored entirely by the Marros Group and, in its upper reaches, by the South Wales Coal Measures Group. Unroofing of the Clydach Valley Subgroup at the apex of the Cwm Afon inlier, at an elevation of about 360 m, created a new resurgence (R2a on Figs. 8 and 9). This effectively breached the down-dip extension of the aquifer and drained it to that level, causing the abandonment of the lower reaches of the Megadrive conduit and the Cwm y Nant resurgence (R1b on Fig. 7). Continuing incision created a succession of resurgences in the Cwm Afon inlier (Figs. 7 and 8) as indicated by successively lower southward-draining conduits in Ogof Draenen (Fig. 9). The vertical spacing of these conduits, and their putative resurgences, typically is about 10 m but, since the resurgence point was migrating downstream as the aquifer was progressively unroofed, so the depth of surface incision between successive resurgences was less than this. We estimate a total resurgence fall of about 40 m between R2a and R2f, equating to approximately 20 m of surface incision or about 4-5 m vertical separation between successive resurgences.

Northward capture and the Cwm Afon sink
The apparent lack of tributaries from the east feeding into known conduits for the Cwm y Nant and Cwm Afon resurgences suggests that the eastward extension of the aquifer was still largely concealed by the overstep of the Marros Group onto the Cwmyniscoy Mudstone. As such these early conduits were fed largely by sinks into the upper part of the Clydach Valley Subgroup at the northern end of the system. Evidence from Ogof Draenen indicates that these conduits, and the Cwm Afon resurgences, were finally abandoned at about 320 m. At about the same time a major new 'subsystem' developed draining northwards towards a resurgence (R3 on Fig. 7) at an elevation of about 310 m in the Clydach valley (Farrant and Simms, 2011). These conduits, developed in the lower part of the Clydach Valley Subgroup, were fed by sinks further south along the western flank of the Usk valley and, as such, testify to sufficient westward retreat of the scarp to have breached the eastern edge of the aquifer. Our model for incision in the Lwyd valley suggests that as the piezometric surface associated with this new Clydach valley resurgence fell to about 310 m, a significant hydraulic gradient would have developed between the limestone exposed at the north end of the Cwm Afon inlier, at an elevation of about 350 m, and the top of the phreatic zone at least 40 m lower. On the evidence from our model it seem probable that this resulted in capture of the Afon Lwyd headwaters at a new sink (S3 on Figs. 8 and 9) with a vadose inlet descending steeply for about 40 m to feed eventually into the sand-choked inlet of Pontypool or Bust to Chocolate Blorenge in Ogof Draenen (Fig. 2). This possibility is certainly not obvious from analysis of the cave's geomorphology (Farrant and Simms, 2011) and has become apparent only through our model of valley incision. What little we do know about this rather enigmatic section of passage does fit in with this suggested scenario. Survey data suggest that it may be the gently ascending limb of a phreatic loop rising eastwards, obliquely up-dip, and perhaps emanating from a more steeply descending, joint-guided, limb extending south towards the putative S3 sink in the Lwyd valley.

The Abersychan and Pontnewynydd resurgences
Incision and westwards retreat of the outcrop of the Clydach Valley Subgroup in the Clydach valley had captured drainage northwards but continued incision in the Lwyd valley eventually exposed the limestone there at a sufficiently low elevation that drainage from the 'East Crop sinks' was captured southwards again, this time to a succession of new resurgence locations

in the lower reaches of the Lwyd valley. Observations in Ogof Draenen indicate that the first of these new resurgences (R4) was at an altitude of about 270 m (Fig. 9), which would locate it about 1 km south of the last of the Cwm Afon resurgences, R2f (Fig. 8). Although this represents a fall of about 50 m in the level of the piezometric surface, it required only about 30 m of incision in the valley floor because of the downstream migration of the resurgence (Fig. 9). This new resurgence was at an elevation that is only about 10 m above that of the downstream limit of the Beyond A Choke streamway (Fig. 2), which currently is the lowest point yet explored in Ogof Draenen, yet it lies 135 m above the current resurgence elevation at Pontnewynydd (R5 on Figs. 8 and 9). Until cavers find a route into the downstream continuation of Beyond A Choke we can only conjecture on subsequent events in the hydrological development of the system, but it might be anticipated that continued valley incision after the establishment of R4 would cause the gradual migration of the resurgence downstream to its present location more than 3 km further south at R5. However, as is evident from Fig. 9, the top of the Clydach Valley Subgroup undulates significantly in the lower reaches of the Lwyd valley and this will have had a considerable bearing on the development of the drainage subsequent to the establishment of resurgence R4. When resurgence R4 represented the lowest exposed point on the limestone, a confined aquifer would have extended for about 3.5 km to the south, confined by the Marros Group clastics downfaulted on the south side of the Trevethin Fault and with a potential hydraulic head of more than 60 m (Fig. 9). However, because of the aforementioned undulations on the Clydach Valley Subgroup, just a little more incision in the valley floor – we estimate perhaps as little as 10 m – would have breached the lower end of this confined aquifer and caused an immediate shift of the resurgence point to a new location, more than 3 km further south and some 70 m lower, at an elevation of about 200 m (R5 on Figs. 7-9). Inevitably this would have drained the aquifer down to this level and consequently it is rather intriguing that the southern end of the Beyond A Choke conduit does not show any evidence for this event in the form of vadose incision (Farrant and Simms, 2011). We suspect that this may indicate the existence of one or more significant perched sumps just downstream of the current explored limit.

Since the final downstream capture of drainage the Trevethin Fault has effectively blocked any further migration of the resurgence southwards, although continued incision has lowered the resurgence level by a further 65 m to its present level (Figs. 7 and 9). Virtually nothing is known of the current route that the conduit follows between the current explored limit of Beyond A Choke and the main resurgence at Pontnewynydd. However, if it is similar to the known passage then it seems likely that it follows an almost straight line between these two points. This supposition is strengthened by the observation that a simple straight-line projection of the Beyond A Choke streamway (Fig. 8) passes exactly through Pontnewynydd Rising! A number of other hydrologically interesting sites, indicated on Fig. 8, lie very close to this line and perhaps may help to constrain its subterranean route. In the upper reaches of the valley the large doline of Coed-avon, near Blaenavon [SO 257 081] (Simms et al., 1996) lies almost directly on this line; there is clear evidence of deliberate anthropogenic attempts to prevent nearby streams from sinking (Simms 1998); and there are anecdotal accounts of the river nearby occasionally sinking in its bed during dry weather. Further south at Abersychan is a 'bouncing field' [SO 272 038] where water emerges from ephemeral estavelles during periods of exceptionally wet weather. This site lies just over 200 m east of the projected line of the Beyond A Choke streamway and has been hydrologically proven to connect to Pontnewynydd Rising (Gascoine, 1995). Its behaviour suggests that it operates as a flood overflow when water backs up behind more constricted conduits further downstream. Immediately north of the 'bouncing field' is the confluence of the Nant Ffrwd with the Afon Lwyd. Temporary stream sinks have opened up in the bed of the Nant Ffrwd near this confluence on at least two occasions (Gascoine, 1995). The precise location of these sinks is not recorded but they must lie very close to the projected line of cave drainage. The altitude, between about 170 m and 200 m, of both the 'bouncing field' and these temporary sinks suggests that old conduits, perhaps associated with the initial capture to Pontnewynydd, may lie at shallow depth below the surface here and are still, on occasion, exploited as sinks or resurgences. Barely 600 m further south, Snatchwood Bridge Rising [SO 270 026] lies only about 250 m west of this line and has been dye-traced from the Beyond A Choke streamway in Ogof Draenen (Gascoine, 1995). Together these features suggest that the downstream continuation of the Beyond A Choke streamway crosses the Lwyd valley a little south of Blaenavon and then passes beneath the west flank of the valley before returning approximately to the line of the valley in its final kilometre or so.

Discussion

Our analysis of the relationship between aquifer geometry, surface topography and various conduits in Ogof Draenen, has enabled us to estimate quantitatively the extent of valley incision and of scarp retreat across the region during the development of this exceptionally complex cave system. As yet we have no radiometric or other dates by which the relative chronology, elucidated within Ogof Draenen and extrapolated to the surface topography, might be anchored. Nonetheless the scale of incision in the Clydach and Lwyd valleys, and the extent of scarp retreat on the western flank of the Usk valley, suggests that the earliest parts of the system were initiated many hundreds of thousands, perhaps even a million or more, years ago. As such their age is likely to extend significantly beyond the range of standard U-Th dating and will require the application of other techniques that have proven successful in cave environments, such as U-Pb (Richards et al., 1998), palaeomagnetism (Sasowsky et al., 1995) or cosmogenic nuclides (Granger et al., 1997).

Scarp retreat

The western scarp of the Usk valley undoubtedly has been a major regional landscape feature throughout the Pleistocene, and quite probably significantly earlier. Our analysis indicates that its areal configuration has changed considerably during the course of evolution of the Ogof Draenen cave system. We estimate that the limit of the Clydach Valley Subgroup beneath the Marros Group overstep lay at most barely one km to the east of the present scarp from Blorenge southwards, but was significantly greater to the north (Fig. 4). Since the Megadrive conduits were active there has been at least 270 m of scarp retreat on the north-east flank of Gilwern Hill and 670 m or more across Cwm Llanwenarth yet, further south, in the Cwm y Nant area this figure may be as low as 50 m. We ascribe this variation to the localized development and growth of glacial cirques, which would have developed preferentially on north or north-east-facing scarps. At least six small examples have been identified between Cwm Llanwenarth and Cwm y Nant (Lewis and Thomas, 2005; Thomas and Humpage, 2007). These have had a minimal effect on scarp retreat but we suggest that several much larger embayments along the scarp, among them the Clydach valley, Cwm Llanwenarth, Cwm-mawr and Cwm y Nant, also originated as cirques. Gordon (2001) identified two main environments of cirque formation; local mountain glaciation, and subglacial erosion beneath larger glaciers. The former develop during phases of limited glaciation or during the initial stages of more extensive glacial episodes, largely through the accumulation of wind-blown snow, while the latter are formed as valley-head sources for larger valley glaciers. Many cirques in the Brecon Beacons have been attributed to local snow accumulation during the Younger Dryas Stadial (Shakesby et al., 2007). Coleman and Carr (2008) considered the Brecon Beacons a marginal area for Younger Dryas glaciation, which accordingly was restricted to optimum topographic locations such as north or north-east facing slopes above 600 m altitude. From their analysis of sites in the central Brecon Beacons it seems inconceivable that cirque glaciers could have developed during the Younger Dryas at any of these sites along the western scarp of the Usk valley, most of which extend below 300 m. Instead, bearing in mind that this region lay very close to the Devensian ice limit (Coleman and Carr, 2007; Jansson and Glasser, 2008), we suggest that these small cirques formed through the accumulation of wind-blown snow from the west during the Last Glacial Maximum, as has been suggested for similar sites on Mynydd Llangattock (Coleman and Carr, 2007). The larger features which we have identified are less sharply defined and, presumably, significantly older, than these small cirques but at least two (Cwm Llanwenarth and Cwm-mawr) have smaller secondary cirques on their back walls. By analogy with the

Cairngorm examples described by Gordon (2001) we interpret these large features as glacial cirques that were repeatedly occupied and enlarged by localized accumulations of ice and wind-blown snow during successive glacial maxima but, lying so close to the ice limit through much of the Pleistocene, were only occasionally overrun and modified by ice-sheets during the most extensive glacial episodes. As these cirques were enlarged, so they would have become more effective at trapping wind-blown snow and, through this process of positive feedback, these areas of the scarp would have retreated at a significantly faster rate than the remainder of the scarp.

