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Speleogenetic evidence from Ogof Draenen for a pre-Devensian glaciation in the Brecon Beacons, South Wales, UK

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ABSTRACT: The British Isles have been affected by as many as 30 glaciations during the Quaternary. However, the evidence for pre-Devensian glaciations in upland regions is scarce. Understanding the extent and timing of earlier upland glaciations is essential for modelling the long-term evolution and sensitivity of the British Ice Sheet. Caves, being protected from surface erosion and weathering, can preserve evidence of earlier glaciations in the form of speleothem and sediment archives. The ~70-km-long Ogof Draenen cave system in South Wales, UK, contains multiple cave levels related to changes in the surface topography and drainage during the past 0.5 Ma. The cave contains evidence of massive influxes of sediment that were sufficient to choke the cave and alter the underground drainage. Analysis of the cave sediments, passage morphology and geometry suggests the cave once acted as a subterranean glacial spill-way before being overridden by ice. Speleothem U-series data demonstrate that this sediment influx occurred before Marine Isotope State (MIS) 9, probably during the Anglian glaciation (MIS 12). Evidence from Ogof Draenen indicates the impact of subsequent glaciations on the landscape evolution of the region was minimal and that much of the surface topography dates from the Anglian. Copyright © 2014 British Geological Survey (NERC). Journal of Quaternary Science © 2014 John Wiley & Sons Ltd.

KEYWORDS: glaciation; landscape evolution; Ogof Draenen; speleothem; U-series dating; U – Th; Wales.

Introduction

Most of the upland karst areas in the north and west of the UK have been glaciated multiple times during the past million years, with the greatest advances during Marine Isotope Stage (MIS) 12 (Anglian) and MIS 2 (Devensian) glaciations. Until recently there was evidence for only a small number of glaciations in the UK (Bowen *et al.*, 1986; Bowen, 1999; Clark *et al.*, 2004). Now perhaps as many as 30 glaciations are known (Toucanne *et al.*, 2009; Lee *et al.*, 2011, 2012; Böse *et al.*, 2012; Thierens *et al.*, 2012), dating back about 2.6 Ma, although the timing of many remains equivocal. Equally, recent work has shown that the climatic thresholds required to build glaciers in Britain were much lower than previously considered with glaciers existing throughout the Little Ice Age (LIA), from the mid-16th to mid-19th centuries (Harrison *et al.*, 2014; Kirkbride *et al.*, 2014). Collectively, they indicate the British Ice Sheet (BIS) was as dynamic and responsive as other Northern Hemisphere ice sheets, and highly responsive to even subtle changes in climate.

Frequently, the evidence for pre-Devensian glacial activity in many upland areas is often lacking, and is often inferred only from exotic clasts in river terrace deposits (Whiteman and Rose, 1992). Typically this absence is attributed to the erosional effect of Devensian ice sheets removing any evidence of former glaciations, particularly during the Last Glacial Maximum (LGM). Bias in the glacial record is particularly evident in South Wales, where evidence for pre-Devensian glaciations is scarce and limited to lowland areas. The Llanddewi Glacigenic Formation on the Gower Peninsula is the only unequivocal Anglian age deposit in South Wales, and represents the margins of the Welsh ice sheet at this time (Gibbard and Clark, 2011).

Based on geomorphological analysis and dating of cave sediments and speleothems, it is clear that cave systems in upland areas of the UK often pre-date the last glaciation (Waltham *et al.*, 1997) and, in some cases, extend back to the early Pleistocene (Rowe *et al.*, 1988; Lundberg *et al.*, 2010; Waltham and Lowe, 2013). These caves can preserve evidence of surface processes, including glacial activity over long timescales. Glaciations can have profound and complex effects upon karst landforms and their underlying aquifers, and may destroy, inhibit, preserve or stimulate karst development (Ford *et al.*, 1983; Ford, 1987; Ford and Williams, 2007). Glacially induced valley incision can instigate major changes to underground drainage systems as the conduits adjust to new, lower base levels. These modifications are recorded within cave systems by changes in passage morphology and geometry, and are analogous to fluvial terraces as recorders of base-level change (Palmer, 1987). Some caves, depending on local circumstances, are affected by glacial meltwater, a modern example being Castleguard Cave in Canada (Ford, 1983). Subglacial water flow can be considerable, especially in active, wet-based ice streams, and at the margins of glaciers and ice sheets. Where these are in contact with karstified aquifers, there is scope for significant input of allogenic meltwater into preexisting cave systems (Lauritzen, 1984, 1986), injecting fluvio-glacial sediment deep underground. These caves act as sediment repositories, protected from subsequent weathering and surface erosion processes on timescales up to 10^6 years. Away from active drainage networks, relict cave passages can be preserved untouched with little or no evidence of subglacial modification.

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(Note: Welsh terms used in this paper: Ogof = Cave, Afon = River, Cwm = Valley, Mynydd = Mountain)

Crucially, caves also host speleothem deposits, which can be accurately dated using uranium-series (U-series) methods (Richards and Dorale, 2003; Meyer *et al.*, 2009). These are often interbedded with or overlie cave sediments, thus allowing both the timing of cave formation and sediment deposition to be constrained over the last 500 ka, and with suitable samples, beyond 500 ka using U–Pb methods (Richards *et al.*, 1998). Given the lack of preserved and datable surface material in glaciated upland areas, cave systems offer some of the best prospects for preserving evidence for pre-Devensian landscape evolution. In this study, we present evidence from speleothem U-series dating, cave sediment analysis and speleo-morphological data for pre-Devensian glacial activity in upland areas of South Wales, an area where the preservation of evidence for earlier glaciations is limited.

The study area

The Brecon Beacons in southern Wales comprise a large upland area (900 km^2) situated on the northern edge of the South Wales coalfield (Fig. 1), which occupies a large elongate east–west-orientated synclinal structure 90 km long and 25 km wide. The Brecon Beacons are composed predominantly of Devonian sandstone (the 'Old Red Sandstone'), which dips gently (between 5 and 20°) to the south. These are overlain by Lower Carboniferous limestones and a thick sequence of Upper Carboniferous siliciclastics, including the Twrch Sandstone Formation ('Millstone Grit') and the 'Coal Measures', a cyclical sequence of sandstones and mudstones with some coal seams (Barclay, 1989). The Lower Carboniferous limestones outcrop around the coalfield, locally forming a relatively narrow but well-developed escarpment, especially along the north-eastern edge of the syncline.

The limestones are well-karstified, particularly on the northern edge of the coalfield. Many sinkholes, stream sinks and cave systems are known, with more than 230 km of cave passage discovered and surveyed. Eight of these cave systems each contain over 8 km of passage (Table 1). Together they represent some of the best examples of interstratal cave systems in the UK (Waltham *et al.*, 1997). All are characterized by extensive high-level relict passages perched above more recent active streamways. Most of them contain copious amounts of silty or sandy sediment preserved in the higher level relict passages long abandoned by active streams. This is true of Ogof Draenen, the caves beneath the adjacent Mynydd Llangattock (Agen Allwedd, Daren Cilau and Craig yr Ffynnon; Smart and Gardner, 1989) and Ogof Ffynnon Ddu, 40 km further west (Smart and Christopher, 1989). This study is focused on Ogof Draenen, where a detailed examination of the cave geomorphology (Farrant and Simms, 2011; Farrant and Smart, 2011) coupled with U-series dating of speleothems from the cave, has enabled a detailed chronology of the cave's formation and sedimentary history to be constructed.

Table 1. Major cave systems of South Wales.