The area of greatest apparent scarp retreat is in the Clydach valley, where the outcrop of the top of the Clydach Valley Subgroup has retreated westwards, down-dip, by as much as 2.4 km from the putative site of the Megadrive sink to its present position. The precursor of the Clydach valley probably also was a large north-east-facing glacial cirque, but fluvial incision subsequently has entrenched deeply into its back wall. Within the Clydach valley the apparently close horizontal distance, less than 250 m, between sink and resurgence (Fig. 5) is an artefact due to comparing one location on the upper slopes (top Clydach Valley Subgroup) with another further downslope (base Clydach Valley Subgroup). Using the slopes of Gilwern Hill as an analogue we estimate that the actual scarp retreat between these two points was at least twice the apparent distance, or about 500 m (Fig. 6). Since the Gilwern Passage resurgence, R3, was established the outcrop has retreated westwards a further 1.5 km (Figs. 5 and 6). This implies that the hydrological events in Ogof Draenen, from the development of the Megadrive conduit through to the northward capture into the Clydach valley via Gilwern Passage, occurred in the first quarter of the cave's long history, at least in terms of total incision and scarp retreat. However, there is an increasing body of evidence, discussed below that erosion rates increased significantly between the early and mid-Pleistocene and so the Megadrive and Gilwern Passsage phases together may account for significantly more of the cave's chronological history.

Valley incision

Quantitative, albeit chronologically unanchored, data on incision has been obtained for both the Clydach and Lwyd valleys and is summarized in Figs. 7 and 9.

In the Clydach valley the locations of the Megadrive sink and the Gilwern Passage resurgence have a vertical separation of about 100 m (Fig. 5). However, whereas the former was located on the top of the Clydach Valley Subgroup, here about 50 m thick (Barclay, 1989), the latter was at its base. Hence the actual depth of incision between the Megadrive sink and Gilwern Passage resurgence was of the order of just 50 m (Figs. 6 and 7). Today the floor of the Clydach valley lies some 180 m lower than the putative elevation of the Gilwern Passage resurgence, and about 240 m below the base of the Clydach Valley Subgroup at the location of the Megadrive sink. This is consistent with the notion that much of the cave's development occurred in the first quarter of its history, at least in terms of total incision depth if not in actual chronological terms.

The Lwyd valley is more interesting in terms of its incision history since there are significantly more data points. Of particular interest is the succession of putative resurgence levels (R2a to R2f), with a vertical spacing of about 10 m, extrapolated from the elevations of southward-draining conduits within Ogof Draenen (Farrant and Simms, 2011). We infer that these relate to progressive downstream unroofing of the Clydach Valley Subgroup aquifer in the floor of the Lwyd valley (Figs. 7 and 9), with each successive 10 m drop in conduit level equating to approximately 4 or 5 m of surface incision in the Lwyd valley. Since the establishment of these Cwm Afon resurgences probably precipitated the final abandonment of the Megadrive conduit, and they in turn were largely abandoned as the Gilwern Passage resurgence became established, they probably represent a relatively short period, perhaps less than a quarter, of the cave's total history, at least in terms of total incision depth. Tentative support for this figure comes from comparing the depth of surface incision between the first and last of the Cwm Afon resurgences, which is about 20 m (Fig. 9), with the 60 m or more of incision that has occurred in the Lwyd valley since they were abandoned (Fig. 7). However, we cannot assume that the approximately 3:1 incision ratios seen here and in the Clydach valley equate to actual time, and there is an increasing body of evidence to suggest that erosion rates have increased markedly since the so-called 'Mid-Pleistocene Revolution (Maslin and Ridgwell, 2005). Hubbard and Lewin (2009) cited evidence from across Europe for rates of fluvial incision increasing by a factor of two or three in the mid- to late Pleistocene while Dowdeswell et al. (2010) found a comparable increase in sediment delivery from the Fennoscandian Ice Sheet in the last 600 ka. In the Swiss Alps the increase is even more extreme, with valley incision rates increasing by an order of magnitude since 800 ka ago (Häuselmann et al., 2007).

The standard interpretation of multi-level cave systems is to regard each conduit level as graded to a local base level (Palmer, 1987). Often these conduits can be correlated with river terraces (e.g. Droppa, 1966; Webb et al., 1992) but multiple cave levels can also be generated by progressive adjustment of groundwater flow paths as the effects of base-level fall propagate upstream through the system (Johnson and Gomez, 1994). The latter model seems unlikely in the case of Ogof Draenen where, with the very low gradients of its phreatic conduits and the small amplitude of phreatic loops, together with the strong hydrological influence of the north-south joint set (Farrant and Simms, 2011), there appears to have been a rapid response within the cave to any external fall in base level in the Lwyd valley. As such we consider the sequential series of abandoned conduits in Ogof Draenen, draining to inferred resurgences in Cwm Afon (Fig. 9), to be analogous to river terraces in surface fluvial systems (Bridgland, 2000). In essence, the Bridgland model envisages cyclical terrace formation driven by the effects of climatic fluctuation on fluvial activity, and overprinted against a background of regional isostatic uplift (Bridgland 2000; Bridgland and Westaway, 2008). The absence of vegetation during cold climate periods lead to erosion in the steeper reaches of rivers and aggradation of the eroded material in the wider and more gently inclined stretches further downstream. In contrast, vegetation cover during warmer periods greatly reduces erosion in the upstream stretches and restricts erosion largely to the narrow river channels further downstream, thereby promoting incision into the unconsolidated sediments deposited there in the previous part of the cycle. In Britain significant terrace formation occurs only once per climatic cycle (Bridgland and Westaway, 2008), during the glacial to interglacial warming transition. In the context of the Ogof Draenen cave system the periods of aggradation are perhaps represented by the upward migration of paragenetic conduits above a floor of accumulating sediment or the development of paragenetic notches (Farrant et al., 1995). Both paragenetic canyons and notches are common in many parts of Ogof Draenen (Waltham et al., 1997; Farrant and Simms, 2011). The intervening periods of surface incision are perhaps represented by vadose entrenchment followed by abandonment of the existing conduit and re-routing of the flow to a new lower resurgence. Fluvial terraces have not been recognized in the Lwyd valley but we suggest that this succession of conduits draining to Cwm Afon represent an underground proxy for cycles of incision and aggradation that would have produced a terrace staircase on the surface. If these conduits do indeed correlate with terrace levels, and hence with glacial-interglacial cycles, then potentially they could be used to determine rates of surface incision if they can be anchored to the Pleistocene chronostratigraphy. Throughout the earlier part of the Pleistocene the regular pattern of climate change was dominated by 41 ka cycles. However, between c.1.2 Ma and 500 ka these were progressively superseded by 100 ka cycles in which the cooling phases were both longer and more intense (Rutherford and D'Hondt, 2000; Huybers, 2007), leading to the increased erosion rates already alluded to. Just a few km to the north of Ogof Draenen, beneath Mynnydd Llangattwg, cave sediments with reversed magnetic polarity occur in Pwll y Gwynt (Noel, 1986) and suggest that cave development was well underway in the region prior to the last magnetic reversal around 780 ka. Considering the scale of outcrop retreat and valley incision that has occurred in the Clydach valley since the Cwm Afon resurgences were finally abandoned (Fig. 7) it is entirely feasible that they too were formed significantly prior to the establishment of the 100 ka cycles, around 800 ka, and hence relate to the shorter cycles. Indeed, the relatively shallow depth of incision between these inferred terraces, of the order of just 4 or 5 m, suggests that they may have been formed by the shorter and less intense 41 ka cycles, in which case the total duration of the Cwm Afon resurgence sequence would be about 200 ka. Many of the conduits draining to Cwm Afon are paragenetic (Farrant and Simms, 2011), with deposition of sediments effectively synchronous with conduit development (Farrant, 2004) and, as such this, part of the system lends itself admirably to palaeomagnetic or cosmogenic dating which could establish if indeed the Cwm Afon resurgences reflect 41 ka rather than 100 ka cycles.

Rather intriguingly, the depth of incision below the last of the Cwm Afon resurgences (R2f) is very similar to that below the later resurgences in the lower reaches of the Lwyd valley (R4 and R5), at 60 m, 70 m and 65 m respectively. From our model for the evolution of the Lwyd valley resurgence sequence, discussed above and summarized in Fig. 9, the similarity of incision depths below R4 and R5 is not entirely unexpected and supports our suggestion that resurgence R4 operated only for a relatively short time before the Marros Group aquiclude was breached at R5. However, we might have expected to see a significantly greater depth of incision below R2f than is actually the case, considering that the interval between R2f and R4 spans almost the entire duration of the major Gilwern Passage resurgence, R3. One possibility is that the conjectured sink at the upstream end of the Cwm Afon inlier (S3 on Figs. 8 and 9) captured much of the headwaters of the Afon Lwyd, thereby greatly reducing interglacial erosion rates in the valley for some distance downstream of this point and for a considerable period of time. In this respect it is interesting to note that our calculated depth of incision below the S3 sink is, at 80 m (Fig. 7), significantly greater than that below R2f (60 m) and perhaps supports the suggestion that fluvial incision rates downstream of the S3 sink were greatly reduced for a considerable period of time.

Taken at face value, incision rates in the Clydach valley appear to have been about three times faster than in the Lwyd valley, with about 180 m of incision below the Gilwern Passage resurgence but just 60 m below the last of the Cwm Afon resurgences and 80 m below the Cwm Afon sink (S3) (Fig. 7). From their contrasting topographic situations, with the Clydach valley facing north-east and the Lwyd valley facing south, and the significant disparity in estimated incision rates between them, we conclude that glacial erosion was a significant component of incision and scarp retreat in the Clydach valley but that fluvial erosion, often under periglacial conditions, predominated during excavation of the Lwyd valley. The low altitude of cirques on the western scarp of the Usk valley, with the floors of most descending below 300 m, indicates that even at the Last Glacial Maximum this south-eastern region of the Brecon Beacons was only lightly glaciated and argues against significant valley glaciation in the Lwyd valley. Montgomery (2002) found that glacial erosion could excavate rock at a rate 2 to 4 times that of fluvial erosion, which is consistent with the discrepancy in incision rates between these two valleys.

Numerous previous studies have used data from cave systems to assess incision rates in adjacent valleys (e.g. Schmidt, 1982; Gascoyne et al., 1983; Waltham, 1986; Farrant, 1991; Sasowsky et al. , 1995; Springer et al., 1997; Hebdon et al., 1997; Granger et al., 1997). Cited incision rates for various sites in the USA that were unglaciated but experienced periglacial conditions range from about 27 mm/ka to about 63 mm/ka. In Britain the data are more widely spread. At Cheddar Gorge, unglaciated but subject to meltwater runoff under periglacial conditions, the figure is estimated at about 250 mm/ka (Farrant, 1991). In some of the glaciated valleys of the Yorkshire Dales the figure is about 120 mm/ka (Gascoyne and Ford, 1984; Waltham, 1986), while in the intensely glaciated Assynt region of north-west Scotland the figure may possibly have been as high as 680 mm/ka and probably not much lower than 470 mm/ka (Hebdon et al., 1997). If we assume, purely for the sake of example, that the incision rate in the Lwyd valley was at the high end of the range, perhaps 60 mm/ka, then this implies that the present day southward drainage was already established more than one million years ago to allow for more than 60 m incision throughout the length of the valley from S3 at the northern end to R5 at the southern end (Fig. 7).

In the Bridgland model of fluvial incision (Bridgland, 2000; Bridgland and Westaway, 2008), regional uplift is considered essential to generate terrace staircases and indeed these staircases are used to estimate tectonic uplift rates. However, Gibbard and Lewin (2009) have questioned the supposed ubiquity of uplift as the driving force behind incision, maintaining that in certain settings uplift is greatly subordinate to climatic and erosional factors. We consider that this is the case for the Lwyd valley and for the terrace staircase analogues draining to it that we have identified in Ogof Draenen. Incision in the Lwyd valley ultimately is influenced by the base level of the lower Usk, of which it is a tributary. From Blaenavon to its confluence with the Usk some 20 km to the south the Afon Lwyd falls about 300 m while over the same distance the River Usk, which approaches to within 5km of the Afon Lwyd near Blaenavon, falls less than 40 m. Uplift may have played a role in the incision of the Usk valley but for the Afon Lwyd it has been very much more a case of climate-influenced erosional catch-up with the Usk base level.

Conclusions

By integrating data from within Ogof Draenen with models encompassing surface topography and aquifer geometry across the region, we have been able to constrain with some precision the location and elevations of former sinks and resurgences beyond the explored limits of the cave system, and even beyond the preserved outcrop of the aquifer. These newly generated data have enabled us to estimate the extent of scarp retreat and valley incision at various points across the region and to throw new light on the evolution of the cave system beneath.

Remarkably, during the cave's history each of the three valleys (Usk, Lwyd and Clydach) has, at different times, been the location both for sinks and resurgences associated with different phases of the cave's development. Initially the aquifer was exposed only in the northern part of the region, towards what is now the Clydach valley, and an extensive confined aquifer extended to the south and west of Blorenge, confined by the Trevethin Fault to the south and the overstep of the Marros Group onto the Cwmyniscoy Mudstone to the east. The earliest phase of significant cave development followed the unroofing of the aquifer by scarp retreat further south and saw the establishment of sinks from the Clydach valley draining south-east to the western flank of the Usk valley south of Blorenge. Drainage from these Clydach sinks was then captured southwards to a succession of resurgences in Cwm Afon, in the middle reaches of the Lwyd valley. Continuing incision and scarp retreat in the Clydach valley, primarily through glacial erosion, caused final abandonment of these southward draining conduits and establishment of a major northward draining system. This linked sinks on the western flank of the Usk valley and in the upper reaches of the Lwyd valley with a resurgence in the Clydach valley. Finally, flow was recaptured southwards, with sinks on the western flank of the Usk valley draining, ultimately, to resurgences near the south end of the Lwyd valley.

Outcrop retreat and incision depths in the Clydach valley indicate that much of the hydrological switching that is recorded in the Ogof Draenen conduits occurred in the first quarter of the cave's history, at least in terms of relative levels of incision, with southward drainage towards the present resurgence dominating the system's hydrology ever since. The succession of conduits draining to resurgences in Cwm Afon are inferred to reflect alternating periods of aggradation and fluvial incision, linked to glacial-interglacial cycles, in the Lwyd valley. The close vertical spacing of these fluvial terrace proxies, and the depth of incision that has occurred since in both the Clydach and Lwyd valleys, suggests to us that the Cwm Afon resurgences may well predate the 'Mid Pleistocene Revolution' and span several 41 ka glacial cycles. An age of a million years or more for the Cwm Afon resurgences is consistent with average incision rates derived from broadly analogous sites elsewhere but, as yet, we have no radiometric, palaeomagnetic or cosmogenic dates by which to constrain our relative chronology for the cave and the landscape with which it is inextricably linked. However, from the complexity of the cave system, the inferred scale of scarp retreat, and the depth of valley incision in the surface landscape, we think it highly likely that the oldest conduits in Ogof Draenen are well in excess of 1 Ma old.

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Figure 1. *Location map for the Brecon Beacons and northern part of the South Wales Coal Basin. The area covered by Figure 4 is indicated by the dashed rectangle.*

Figure 2. *Plan survey of Ogof Draenen showing the location of all passages cited in the text.*

Figure 3. *Generalised vertical section through the Lower Carboniferous of the Abergavenny area (after Barclay, 1989).*

Figure 4. *Sketch map of the geology across the Ogof Draenen region showing structure contours for the top and base of the Clydach Valley Subgroup aquifer and its eastern limit below the Marros Group overstep. The main topographic locations, and the position of the cave system relative to them, are indicated. Geological map is based on the British Geological Survey 1:50 000 scale map sheet 232 Abergavenny*

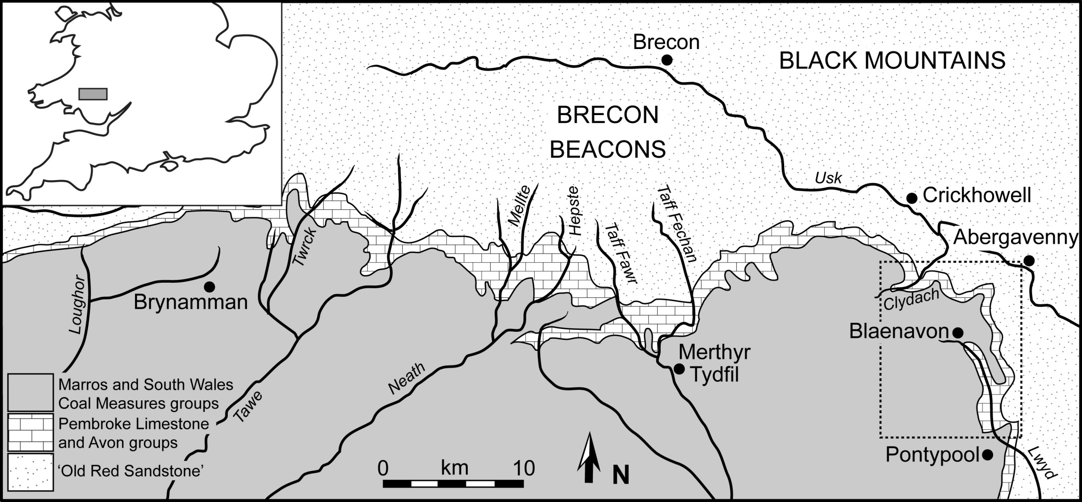
Figure 5. *Detail of geology and structure contours in the northern part of the region, with former sink and resurgence locations in the Clydach valley indicated. Geological map is based on the British Geological Survey 1:50 000 scale map sheet 232 Abergavenny.*

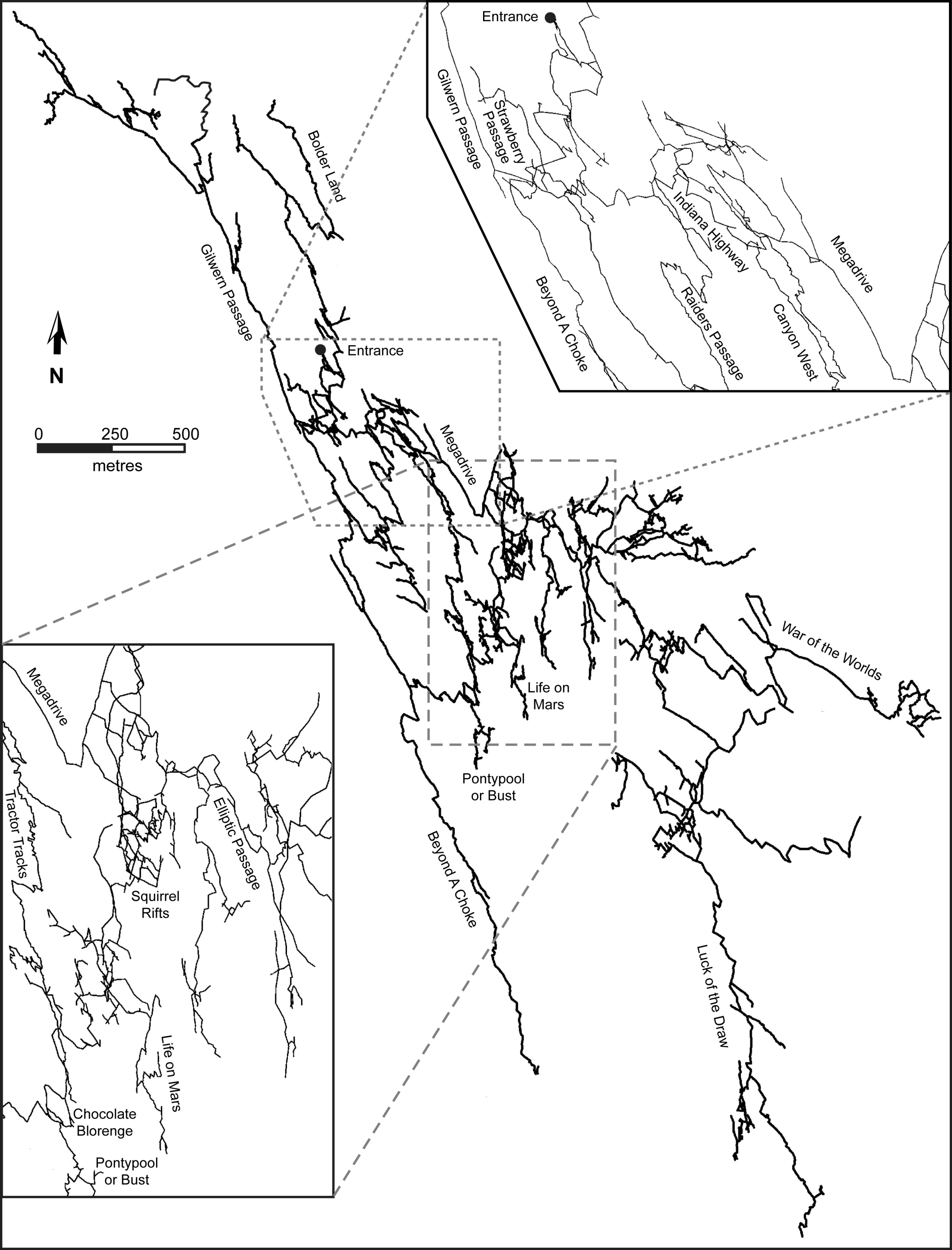
Figure 6. *Diagrammatic profile along the Clydach valley showing outcrop retreat and scarp decline from the initial development of the Megadrive sink (S1b), through the Gilwern Passage resurgence (R3), to the present day, and the effect of faulting on the aquifer.*