Cave system	Location	Length (km)	Depth (m)
Ogof Draenen	Blaenavon	~70.0	151
Ogof Ffynnon Ddu	Upper Tawe valley	~50.0	308
Agen Allwedd	Mynydd Llangattock	32.5	160
Ogof Daren Cilau	Mynydd Llangattock	28.0	232
Dan-yr-Ogof	Upper Tawe valley	16.0	150
Ogof Carno	Mynydd Llangyndir	8.9	63
Little Neath River Cave	Ystradfellte	8.8	125
Ogof Craig A Ffynnon	Mynydd Llangattock	8.0	115

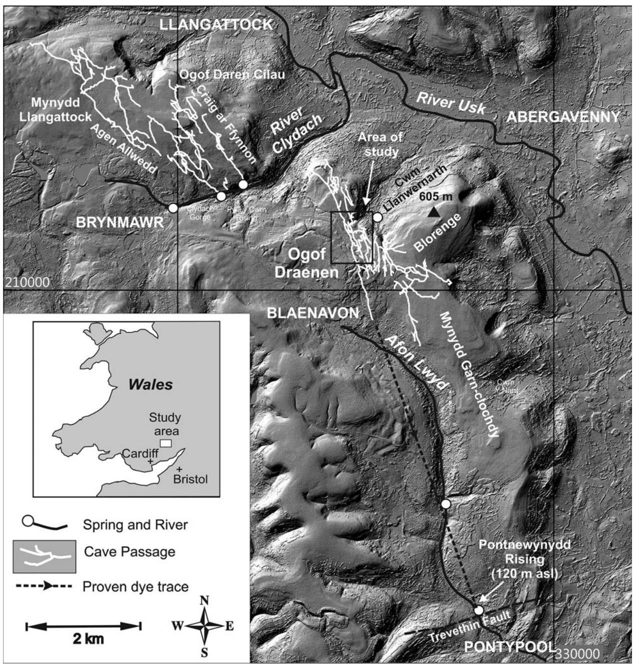

Figure 1. NEXTMap® hill-shaded surface model image of the north-eastern part of the South Wales coalfield and the Usk valley, showing the location of Ogof Draenen and the Mynydd Llangattock cave systems. NEXTMap® Britain elevation data from Intermap Technologies.

Ogof Draenen

Ogof Draenen (51.79966°N, 3.09439°W) is a complex multi-phase intrastratal cave system located near Blaenavon, 6 km south-west of Abergavenny, South Wales (Fig. 1). It currently stands as one of the longest cave systems in the UK, with ~70 km of surveyed passages spanning a vertical range of >150 m (Stevens, 1997; Waltham *et al.*, 1997). The cave underlies Gilwern Hill, The Blorenge and Mynydd y Garnfawr, which together form the interfluve between the deeply incised Usk valley and the smaller Afon Lwyd valley. The cave has a long and complex history (Simms *et al.*, 1996; Waltham *et al.*, 1997) which is discussed in detail by Farrant and Simms (2011). Speleogenesis combined with valley incision and base-level lowering has left a vertically stacked series of relict passages preserved in the limestone beneath the Twrch Formation cap-rock. The highest and therefore the oldest cave levels are preserved up to 150 m above the present cave stream with progressively younger, lower passages developed sequentially down dip to the west. Tracer tests show the cave stream resurges 6 km beyond the present southern limit of the cave in Pontypool (Maurice and Guilford, 2011). A relative chronology of cave evolution has been constructed from speleo-morphological observations throughout the cave, including passage geometry, dimensions and morphology, and the analysis of palaeoflow directions from dissolutional scallops, stratified cave deposits, cross bedding and ripple marks. Other observations, such as the transition from vadose to phreatic passage morphologies, have enabled palaeo-watertable elevations to be fixed. Analysing the relationship between aquifer geometry, surface topography and the various active and relict conduits in Ogof Draenen has enabled us to relate these palaeo-watertable elevations and cave levels to changes in the surface landscape (Simms and Farrant, 2011).

Ogof Draenen comprises four vertically stacked, genetically separate cave systems linked by phreatic under-captures (passages developed in the phreatic zone by water draining from an existing conduit into a newer conduit), shaft drains, chance passage intersections and invasive vadose inlets. Only the lowest level is hydrologically active today, although some relict passages contain misfit streams. The present autogenic catchment is very small because the limestone forms only a relatively narrow outcrop along the steep scarp of the Usk valley. Consequently, recharge throughout the cave's history has been predominantly allogenic, derived principally from numerous small streams draining the Upper Carboniferous siliciclastics that overlie the cave. Streams draining the sandstone feed into a series of conduits that drain initially down dip and then trend approximately along strike to resurge at springs in the surrounding valleys. The oldest relict underground drainage system is represented by the Megadrive conduit and the associated War of the Worlds conduit (Fig. 2A). This conduit system drained south-east, roughly along strike to former resurgences at ca. 360 m above sea level (asl) in the Usk valley (Farrant and Simms, 2011). This was abandoned when the drainage was captured southward to a suite of progressively lower resurgences at 360–320 m asl following incision in the Afon Lwyd valley. Continued landscape evolution led to a second major change in the underground drainage pattern, this time in response to valley incision in the Clydach Gorge to the north, effectively reversing the hydraulic gradient. This allowed the development of a new, lower level series of passages, the 'The Score–Gilwern Passage' conduit, to develop down dip to the west. This drained north-west to a former resurgence in the Clydach Gorge at 320–300 m asl (Fig. 2B). Renewed incision in the Afon Lwyd valley caused a second reversal in flow direction, this time to the south. Ultimately, new springs developed 10 km to the south near Pontypool at 120 m asl (Fig. 2C) to which the 'Beyond a Choke' streamway presently drains. Ogof Draenen thus represents a hydrological see-saw, with successive conduits at progressively lower elevations each draining to different resurgences in response to incision in three separate valleys. This sequence of events is thought to span much of the Middle to Late Pleistocene, possibly extending back over a million years into the Early Pleistocene (Simms and Farrant, 2011).

Cave sediments

Cave sediments are a conspicuous feature in parts of Ogof Draenen. Observation of the sediment fills in and around the northern end of the 'Beyond a Choke' streamway and its tributaries (Gilwern Passage, Upstream Passage, 'The Score' and Pen-y-Galchen Passages; Fig. 3) suggests that three distinct sediment facies occur in this area. The first, restricted to the active stream passages, is dominated by coarse, poorly sorted sandy gravel consisting of mostly allogenic, manganese-stained mudstone and sandstone clasts derived from the overlying Upper Carboniferous siliciclastics. Most of the