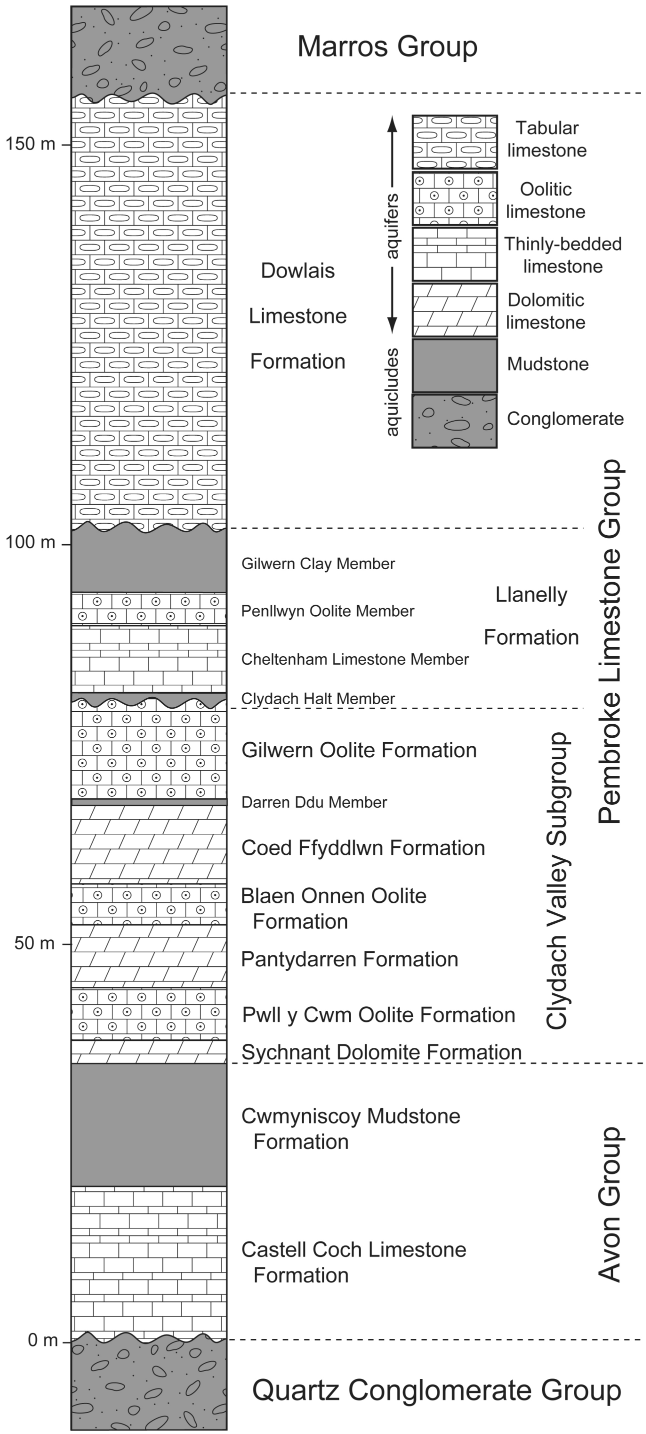
Figure 7. *Diagram summarising the location and elevation of sinks and resurgences associated with the Ogof Draenen system, their relationship to the Clydach Valley Subgroup aquifer, and the extent of subsequent modification of the surface topography through valley incision and scarp retreat.*

Figure 8. *Detail of geology in the Lwyd valley, showing the location of putative resurgences and sinks associated with Ogof Draenen. Geological map is based on the British Geological Survey 1:50 000 scale map sheet 232 Abergavenny.*

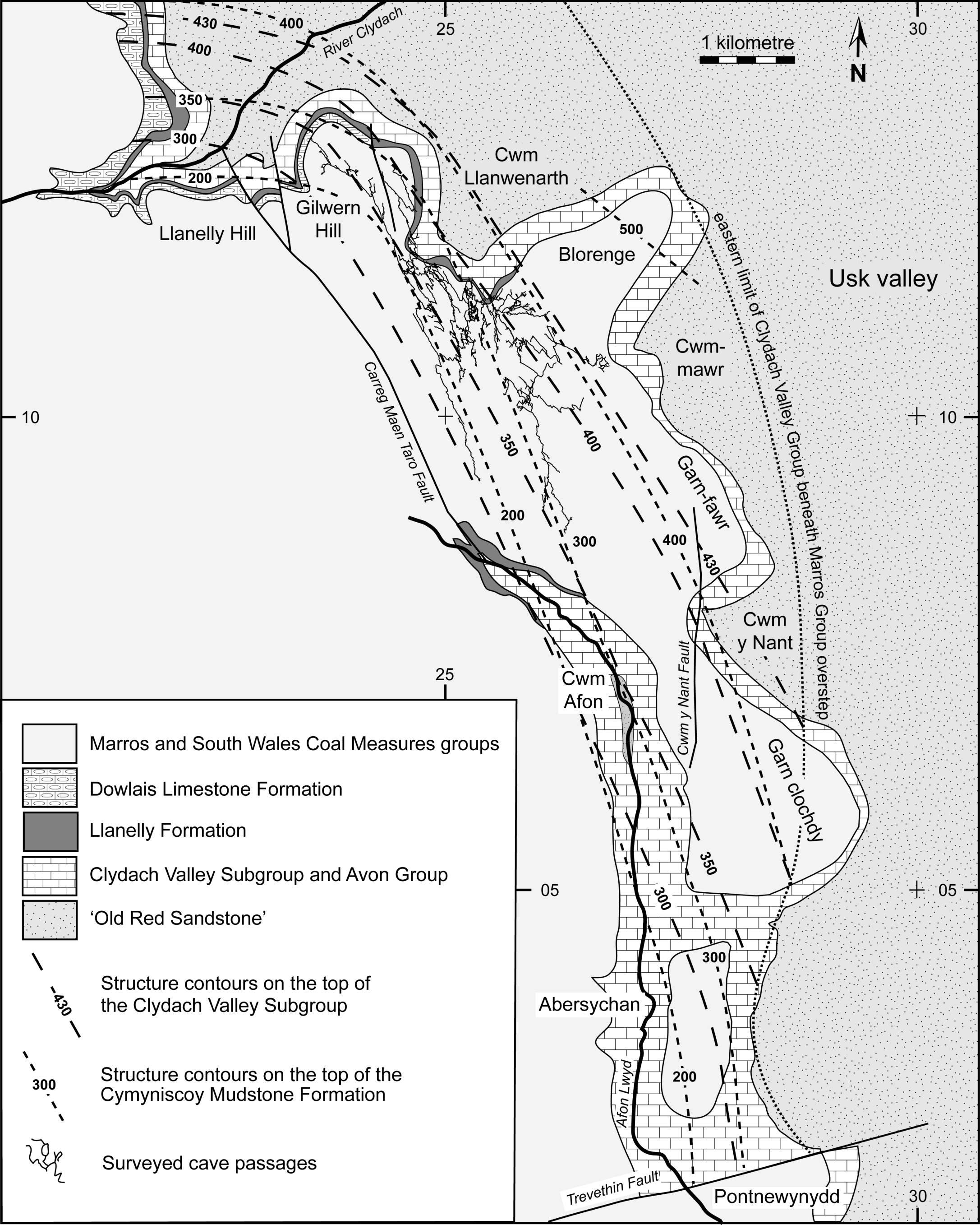
Figure 9. *Diagrammatic long-section through the Lwyd valley, showing geometry of the Clydach Valley Subgroup aquifer, its relationship to the river profile through time, and the relationship of both to the location of resurgences and sinks in the floor of the valley.*


Brecon
BLACK MOUNTAINS
BRECON BEACONS
Usk
Crickhowell
Abergavenny
Mellte
Hepste
Taff Fawr
Taff Fechan
Twrck
Loughor
Brynamman
Clydach
Blaenavon
Merthyr Tydfil
Neath
Tawe
Pontypool
Lwyd
Marros and South Wales Coal Measures groups
Pembroke Limestone and Avon groups
'Old Red Sandstone'
0 km 10
N

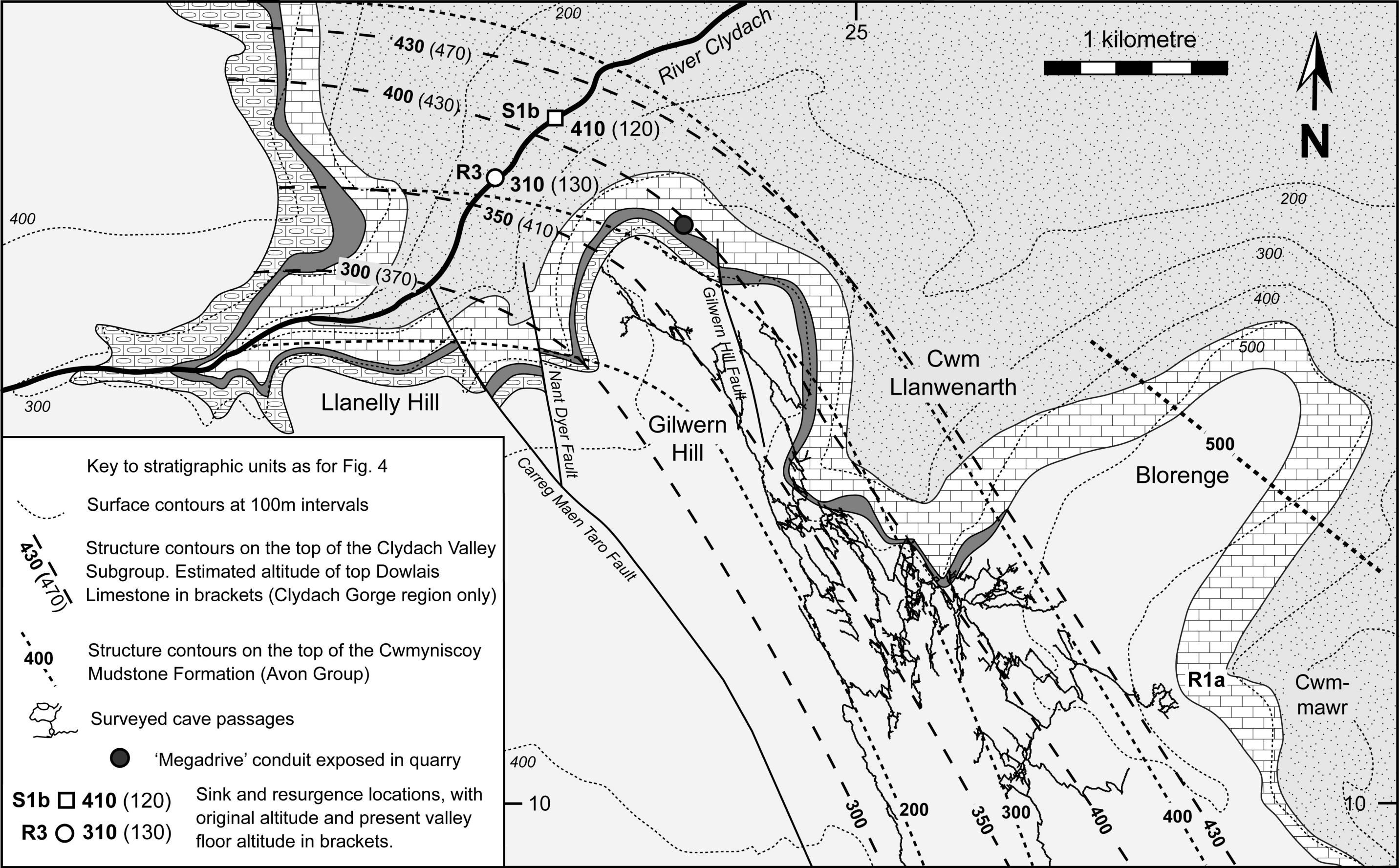

Entrance
Gilwern Passage
Strawberry Passage
Indiana Highway
Megadrive
Beyond A Choke
Raiders Passage
Canyon West
Bolder Land
N
0
250
500
metres
Entrance
Life on Mars
Pontypool or Bust
War of the Worlds
Luck of the Draw
Tractor Tracks
Elliptic Passage
Squirrel Rifts
Chocolate Blorenge



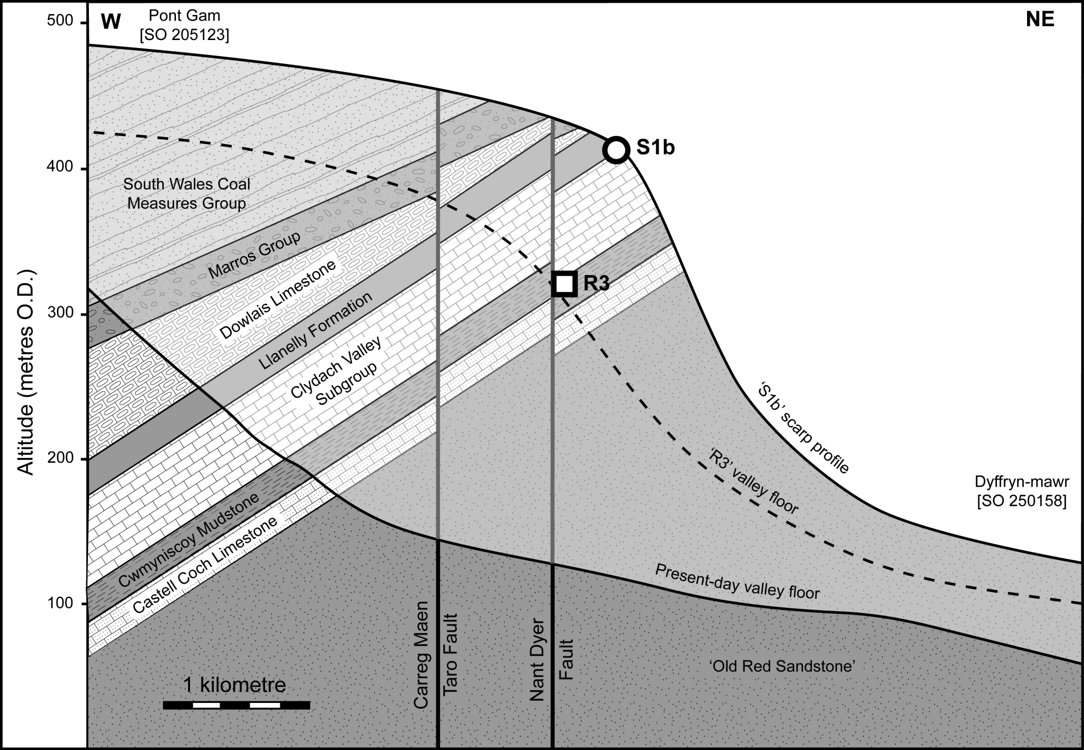
Marros Group
150 m
100 m
50 m
0 m
Tabular limestone
Oolitic limestone
Thinly-bedded limestone
Dolomitic limestone
Mudstone
Conglomerate
aquifers
aquicludes
Dowlais Limestone Formation
Gilwern Clay Member
Penllwyn Oolite Member
Cheltenham Limestone Member
Clydach Halt Member
Llanelly Formation
Pembroke Limestone Group
Gilwern Oolite Formation
Darren Ddu Member
Coed Ffyddlwn Formation
Blaen Onnen Oolite Formation
Pantydarren Formation
Pwll y Cwm Oolite Formation
Sychnant Dolomite Formation
Clydach Valley Subgroup
Cwmyniscoy Mudstone Formation
Castell Coch Limestone Formation
Avon Group
Quartz Conglomerate Group

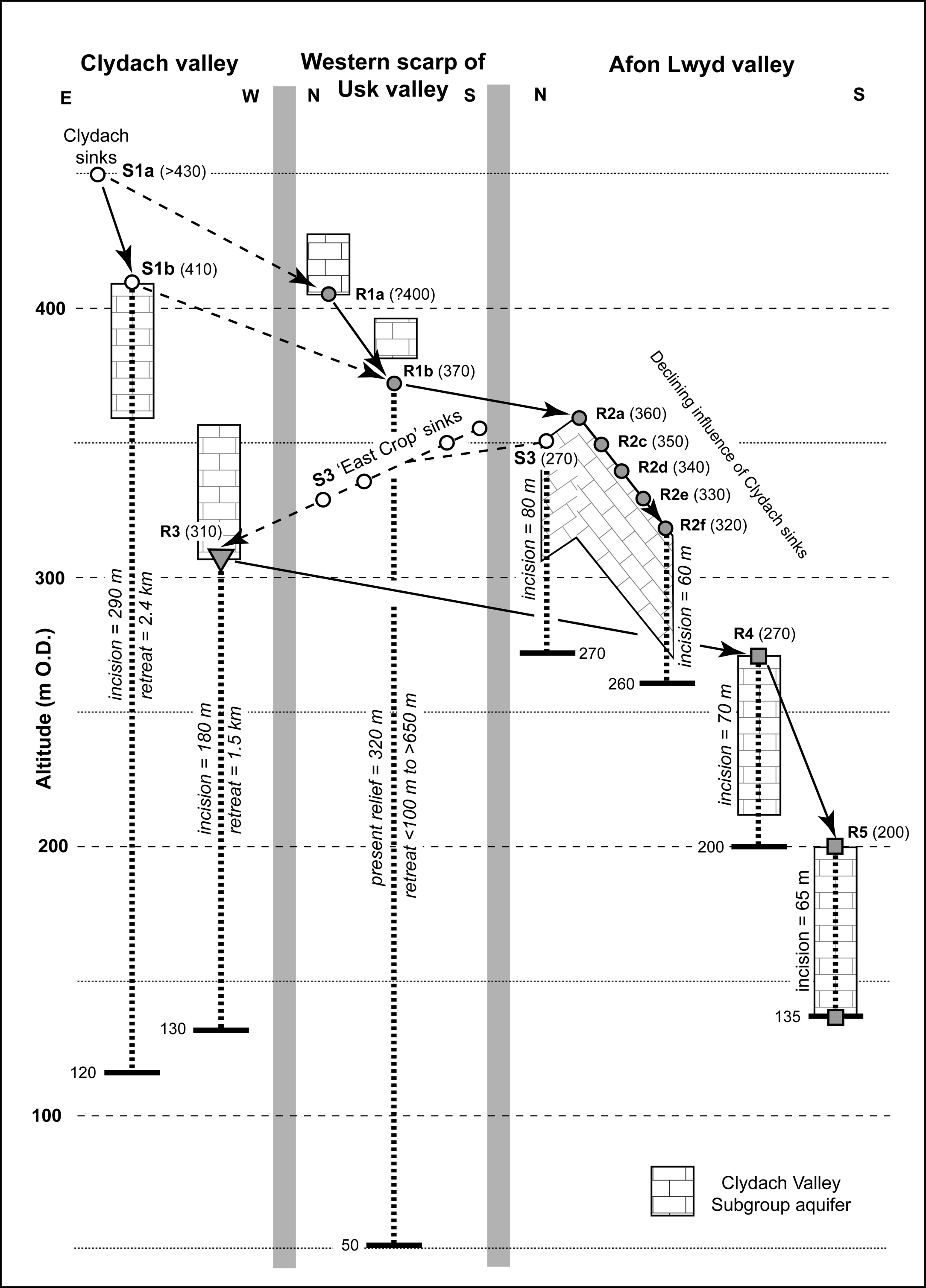


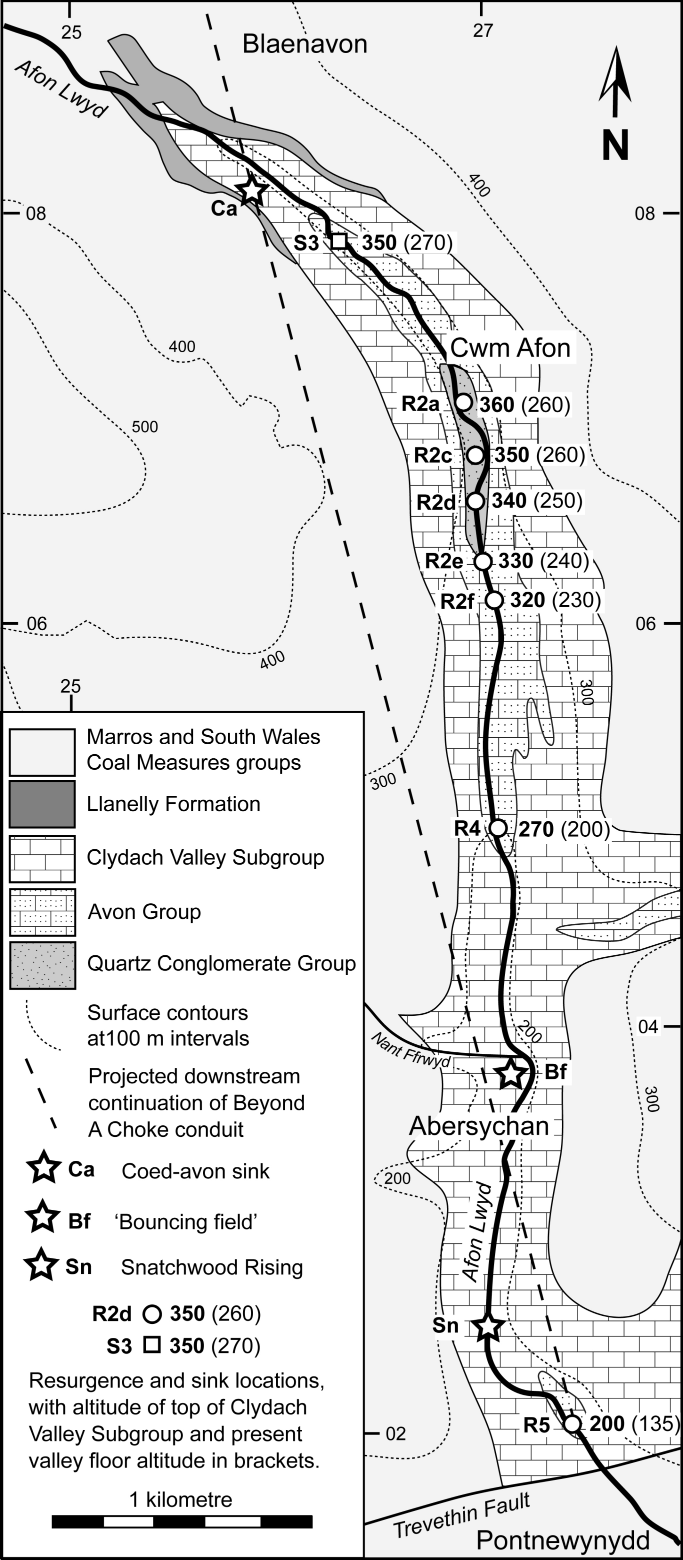
River Clydach
1 kilometre
N
25
30
430
400
400
350
300
200
Cwm
Llanwenarth
Llanelly Hill
Gilwern
Hill
500
Blorenge
Usk valley
eastern limit of Clydach Valley Group beneath Marros Group overstep
Cwm-
mawr
Carreg Maen Taro Fault
10
10
350
400
Garn-fawr
200
300
400
430
Cwm
y Nant
25
Cwm
Afon
Cwm y Nant Fault
Garn clochdy
350
05
05
300
300
Abersychan
200
Afon Lwyd
Trevethin Fault
Pontnewynydd
30
Marros and South Wales Coal Measures groups
Dowlais Limestone Formation
Llanelly Formation
Clydach Valley Subgroup and Avon Group
'Old Red Sandstone'
430
Structure contours on the top of
the Clydach Valley Subgroup
300
Structure contours on the top of the
Cymyniscoy Mudstone Formation
Surveyed cave passages