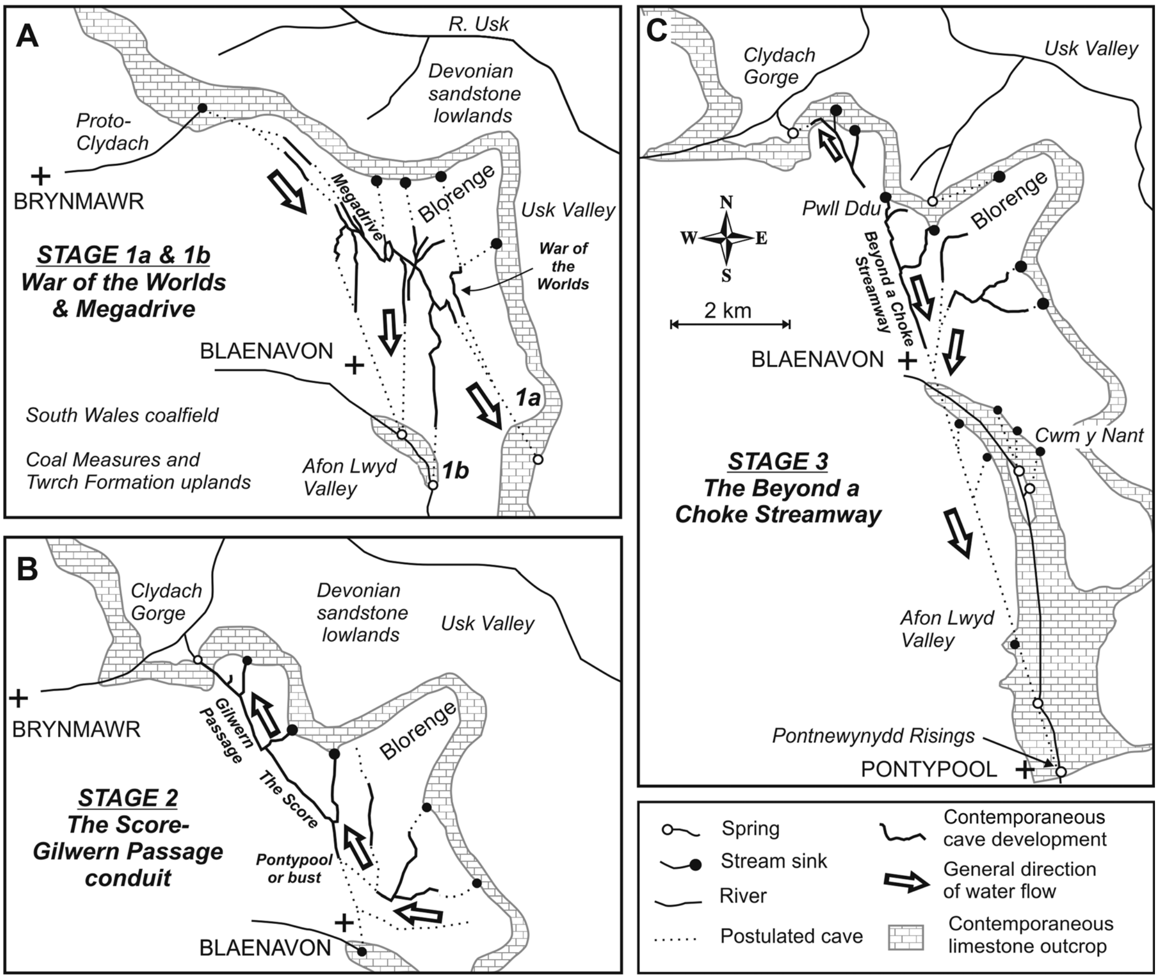

Figure 2. Schematic evolution of the Ogof Draenen system. (A) Initial conduits develop south-east to springs in the Usk valley, subsequently captured to the south by new springs in the Afon Lwyd valley. (B) Incision in the Clydach Gorge allows the north-draining 'The Score–Gilwern Passage' conduit to develop. (C) Renewed incision in the Afon Lwyd allows drainage to revert to the south, creating the 'Beyond a Choke' streamway. More details are given in Farrant and Simms (2011).

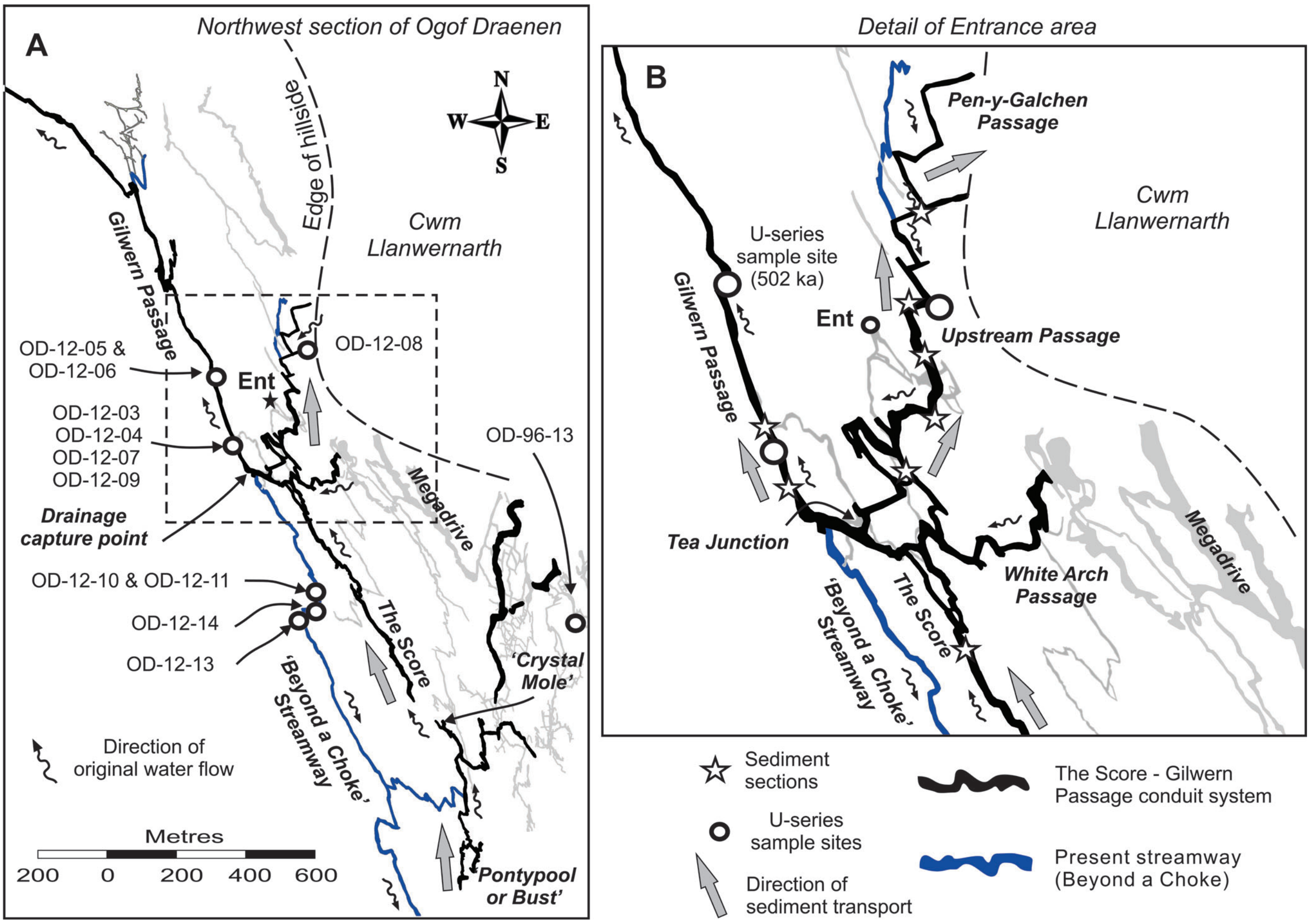

Figure 3. Outline centre-line survey of Ogof Draenen, adapted from surveys by Stevens (1997). (A) Outline survey of the north-western part of the cave. (B) Inset of area around the cave entrance (Ent). The black passages are those developed during the 'The Score–Gilwern Passage' conduit phase of development, while the 'Beyond a Choke' streamway (dark grey) represents the final phase of cave development. Directions of water flow are those when the passage was formed. The rest of the cave is shaded pale grey. The location of the speleothem sample from War of the Worlds (OD-12-02) is shown in Fig. 1. A colour version is available online.

clasts are angular to subrounded. Angular clasts of limestone derived from passage collapse and breakdown are common, but do not appear to be undergoing significant transport. These sediments are typical of the thalweg facies of Bosch and White (2004), where the finer grained component has been winnowed away by stream action. They are common at floor level in the 'Beyond a Choke' streamway and in the upstream tributaries (Upstream Passage and White Arch Passage), where they are generally restricted to the present stream channel. Locally, gravel terraces of similar composition occur up to 0.5 m above the present stream level, representing former channel stages.

The second facies is significantly more extensive and occurs within many of the higher level relict passages in the northern part of Ogof Draenen (Fig. 3), but not in the present streamway to the south of the junction with Gilwern Passage. It occurs as relict sediment banks and remnant deposits preserved up to 21 m above the stream level at Tea Junction. These are characterized by fine- to medium-grained, moderately sorted, pale grey, brown and black, cross-bedded sand, silty sand and silt. Minor amounts of coarse sand and fine gravel comprising mudstone and quartz occur in places, but few large clasts are present. The presence of fine fragments of sandstone and mudstone, together with abundant quartz sand clearly indicates an allogenic source, most probably from the overlying Upper Carboniferous siliciclastics. Sedimentary structures are often picked out by conspicuous, very distinctive, dark grey or black laminae, comprising coal, carbonaceous or manganese-stained material. These cross-bedded sands are more typical of the channel deposits of Bosch and White (2004). Locally these sands are capped by a third facies comprising laminated silts characteristic of the slackwater facies. These silts, up to 1 m thick, have very regular millimetres-scale laminae and in places show minor growth faulting and surface desiccation cracks.