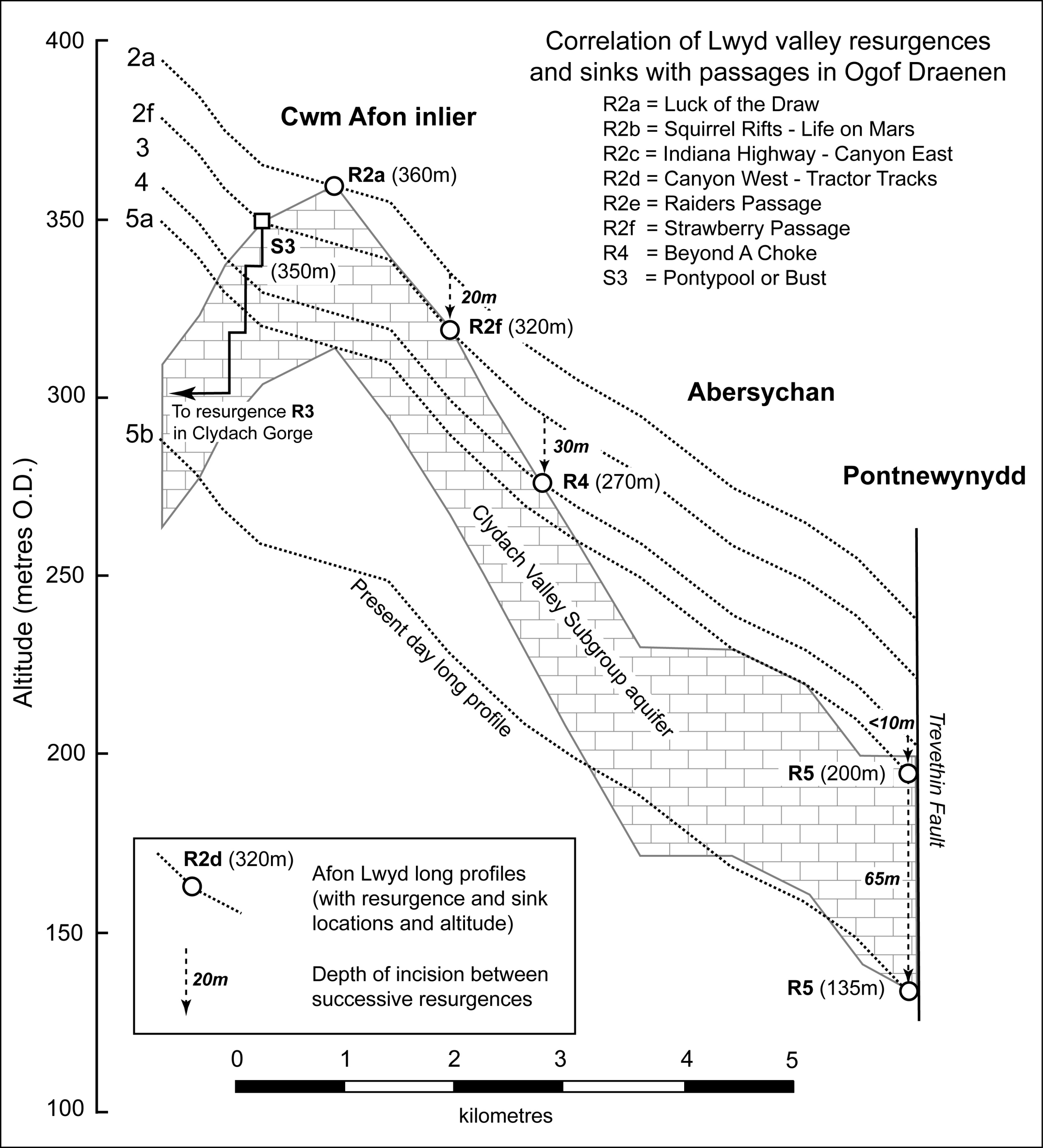
1 kilometre
N
25
10
10
River Clydach
S1b
410 (120)
R3
310 (130)
430 (470)
400 (430)
350 (410)
300 (370)
200
400
300
200
300
400
500
500
400
Llanelly Hill
Gilwern Hill
Cwm Llanwenarth
Blorenge
R1a
Cwm-mawr
Gilwern Hill Fault
Nant Dyer Fault
Carreg Maen Taro Fault
300
200
350
300
400
400
430
Key to stratigraphic units as for Fig. 4
Surface contours at 100m intervals
Structure contours on the top of the Clydach Valley Subgroup. Estimated altitude of top Dowlais Limestone in brackets (Clydach Gorge region only)
430 (470)
400
Structure contours on the top of the Cwmyniscoy Mudstone Formation (Avon Group)
Surveyed cave passages
'Megadrive' conduit exposed in quarry
S1b □ 410 (120)
R3 ○ 310 (130)
Sink and resurgence locations, with original altitude and present valley floor altitude in brackets.

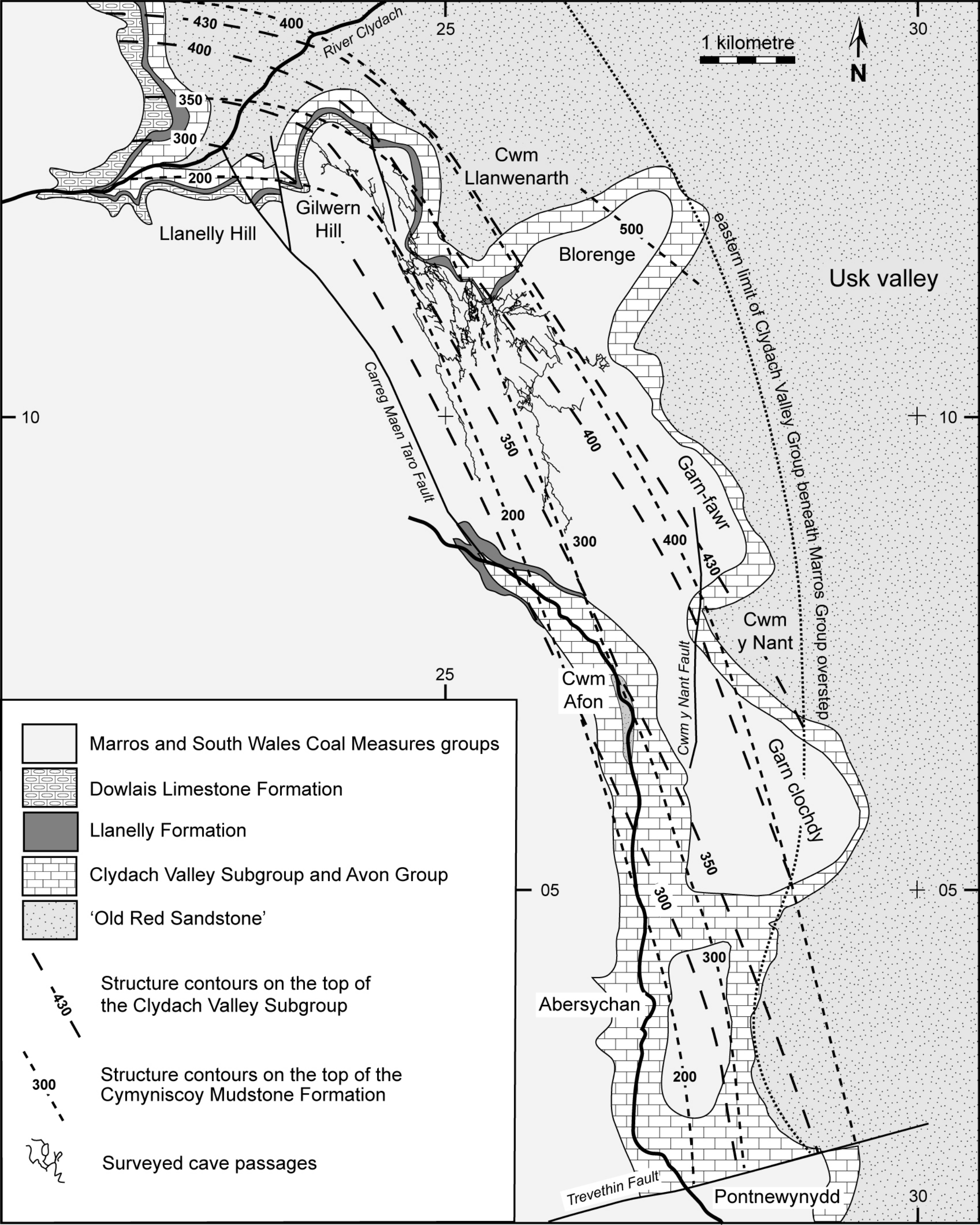

W
Pont Gam
[SO 205123]
NE
500
400
300
200
100
Altitude (metres O.D.)
S1b
R3
South Wales Coal
Measures Group
Marros Group
Dowlais Limestone
Llanelly Formation
Clydach Valley
Subgroup
Cwmyniscoy Mudstone
Castell Coch Limestone
'S1b' scarp profile
'R3' valley floor
Present-day valley floor
Dyffryn-mawr
[SO 250158]
'Old Red Sandstone'
1 kilometre
Carreg Maen
Taro Fault
Nant Dyer
Fault


Clydach valley
Western scarp of Usk valley
Afon Lwyd valley
E
W
N
S
N
S
Clydach sinks
S1a (>430)
S1b (410)
R1a (?400)
R1b (370)
R2a (360)
R2c (350)
R2d (340)
R2e (330)
R2f (320)
S3 'East Crop' sinks
S3 (270)
R3 (310)
R4 (270)
R5 (200)
Declining influence of Clydach sinks
400
300
200
100
Altitude (m O.D.)
incision = 290 m
retreat = 2.4 km
incision = 180 m
retreat = 1.5 km
present relief = 320 m
retreat <100 m to >650 m
incision = 80 m
incision = 60 m
incision = 70 m
incision = 65 m
120
130
50
270
260
200
135
Clydach Valley
Subgroup aquifer