Excellent exposures occur in Gilwern, Upstream and Pen-y-Galchen passages (Fig. 4). In Upstream Passage, laminated silts up to 1 m thick overlie sand and limestone breakdown at an elevation of 320 m. Further upstream, plaques of cross-bedded sands (Fig. 5) can be seen high up on the passage walls, at least 4–5 m above the present passage floor and extending to within a couple of metres of the roof, here around 8–10 m high. Well-defined cross-bedding foresets, ~0.5 m high, are picked out by the dark grey and black carbonaceous or manganiferous laminae and indicate a northerly flow, opposite to that of the present stream. A short distance further on, the large passage ends in a sediment choke comprising 2–3 m of fine-grained dark grey sands with ripple cross-lamination, again showing northward flow. Remnants of similar but coarser sand, also with northerly dipping cross-beds and sometimes cemented by calcite, can be seen on the walls of the adjacent tributary, Pen-y-Galchen Passage, at ca. 320 m asl. This passage is very close to the headwall of Cwm Llanwenarth, a small valley cut into the north-eastern face of the escarpment. The flow directions suggest this passage may have acted as an outlet

Figure 4. Desiccated, cracked laminated silts overlying fine-grained silty sand, draped over breakdown, Upstream Passage. Photo: M. J. Simms. This figure is available in colour online at wileyonlinelibrary.com.

during the period of sediment input, the water resurging into Cwm Llanwenarth. Similar coal-rich sediments occur further south in 'The Score', an inlet passage off White Arch Passage, at 313 m asl. This passage is part of the northward-draining 'The Score–Gilwern Passage' conduit, one of the main drains during the evolution of the cave (Farrant and Simms, 2011). It contains an abundant sandy fill throughout. Similar sands are evident in inlet passages further upstream to the south ('Crystal Mole' passage and 'Pontypool or Bust') where the passages are locally almost choked with sand. Flow markings suggest these inlet passages were the main source of sediment into the northern part of Ogof Draenen. Some side passages contain a conspicuous coating of manganese oxide on the passage walls, probably indicating the maximum level of ponded water. In the Entrance Series, this staining occurs up to ca. 325 m asl. In passages with active streams, most of the fill has since been largely removed; however, abundant evidence of former sediment levels remains on the passage walls and in alcoves. By contrast, the sandy fill and laminated silts are conspicuous by their absence in the 'Beyond a Choke' streamway south of the junction with Gilwern Passage.

It is clear from the distribution of these deposits that these higher level relict passages were largely choked with sediment at some time in the past. These sediments overlie extensive breakdown indicating that they were deposited after a considerable period of vadose incision and collapse, and thus post-date the main period of cave formation. Moreover, the sedimentary structures preserved within the sands in Upstream Passage and its tributaries indicate flow to the north, which is in the opposite direction to the present stream and regional hydraulic gradient (Fig. 2). Cross-bedding suggests sediment-laden water was forced 'upstream' into progressively smaller vadose inlet passages. This implies that when the sediments were emplaced, hydraulic gradients and drainage patterns were locally reversed, at least in Upstream Passage and its tributaries. This must have been a temporary reversal, as these sediments have since been flushed out and the former hydraulic gradients restored. Moreover, despite the large quantities of sediment injected into the system, no

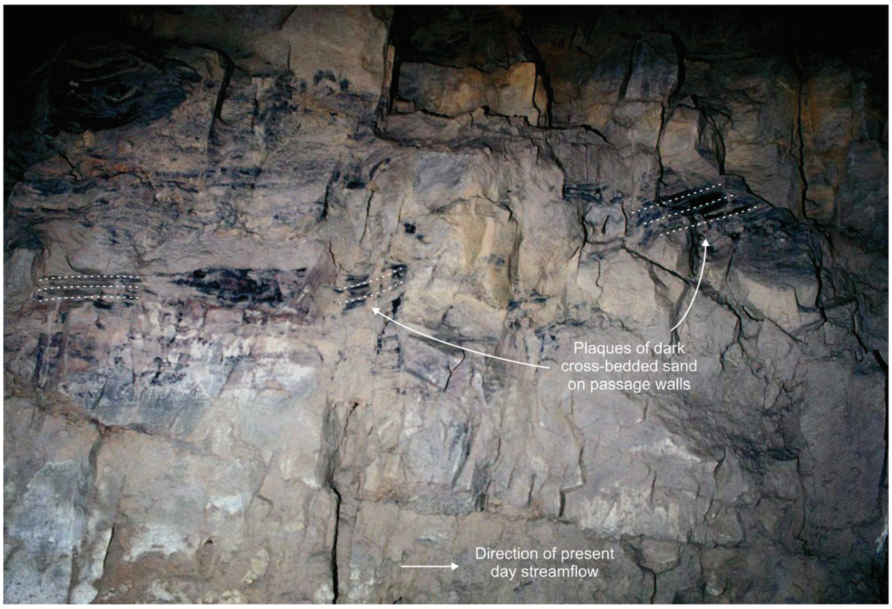

Figure 5. Cemented remnants of cross-bedded carbonaceous sand preserved on the bedrock wall several metres above the floor of Upstream Passage. Cross-bedding picked out by darker lamina indicates flow to the left ('upstream'). Height of face shown is about 3 m. Photo: M. J. Simms. This figure is available in colour online at wileyonlinelibrary.com.

pendants, notches, wall anastomoses, anomalous scalloping or half tubes associated with cave development under conditions of high sediment flux (known as paragenesis, Farrant and Smart, 2011) have been identified in Upstream Passage, Gilwern Passage or their tributaries. This suggests that there was little dissolution or paragenetic overprinting of the existing passage morphology and implies that this episode of sediment emplacement was short-lived. The deposition of the laminated silts indicates a period of ponding after the main sediment infill when this part of the cave was inundated. The lack of any slumping, channelling or other signs of a significant erosional unconformity or any indication of autogenic breakdown at the contact between the sands and the laminated silts suggests that the laminated silts were deposited shortly after the main influx of sediment.

Significantly, no relict sediment deposits occur in the 'Beyond a Choke' streamway, which dominates the drainage in the cave today. This streamway is a relatively late-stage under-capture off the relict 'The Score–Gilwern Passage' conduit (Farrant and Simms, 2011). The point of capture is clearly marked at the southern end of Gilwern Passage where the stream that flows down from Upstream Passage swings south into a smaller, lower level passage, while the roof tube swings north into the higher level Gilwern Passage. The fine-grained sediments that formerly choked the passages under discussion were clearly deposited under very different hydrological conditions from those currently in transport. Today, even in extreme flood conditions, water levels in Upstream Passage are rarely >1 m in depth and 4–6 m below the relict cross-bedded sands observed on the passage walls at the northern end of Upstream Passage. Very little sediment is transported during these floods; indeed, many of the gravel banks in the inlet streams are cemented with a manganese and iron oxide coating (Gascoyne, 1982).

To characterize these sediment facies, samples were collected from over 30 sites and subjected to clast size, lithology and facies analyses (Pash, 2003; Trowbridge, 2003). Clast lithology data from the cave and two surface streams for comparison are shown in Table 2 while particle size cumulative frequency graphs are shown in Fig. 6. The evidence clearly indicates the finer grained carbonaceous deposits seen in Gilwern Passage, The Score and Upstream Passage are significantly different from the poorly sorted sand and gravel within the 'Beyond a Choke' streamway regarding composition, fabric and volume of sediment in transport. Analysis of the sediments suggests both facies seen in Ogof Draenen are fluvial in origin, but they are genetically distinct.

Table 2. Clast lithologies for the 2000–3350-mm particle size range (mean%) for the present 'Beyond a Choke' streamway (BAC), Gilwern Passage (GP) and two surface sites representing typical examples of glacial till (Till) and a stream draining the Coal Measures outcrop (CM). 'Total Sandstone' is a combination of the Twrch Formation and Devonian sandstone. Glacial till samples were collected from Forgeside, near Blaenavon (51.77243°N, 3.09258°W), while the Coal Measures sample was taken from a tributary feeding the River Clydach (51.80598°N, 3.13908°W]. Data from Pash (2003).

Lithology	BAC	GP	Till	CM
Mudstone (Shale)	67.4	58.9	28.0	100.0
Sandstone	16.2	20.7	38.4	0
Twrch Fm	7.1	11.5	25.1	0
Quartz	6.7	7.5	6.5	0
Limestone	1.1	0.7	0.0	0
Total sandstone	23.3	32.2	63.5	0
Carbonaceous clasts	1.4	0.7	2.0	0

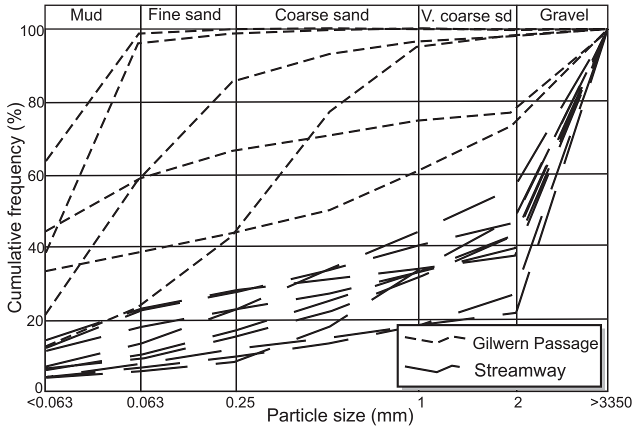

Figure 6. Cumulative frequency plots for the streamway and Gilwern Passage sediments.

As such they must have been brought into the cave system under very different hydrological conditions. The sediments currently in transport in the 'Beyond a Choke' streamway can be fairly easily explained as winnowed lag gravels reworked from some of the older relict fills, with an admixture of fresh allogenic material brought in by surface streams and collapse, and some autogenic breakdown. However, the origin of the finer grained, high-level, relict sediments is more problematic. Fluvial transport under present climatic conditions in Ogof Draenen or any other caves in South Wales cannot account for these anomalous sediments. The required increase in allogenic sediment production, injection and deposition sufficient to clog up and reverse the existing vadose drainage network indicates major changes in the surface catchment. The most plausible explanation is that the sediments were emplaced during glacial or pro-glacial conditions when glacial meltwater was able to transport significant amounts of sediment into the cave. This hypothesis has been invoked for the extensive sediment fills in the Mynydd Llangattock caves, notably Ogof Agen Allwedd (Bull, 1976; Smart and Gardner, 1989; Simms and Hunt, 2008), a few kilometres to the north across the Clydach Gorge (Fig. 1). We have used dated speleothems to constrain the ages of passage development and sediment infill.

Speleothem dating

Speleothem deposition can only occur in conduits within vadose (unsaturated) and epiphreatic (intermittently saturated) zones, because calcite precipitation is primarily driven by the degassing of CO_2 from drip waters as they come into contact with the cave atmosphere/air. The lower CO_2 partial pressure (pCO_2) of the cave air allows the pCO_2 of saturated groundwaters to equilibrate with the air, resulting in calcite precipitation and speleothem growth. Therefore, speleothem growth in the phreatic (saturated) zone is impossible, but may be found in formerly phreatic conduits, as the groundwaters are drained, The basal age of a drip-type speleothem thus provides a minimum age for conduit dewatering (Atkinson and Rowe, 1992). To constrain the timing of passage development, dewatering and sediment infill in Ogof Draenen, 16 speleothem samples were collected for dating from selected key sites where old speleothem was thought to occur: eight from two sites in Gilwern Passage, two samples from War of the Worlds, one from Upstream Passage, and a further five samples from three sites in the 'Beyond a Choke' streamway (Fig. 3). Two of the Gilwern Passage samples (OD-12-05 and OD-12-06) were collected at the 'Second

Inlet' from the base of a large, shattered flowstone bank 280 m north of the junction. However, it is not clear from the local stratigraphy whether this speleothem post-dates the sediment fill or if sediment deposition represents a later stage reactivation of the passage. The other six samples (OD-96-06, OD-12-03A, OD-12-03B, OD-12-04, OD-12-07 and OD-12-09) were collected from a thick, multiphase flowstone bank known as 'Giles Barker's Shirt', 80 m north of the streamway junction. These samples appear to post-date the sediment fill. The samples from the 'Beyond a Choke' streamway were collected from three sites downstream of the junction with Gilwern Passage (Fig. 3). Samples OD-12-10 and OD-12-11 were collected from a flowstone 8 m above the stream, 380 m south-southeast of the junction with Gilwern Passage, and some 6 m below the passage roof. OD-12-13 was taken from a locally derived fallen block, some 440 m from the Gilwern Passage junction, while OD-12-14 was taken from flowstone approximately 2 m above the streamway (ca. 10 m below roof level), a short distance upstream from OD-12-13. The Upstream Passage sample (OD-12-08) was a small stalagmite growing on a deeply eroded sediment bank close to the present stream level at the northern end of the passage. The two War of the Worlds samples (OD-12-01 and OD-12-02), broken stalactite fragments, were collected from a small ledge comprising a flowstone cascade formation ~3–4 m above the passage floor. Sample OD-96-13 was taken from a flowstone formation overlying sediments at Big Beauty Junction, part of the high-level Megadrive conduit system.

U-series analyses were performed at the Bristol Isotope Group (BIG) facilities, University of Bristol. Subsamples of between 30 and 150 mg were obtained for ^{238}U–^{234}U–^{230}Th dating from individual growth layers consisting of clean, dense crystalline calcite. Chemical separation and multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) of U and Th isotopic ratios were carried out using similar procedures to those described by Hoffmann *et al.* (2007). Uncertainties for all analytical variables were propagated using a Monte Carlo procedure to determine the final error for reported isotope activity ratios, and are quoted at 95% confidence intervals (Hoffmann *et al.*, 2007). All reported ages are given in ka (thousands of years before present) and reported with respect to the year 2013 as the 'present-day' datum.

U-series results

Analytical data for all samples are provided in Supporting information, Table S1. Sample ages range from 1.8 ka for stalagmite OD-12-08, deposited at an elevation of 319 m asl in Upstream Passage, to three samples (OD-96-13, OD-12-02 and OD-12-05) at elevations from 308 to 390 m asl approaching secular equilibrium (>500 ka) and the effective limit of the U–Th dating technique (Fig. 7). Intersample U concentrations are highly variable, ranging from 146 to 52 570 ng g^{-1}. U content also varied significantly on an intrasample level, with stalagmite OD-12-05 (Second Inlet, Gilwern Passage) yielding concentrations between 8721 and 52 570 ng g^{-1}. In some cases, the degree of intrasample U variability can be attributed to open system behaviour resulting from U loss to the calcite crystal lattice structure. This is particularly apparent for sample OD-12-14, a partially re-dissolved stalagmite from the 'Beyond a Choke' streamway, where U concentrations varied by two orders of magnitude. Measured ^{230}Th/^{232}Th activity ratios ranged from 6.2×10^0 to 3.1×10^5. For the majority of samples, contributions of detrital ^{230}Th were minimal, resulting in only minor corrections to the final U–Th ages; however, OD-12-13 and OD-12-14 from the 'Beyond a Choke' streamway exhibited substantial contributions of detrital ^{230}Th, resulting in corrected U–Th ages with significantly increased age errors (Fig. S1, in supporting Appendix S1). All U – Th ages were corrected for detrital ^{230}Th using a mean bulk earth ratio of 0.746 ± 0.2 for the initial ^{230}Th/^{232}Th activity ratio. Due to the limitations of the U–Th dating technique, the absolute precision on isotopic ages decreases as samples approach the line of secular equilibrium. This is apparent for the oldest finite U–Th ages for samples OD-96-13, OD-12-02 and OD-12-05, as age errors are substantially >2%. Given the age