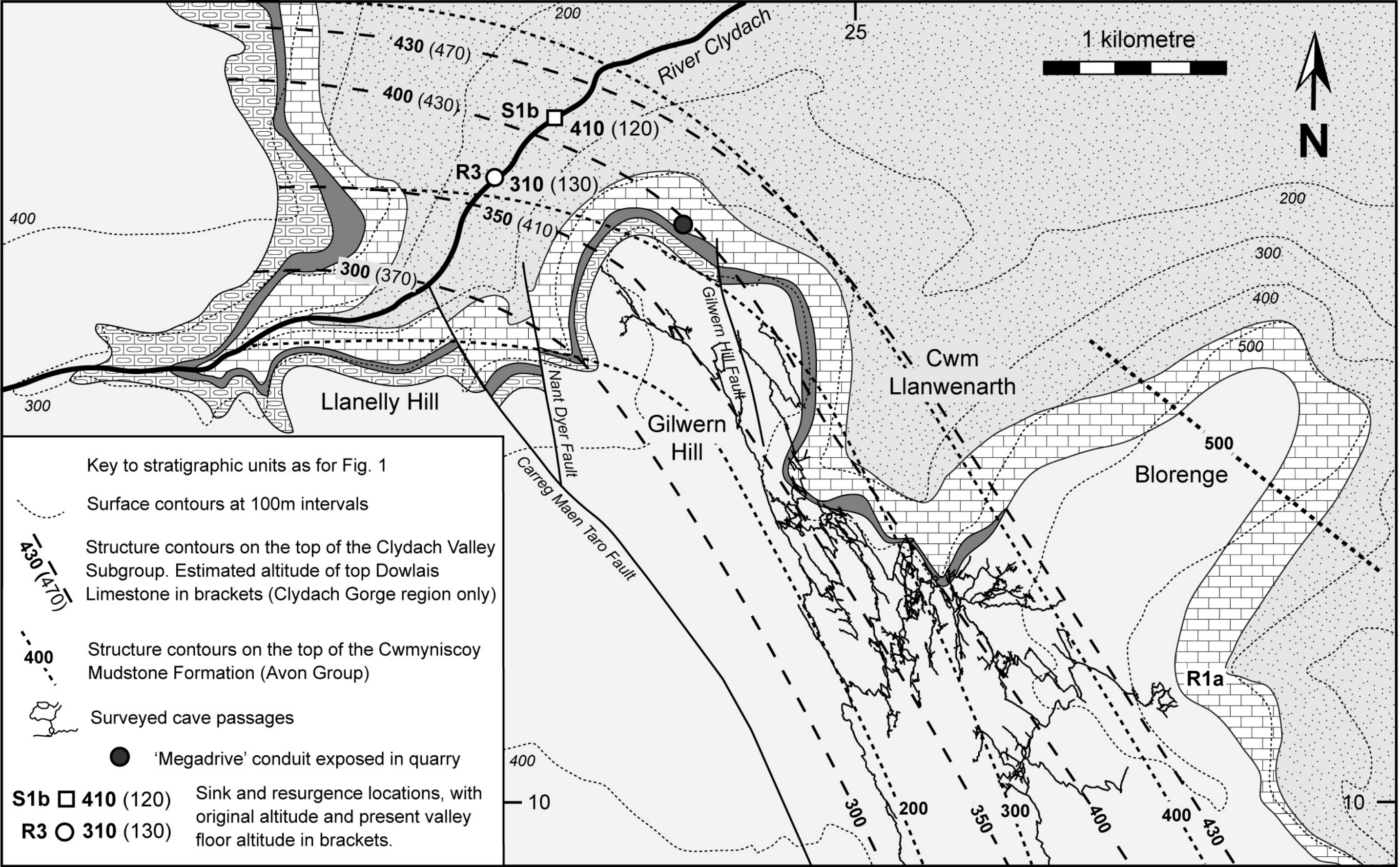


25
27
Blaenavon
Afon Lwyd
N
400
08
Ca
S3
350 (270)
08
400
500
Cwm Afon
R2a
360 (260)
R2c
350 (260)
R2d
340 (250)
R2e
330 (240)
R2f
320 (230)
06
400
06
25
300
300
R4
270 (200)
Marros and South Wales Coal Measures groups
Llanelly Formation
Clydach Valley Subgroup
Avon Group
Quartz Conglomerate Group
Surface contours at100 m intervals
Projected downstream continuation of Beyond A Choke conduit
Ca Coed-avon sink
Bf 'Bouncing field'
Sn Snatchwood Rising
R2d 350 (260)
S3 350 (270)
Resurgence and sink locations, with altitude of top of Clydach Valley Subgroup and present valley floor altitude in brackets.
1 kilometre
04
200
Nant Ffrwyd
Bf
300
Abersychan
200
Afon Lwyd
Sn
R5
200 (135)
02
Trevethin Fault
Pontnewynydd

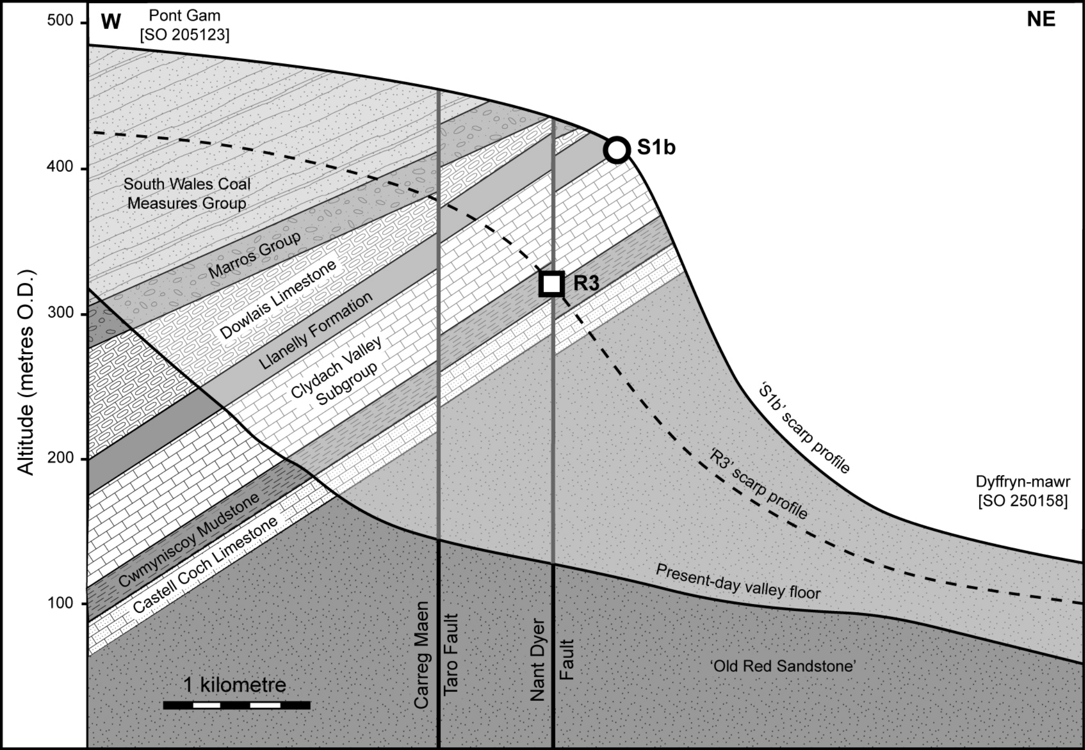

Correlation of Lwyd valley resurgences and sinks with passages in Ogof Draenen
R2a = Luck of the Draw
R2b = Squirrel Rifts - Life on Mars
R2c = Indiana Highway - Canyon East
R2d = Canyon West - Tractor Tracks
R2e = Raiders Passage
R2f = Strawberry Passage
R4 = Beyond A Choke
S3 = Pontypool or Bust
Cwm Afon inlier
Abersychan
Pontnewynydd
Altitude (metres O.D.)
400
350
300
250
200
150
100
2a
2f
3
4
5a
5b
R2a (360m)
S3 (350m)
20m
R2f (320m)
30m
R4 (270m)
<10m
R5 (200m)
65m
R5 (135m)
To resurgence R3 in Clydach Gorge
Clydach Valley Subgroup aquifer
Present day long profile
Trevethin Fault
R2d (320m)
Afon Lwyd long profiles (with resurgence and sink locations and altitude)
20m
Depth of incision between successive resurgences
0
1
2
3
4
5
kilometres

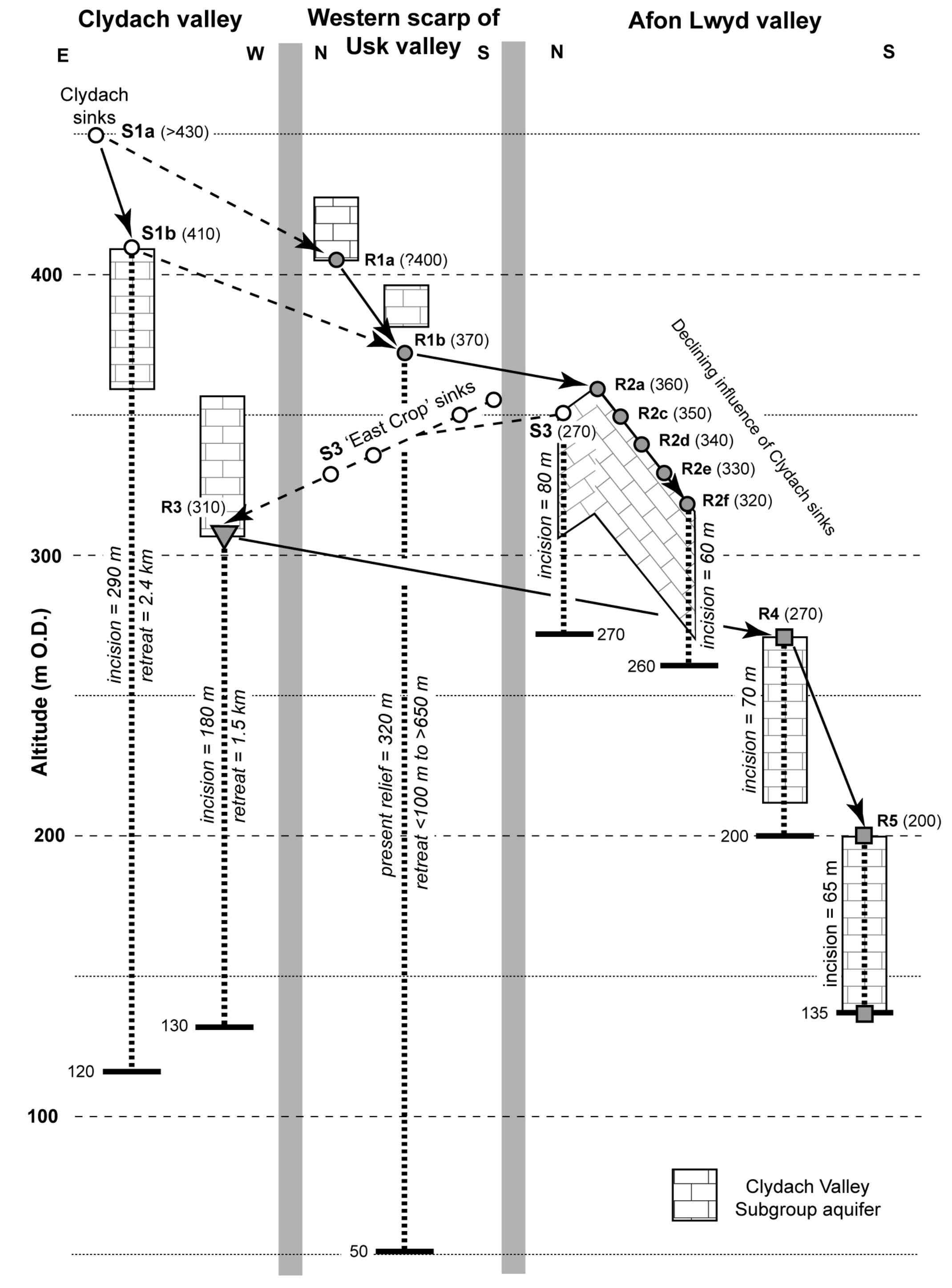


River Clydach
25
30
1 kilometre
N
430
400
400
350
300
200
Cwm
Llanwenarth
Gilwern
Hill
Llanelly Hill
500
Blorenge
Usk valley
eastern limit of Clydach Valley Group beneath Marros Group overstep
Carreg Maen Taro Fault
10
10
350
400
Garn-fawr
200
300
400
430
Cwm
y Nant
25
Cwm
Afon
Cwm y Nant Fault
Garn clochdy
350
05
05
300
300
Abersychan
200
Trevethin Fault
Pontnewynydd
30
Marros and South Wales Coal Measures groups
Dowlais Limestone Formation
Llanelly Formation
Clydach Valley Subgroup and Avon Group
'Old Red Sandstone'
430
Structure contours on the top of
the Clydach Valley Subgroup
300
Structure contours on the top of the
Cymyniscoy Mudstone Formation
Surveyed cave passages