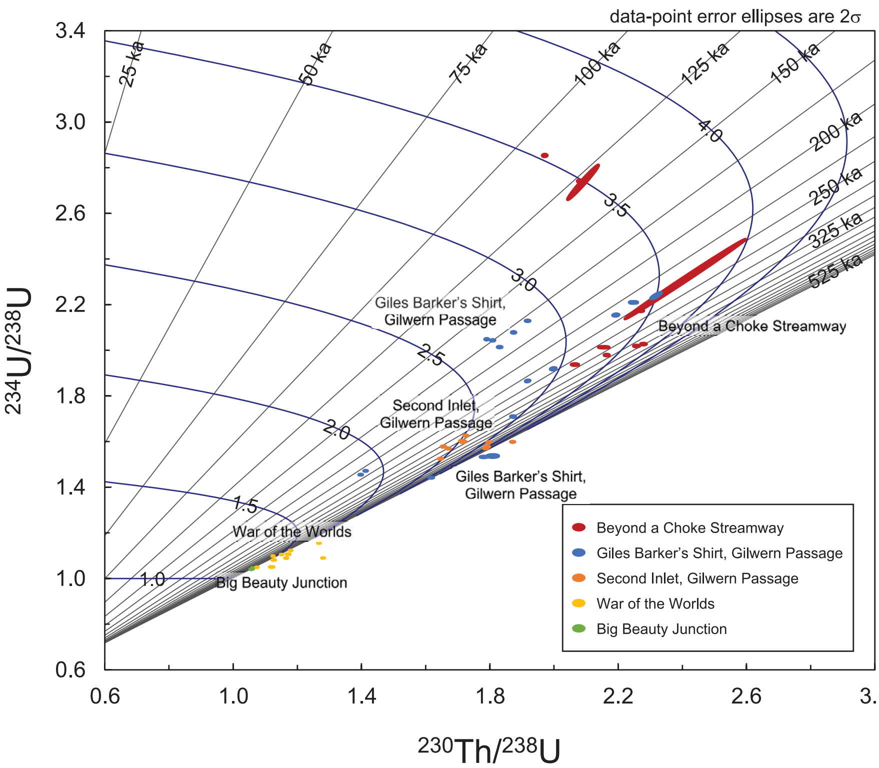

Figure 7. Corrected ^{230}Th/^{238}U–^{234}U/^{238}U activity ratios for Ogof Draenen speleothem samples analysed in this study, excluding OD-12-08. Sub-vertical grey lines are isochrons of constant age [given in thousands of years (ka) before present (2013)]; curved blue lines depict the evolution of ^{234}U/^{238}U with time in a closed system (no loss or gain of parent/daughter isotopes). This figure is available in colour online at wileyonlinelibrary.com.

and high U concentrations of these samples (from 2677 to 52 570 ng g^{-1}), these deposits would be ideally suited for U–Pb dating, enabling more accurate and precise age determinations than currently available by U–Th dating methods.

Age of deposition

Two strands of evidence suggest that the relict sediments are of considerable antiquity and significantly pre-date the last Devensian (MIS 2) glaciation. First, the absence of any fine-grained sediment (both the sands and the laminated silts) in the younger 'Beyond a Choke' streamway suggests the streamway developed after the main influx of sediment input into the higher level, relict 'The Score–Gilwern Passage' conduit. The present streamway is a deep vadose trench 10–20 m deep and 2–4 m wide and is far too large to have developed since the end of the last glaciation given typical rates of passage formation (Palmer, 1991). Secondly, much of the sediment fill in the upstream tributary passages has been flushed out, leaving remnants preserved up to 6 m above the floor.

The results of U-series analysis demonstrate that most speleothem growth occurred before 230 ka, predominantly between 350 and 255 ka (corresponding to the onset of MIS 6 and termination of MIS 9, see Fig. 8). However, several samples from Gilwern Passage (OD-12-05), Big Beauty Junction (OD-96-13) and War of the Worlds (OD-12-02) pre-date this phase of growth, yielding isotopic ages >500 ka. Due to the limitations of the U–Th chronometer for dating materials at or approaching secular equilibrium (i.e. >500 ka) the errors on the age for these determinations all exceed 2%, severely limiting the utility of these determinations for high-precision chronology. However, these ages are sufficient to demonstrate that passage dewatering within the higher levels of Ogof Draenen occurred prior to >500 ka. The oldest reliably dated sample from Gilwern Passage (Second Inlet) yielded a corrected age of 524.6 ka for OD-12-05. In addition to OD-12-05, OD-12-09, also from Gilwern Passage (Giles Barker's Shirt), yielded a corrected age of 578 ka at 33 mm above base; however, analyses performed at 3 and 11 mm above base yielded isotopic ratios showing clear signs of open system behaviour. Consequently, we reject this date for OD-12-09, as much of the sample appears to be open system, violating one of the major tenets of U-series dating, namely that a closed system can have experienced no loss of parent and/or daughter isotopes. Despite this, the basal age for OD-12-05 demonstrates the relict northward-draining 'The Score–Gilwern Passage' conduit was in existence and sufficiently drained to allow speleothem growth before 525 ka, and thus pre-dates that Anglian glaciation (MIS 12). Samples from Giles Baker's Shirt confirm the passage is older than MIS 9. The minimum age of the 'Beyond a Choke' streamway is constrained by stalactite OD-12-10, which yielded ages of 347.1 and 339.9 ka at 25 and 31 mm above base, respectively. The other streamway deposits OD-12-11, OD-12-13 and OD-12-14 yielded basal ages of 313.2 , 257.6 and 109.2 ka, respectively. These dates demonstrate that the present-day streamway had formed and a >6-m-deep vadose trench had developed before the onset of MIS 9. To incise a canyon this deep assuming a fairly typical vadose incision rate of ~5 cm ka^{-1} would require 120 ka. Consequently, the sediment influx in the relict high-level passages must have occurred a considerable time before MIS 9, probably during the Anglian glaciation (MIS 12) between 478 and 424 ka. The only speleothem (OD-12-08) unequivocally growing on top of a deeply eroded sediment bank yielded an age of 6.2 ka, which demonstrates that much of the sediment was flushed out before the early to mid-Holocene.

Glacial geomorphology and landscape evolution

Glacial deposits in South Wales suggest the region was glaciated on at least two occasions through the Pleistocene: during the Anglian and more recently during the Devensian (Barclay, 1989). However, given the evidence for multiple glaciations spanning more than 2 Ma (Lee *et al.*, 2001, 2012; Toucanne *et al.*, 2009; Böse *et al.*, 2012; Thierens *et al.*, 2012), it is highly likely that the region was glaciated on other occasions, despite there being is little evidence for them in

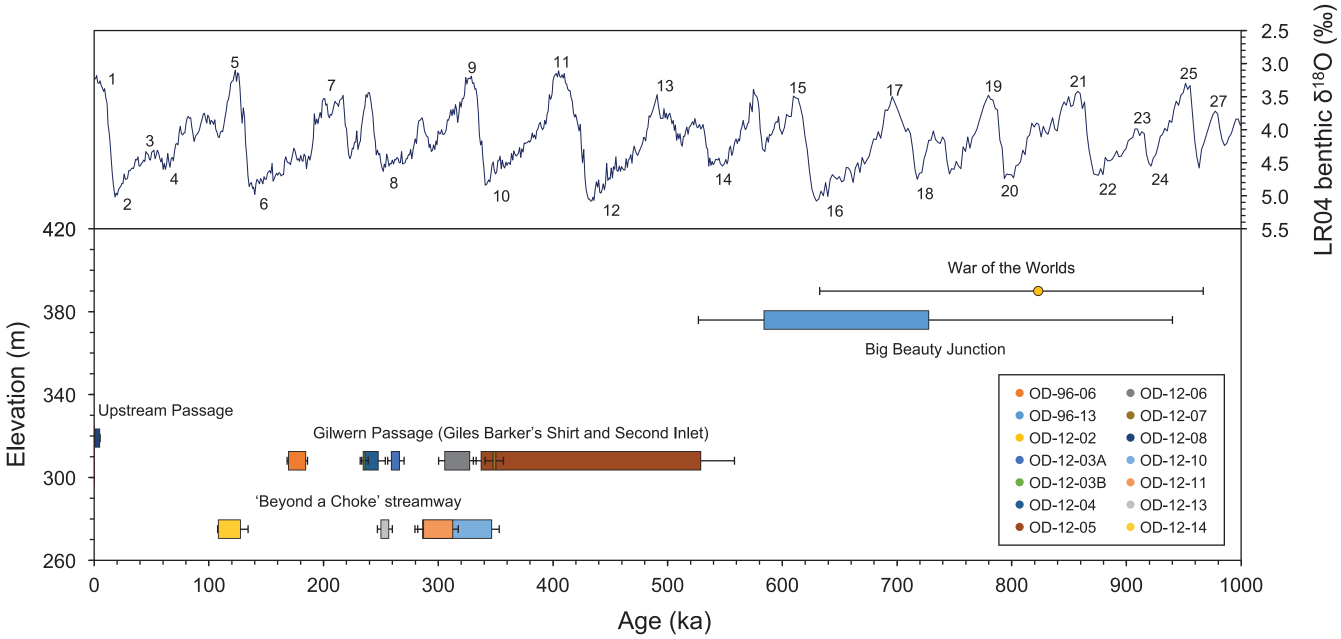

Figure 8. Phases of speleothem growth versus passage elevations plotted against the LR04 benthic $\delta^{18}O$ stack (Lisiecki and Raymo, 2005). Circular plots denote a single U-series age, while rectangular plots include two or more U-series age determinations. Upper and lower limits for each speleothem growth phase are given by the 2σ age errors for the youngest and oldest stratigraphic ages for each speleothem. This figure is available in colour online at wileyonlinelibrary.com.

South Wales. Reconstructions of the BIS (Ehlers and Gibbard, 2004) indicate that Ogof Draenen would have been at or close to the southern margin of the BIS at various times during the Mid–Late Pleistocene. These ice caps probably had several spreading centres, principally in mid and north Wales, but a local dispersion centre was also likely over the Brecon Beacons during more intense glacial maxima.

Extensive spreads of till, sand and gravel of presumed Devensian age have been mapped throughout the study area (Barclay, 1989), particularly in the Usk valley and along the northern fringe of the South Wales coalfield (Fig. 9). However, evidence from ice sheet modelling (Patton *et al.*, 2013a, 2013b) suggests the region was largely ice free during most of the Devensian glaciation except for a relatively short period (<2 ka) during the LGM. Even at its maximum extent, the Usk glacier was confined largely to the present valley (Barclay, 1989; Lewis and Thomas, 2005; Patton *et al.*, 2013a, 2013b). Some outcrops of till occur up to elevations of 445 m asl within some of the north-facing tributary valleys in the Llangattock area, but around Abergavenny the ice surface was not much above 250 m. The upper limit of glacial till falls uniformly from around 150 m asl south of Abergavenny to 45 m asl near Llancayo (Fig. 9) and the Devensian glacial limit is marked by a complex series of moraines just north of the town of Usk. Glacial till has been mapped across parts of Mynydd Llangattock and till forms an extensive sheet at ca. 350–400 m asl around Brynmawr (Barclay, 1989). These appear to be derived from local, predominantly cold-based ice caps (Patton *et al.*, 2013b) mantling the plateau across Mynydd Llangattock, Gilwern Hill and Mynydd Garnclochdy. To the south the ice was funnelled into a series of small valley glaciers, including one occupying the Afon Lwyd valley. Locally derived gravelly till (of presumed Devensian age) over 10 m thick is present in the Forgeside borehole (51.76816°N, 3.08770°W; 345 m asl) near Blaenavon (Barclay and Jones, 1978), and thin tills, largely confined to the valley bottom, extend south as far as Pontypool, which marks the Devensian limit. Thin remanié patches of probably pre-Devensian, gravelly tills with small Upper Carboniferous sandstone fragments occur on the limestone outcrop high on the east side of the valley and suggest the Afon Lwyd valley was more extensively glaciated before MIS 2 (Barclay, 1989).

Patches of morainic material demonstrate that the small north- and east-facing cirques on The Blorenge and Mynydd Garnclochdy contained small glaciers or snow patches. Many glacial cirques in the Brecon Beacons have been attributed to local snow accumulation during the Younger Dryas stadial (Shakesby *et al.*, 2007). However, ice sheet modelling (Patton *et al.*, 2013a, 2013b) suggests this is unlikely in the eastern Brecon Beacons given the low elevation of the cirques along the western scarp of the Usk valley, most of which extend below 300 m (Coleman and Carr, 2008). Indeed, it is debatable whether conditions even during the LGM were sufficient to generate these cirques given the short time when ice was present across the region and they may well date from earlier glaciations.

The short duration of active glaciation during the LGM suggests that glacially induced valley incision was not significant during this time. Speleothem U-series evidence presented here indicates that the Afon Lwyd valley was already incised sufficiently deeply to allow groundwater to flow south towards Pontypool before MIS 9. Given the time needed to initiate, develop and incise the present streamway to sufficient depth to allow speleothem growth, we suggest that the incision of the Afon Lwyd valley required to capture the drainage occurred mostly during or shortly after the Anglian glaciation. Moreover, a significant glacier in the Afon Lwyd valley is likely to have generated copious amounts of sediment-laden meltwater, particularly during the interglacial–glacial transition (Bridgland, 2000) and following deglaciation. The presence of a glacier in the Afon Lwyd valley at elevations above 350 m, and a probable ice surface below 300 m in the lower Usk valley, coupled with open cave passages extending through the intervening ridge would have

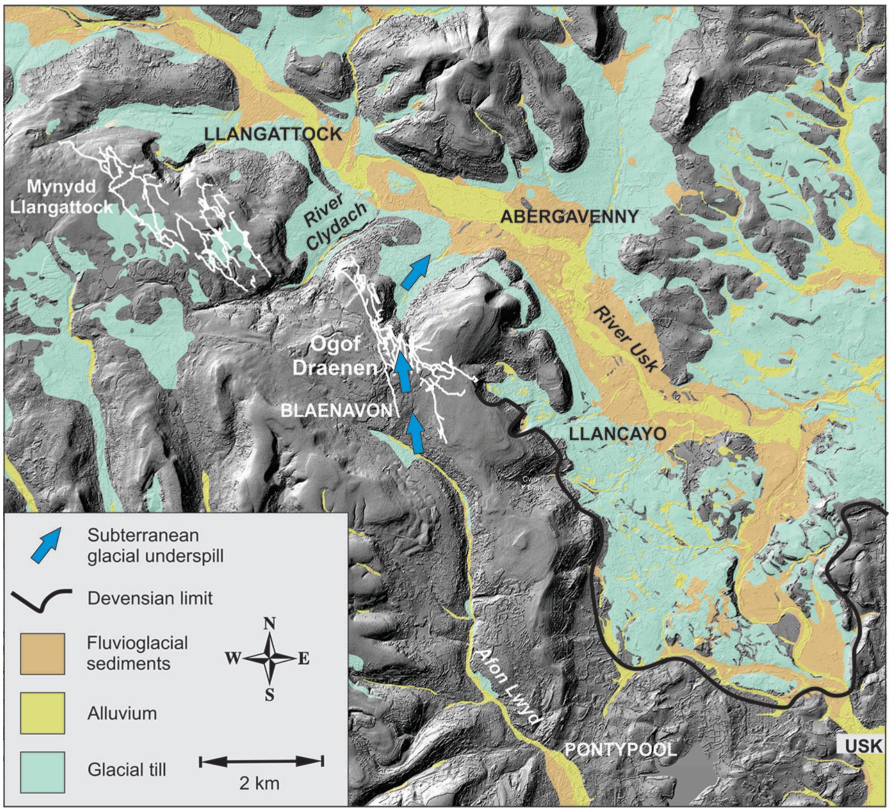

Figure 9. Superficial deposits in the Blaenavon area, showing the distribution of assumed Devensian age till, fluvioglacial deposits and post-glacial alluvium, and the limit of the Devensian ice sheet. Mapping based on NEXTMap® Britain elevation data from Intermap Technologies and superficial geological mapping based on the British Geological Survey 1:50 000 scale Geological Map Sheet 232 (Abergavenney). The direction of the proposed subterranean glacial underspill is shown. This figure is available in colour online at wileyonlinelibrary.com.