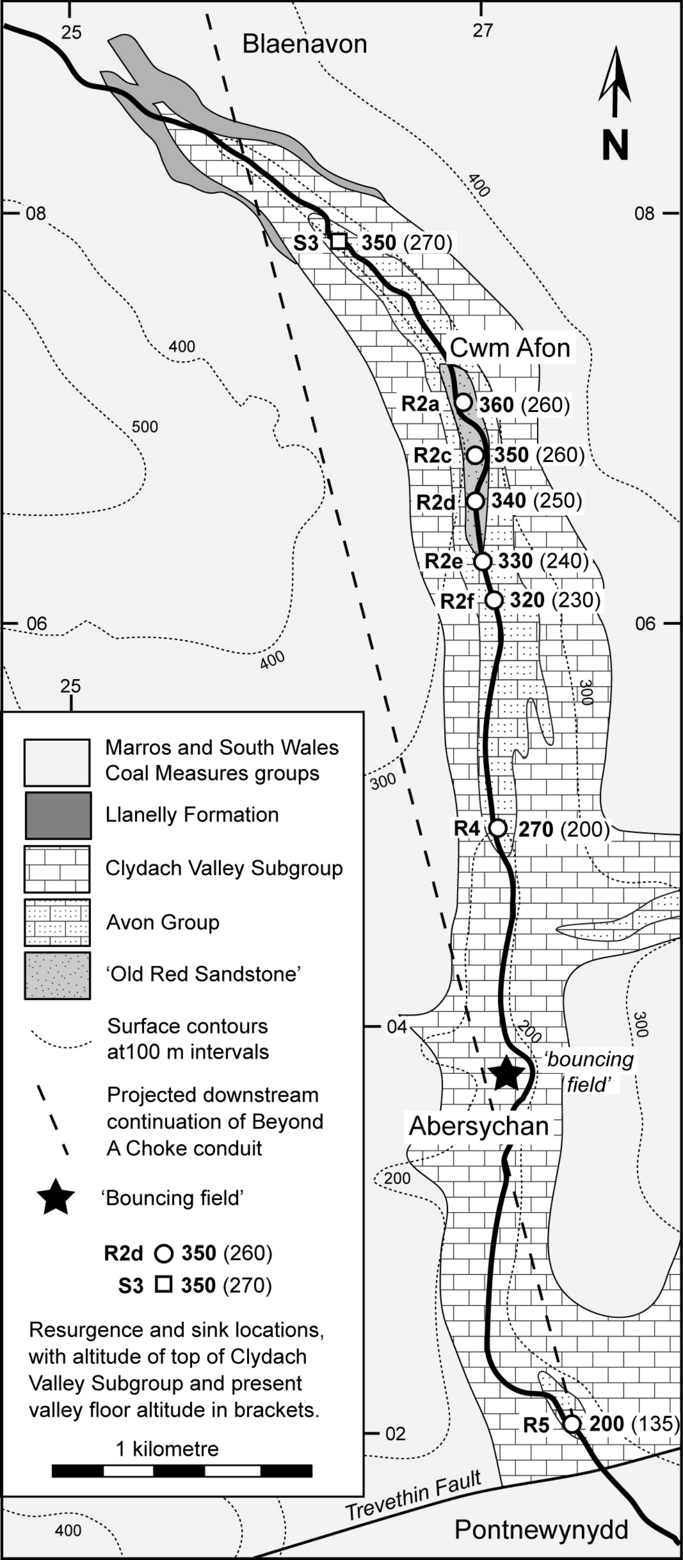


River Clydach
25
1 kilometre
N
200
430 (470)
400 (430)
S1b
410 (120)
R3
310 (130)
350 (410)
300 (370)
400
300
200
300
400
500
Cwm Llanwenarth
Llanelly Hill
Gilwern Hill
Gilwern Hill Fault
Nant Dyer Fault
Carreg Maen Taro Fault
Blorenge
500
R1a
400
10
10
300
200
350
300
400
400
430
Key to stratigraphic units as for Fig. 1
Surface contours at 100m intervals
430 (470)
Structure contours on the top of the Clydach Valley Subgroup. Estimated altitude of top Dowlais Limestone in brackets (Clydach Gorge region only)
400
Structure contours on the top of the Cwmyniscoy Mudstone Formation (Avon Group)
Surveyed cave passages
'Megadrive' conduit exposed in quarry
S1b □ 410 (120)
R3 ○ 310 (130)
Sink and resurgence locations, with original altitude and present valley floor altitude in brackets.

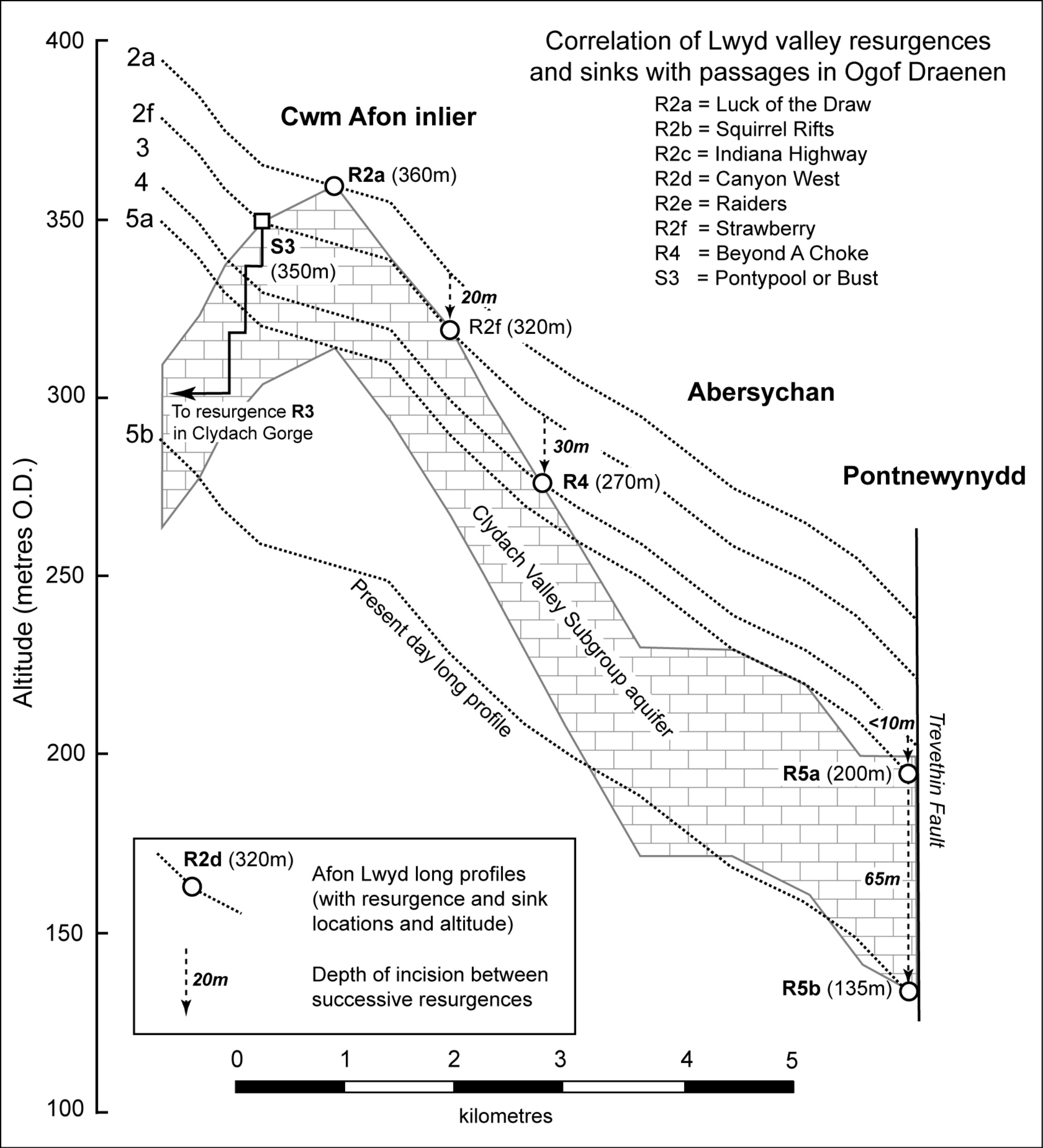

W
Pont Gam
[SO 205123]
NE
500
400
300
200
100
Altitude (metres O.D.)
S1b
R3
South Wales Coal
Measures Group
Marros Group
Dowlais Limestone
Llanelly Formation
Clydach Valley
Subgroup
Cwmyniscoy Mudstone
Castell Coch Limestone
'S1b' scarp profile
'R3' scarp profile
Dyffryn-mawr
[SO 250158]
Present-day valley floor
'Old Red Sandstone'
1 kilometre
Carreg Maen
Taro Fault
Nant Dyer
Fault



Clydach valley
Western scarp of Usk valley
Afon Lwyd valley
E
W
N
S
N
S
Clydach sinks
S1a (>430)
S1b (410)
R1a (?400)
R1b (370)
R2a (360)
R2c (350)
R2d (340)
R2e (330)
R2f (320)
S3 (270)
S3 'East Crop' sinks
R3 (310)
R4 (270)
R5 (200)
Declining influence of Clydach sinks
Altitude (m O.D.)
400
300
200
100
incision = 290 m
retreat = 2.4 km
incision = 180 m
retreat = 1.5 km
present relief = 320 m
retreat <100 m to >650 m
incision = 80 m
incision = 60 m
incision = 70 m
incision = 65 m
120
130
50
270
260
200
135
Clydach Valley Subgroup aquifer



25
27
Blaenavon
N
400
08
08
S3 350 (270)
400
Cwm Afon
R2a 360 (260)
500
R2c 350 (260)
R2d 340 (250)
R2e 330 (240)
R2f 320 (230)
06
06
400
25
300
300
Marros and South Wales Coal Measures groups
Llanelly Formation
Clydach Valley Subgroup
Avon Group
'Old Red Sandstone'
Surface contours at100 m intervals
Projected downstream continuation of Beyond A Choke conduit
'Bouncing field'
R2d 350 (260)
S3 350 (270)
Resurgence and sink locations, with altitude of top of Clydach Valley Subgroup and present valley floor altitude in brackets.
1 kilometre
R4 270 (200)
300
04
200
'bouncing field'
Abersychan
200
R5 200 (135)
02
Trevethin Fault
400
Pontnewynydd


Correlation of Lwyd valley resurgences and sinks with passages in Ogof Draenen
R2a = Luck of the Draw
R2b = Squirrel Rifts
R2c = Indiana Highway
R2d = Canyon West
R2e = Raiders
R2f = Strawberry
R4 = Beyond A Choke
S3 = Pontypool or Bust
Cwm Afon inlier
Abersychan
Pontnewynydd
2a
2f
3
4
5a
5b
R2a (360m)
S3 (350m)
20m
R2f (320m)
30m
R4 (270m)
<10m
R5a (200m)
65m
R5b (135m)
To resurgence R3 in Clydach Gorge
Clydach Valley Subgroup aquifer
Present day long profile
Trevethin Fault
Altitude (metres O.D.)
400
350
300
250
200
150
100
0
1
2
3
4
5
kilometres
R2d (320m)
Afon Lwyd long profiles (with resurgence and sink locations and altitude)
20m
Depth of incision between successive resurgences