provided suitable conditions for the reactivation of these relict passages by glacial meltwater. We postulate that sediment-laden meltwater from an Anglian glacier flowed into the cave via inlets along the eastern margin of the Afon Lwyd valley around Blaenavon (>320 m asl). From these and other inlets, water flowed north via a currently sediment-choked passage ('Pontypool or Bust') into 'The Score' and then into the start of Gilwern Passage and the surrounding area. In so doing, it deposited fine-grained sand and silt up to an elevation of ca. 320–325 m asl. Outlets to the north, in the Clydach Gorge, were probably blocked by glacial ice, sediment or internal collapse (as at present). With the present Beyond a Choke streamway not yet in existence, the only available outlet was Cwm Llanwenarth, a small tributary to the Usk valley. Although this valley doubtless contained a small cirque glacier during the Anglian, the glacier surface almost certainly was considerably lower than that in the Afon Lwyd (Fig. 10). Consequently, water flowed 'upstream' through the system, via a series of former inlet passages at the eastern end of Upstream Passage, including Pen-y-Galchen Passage. The upstream portions of these passages had previously been truncated by valley incision at the head of Cwm Llanwenarth, but, because they form the lowest overspill point in the cave system, they were subsequently reactivated as temporary

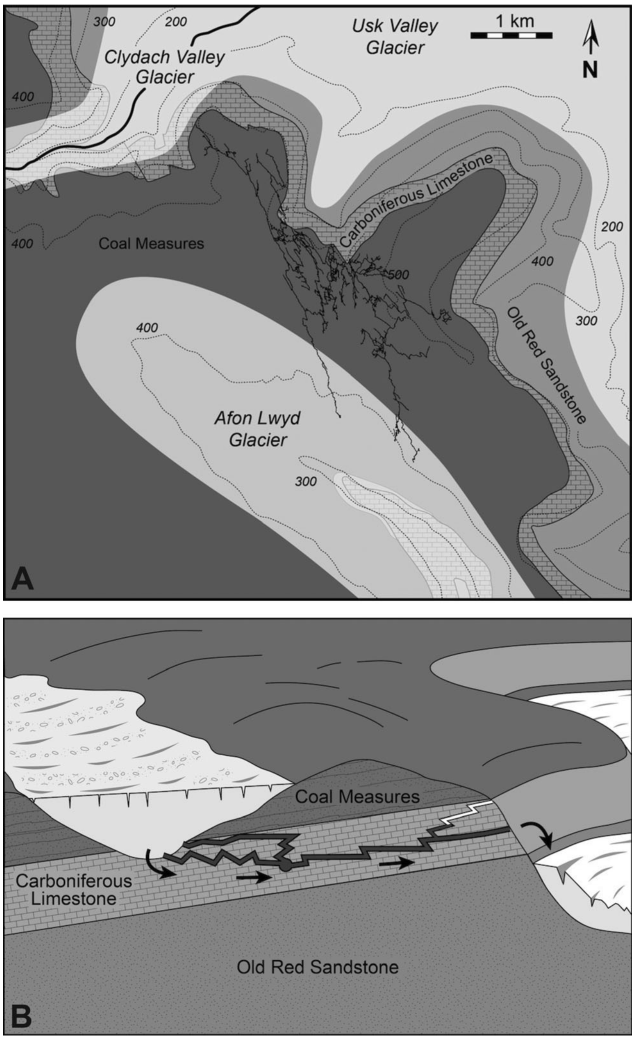

Figure 10. Proposed glacial setting during periods of subterranean glacial under-spill through Ogof Draenen during MIS 12 (Anglian glaciation). (A) Plan view with the Afon Lwyd glacier feeding meltwater into the southern end of Ogof Draenen. (B) Schematic cross-section between the Afon Lwyd valley to the west (left) and the Cwm Llanwenarth valley to the east (right).

resurgences. The deposition of the laminated silts above the cross-bedded sands suggests that the cave was partially or wholly inundated for a period before the cave was drained. This was probably due to continued ice advance, with the laminated silts being laid down as the ice over-rode the area, blocking the outlets at the head of Cwm Llanwenarth and causing ponding in the cave.

Similar evidence for glacial modification of preexisting cave systems through meltwater recharge occurs elsewhere in South Wales, suggesting this was a regional event. Copious amounts of sediment have been introduced by glacial meltwater into many other caves, notably Ogof Ffynnon Ddu in the Tawe valley and those under Mynydd Llangattock (Smart and Gardner, 1989), including Agen Allwedd where a similar sand and laminated silt sequence is seen (Bull, 1976). Simms and Hunt (2008) provide evidence of sediment influx, glacial flooding and impoundment in Agen Allwedd and suggest that glacial damming and recharge from meltwater might have been a significant factor in the development of the Llangattock caves. The influx of sediment led to ponding and localized paragenesis, blocking some passages, reactivating others and, in some cases, facilitating the development of new conduits (Farrant and Smart, 2011). Evidence of speleothem capping sediment in Ogof Ffynnon Ddu dated to ~270 ka by alpha-spectrometry (Smart and Christopher, 1989) suggests a pre-MIS 7 age for the fill. The subsequent period of vadose cave development was doubtless a result of Anglian glacial incision altering base-levels, allowing resurgences to develop at lower elevations.

The cave sediment record from Ogof Draenen and Mynydd Llangattock implies only one period in which glaciation may have overtopped the limestone escarpment. Subsequent lesser glaciations during the Devensian, in MIS 6 and perhaps MIS 8 were confined to the adjacent valleys. The relationship of the cave to the surface landscape indicates the eastern Brecon Beacons attained much of its present morphology during or before the Anglian glaciation, with relatively little modification in subsequent glacial advances.

Conclusions

Detailed speleogenetic and sedimentological observations within the Ogof Draenen cave system has revealed a complex history of cave development, and identified several distinct sediment facies within the network of passages around Gilwern Passage, Upstream Passage, The Score and the present 'Beyond a Choke' streamway. Speleothem U-series ages show much of the Ogof Draenen cave system to be >500 ka, with several samples exceeding the upper dating limit of the U–Th chronometer. Further dating of speleothem samples by U–Pb methods may be able to provide tighter constraints on the timing of cave development before MIS 13. The deposition of a distinctive suite of fine-grained sediments that infilled parts of the cave to depths of more than 20 m is ascribed to the influx of sediment-laden glacial meltwater. Passage morphology suggests the deposition of this sediment occurred before the development of the present streamway. The U-series dates imply the sediment influx occurred before ~350 ka, most probably during the Anglian glaciation. Meltwater derived from the base of a glacier in the Afon Lwyd valley flowed into the lower part of Ogof Draenen via preexisting inlets. As the level of glacial ice in the neighbouring Usk valley was significantly lower, this meltwater was able to flow north or north-east through the cave (locally in the opposite direction to normal interglacial drainage), over spilling through various truncated inlet passages in the headwall of the Cwm Llanwenarth cirque to form a series of temporary springs at ca. 320 m asl. The cave thus acted as a subterranean glacial spillway, transferring water from one catchment to another. Following the emplacement of these sands, inundation and ponding occurred, probably due to ice overriding the cave and leading to the deposition of the laminated slack-water facies. Much of this infill was subsequently removed when normal drainage was restored following deglaciation. Subsequent glacial advances were largely confined to the present valleys and did not impact significantly on the cave. Evidence for other pre-Devensian upland glaciations is likely to be preserved in other karst areas in the UK and elsewhere.

Supporting Information

Additional supporting information can be found in the online version of this article:

Table S1. U and Th concentrations, measured isotope activity ratios and detritally corrected U–Th ages. Reported errors are 2σ.

Appendix S1. U-series dating methods, and Measured versus corrected $^{230}Th/^{238}U$ versus $^{234}U/^{238}U$ activity ratios (in Figs S1 to S5).

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Abbreviations. BIS, British Ice Sheet; LGM, Last Glacial Maximum; MIS, Marine Isotope Stage.

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