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 (BIS). 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 demonstrates 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.

Keywords: speleothem, glaciation, Wales, U-series dating, U–Th, landscape evolution, Ogof Draenen

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

1. 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, 1999; Bowen *et al.*, 1986; Clark *et al.*, 2004). Now perhaps as many as 30 glaciations are known (Böse *et al.*, 2012; Lee *et al.*, 2012; Lee *et al.*, 2011; Thierens *et al.*, 2012; Toucanne *et al.*, 2009), 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 Late 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 (Lundberg *et al.*, 2010; Rowe *et al.*, 1988; 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, 1987; Ford *et al.*, 1983; 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). Sub-glacial 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 pre-existing 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 sub-glacial modification.

Crucially, caves also host speleothem deposits, which can be accurately dated using uranium-series (U-series) methods (Meyer *et al.*, 2009; Richards and Dorale, 2003). 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.

2. The study area

The Brecon Beacons in southern Wales is a large upland area (900 km^2) situated on the northern edge of the South Wales coalfield (Figure 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 characterised 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.

3. Ogof Draenen

Ogof Draenen [51.79966ºN, 3.09439ºW] is a complex multiphase intrastratal cave system located near Blaenavon, 6 km south-west of Abergavenny, South Wales (Figure 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 Garn-fawr, 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 in 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 (Figure 2a). This conduit system drained south-east, roughly along strike to former resurgences at c. 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 northwest to a former resurgence in the Clydach Gorge at 320-300 m asl (Figure 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 (Figure 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).

4. 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; Figure 3) suggest 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 comprised of mostly allogenic, manganese-stained mudstone and sandstone clasts derived from the overlying Upper Carboniferous siliciclastics. Most of the clasts are angular to sub rounded. 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 (Figure 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, comprised of 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 slack-water facies. These silts, up to 1 m thick have very regular mm-scale laminae and in places show minor growth faulting and surface desiccation cracks.

Excellent exposures occur in Gilwern, Upstream and Pen-y-Galchen passages (Figure 4). In Upstream Passage, laminated silts up to a metre thick overlie sand and limestone breakdown at an elevation of 320 m. Further upstream, plaques of cross bedded sands (Figure 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 c. 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 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 c. 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 postdate 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 (Figure 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 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 subsequent to 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, whilst 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 to 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 is shown in Table 2 while particle size cumulative frequency graphs are shown in Figure 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 in terms of 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. 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 is indicative of 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; Simms and Hunt, 2008; Smart and Gardner, 1989), a few kilometres to the north across the Clydach Gorge (Figure 1). We have used dated speleothems to constrain the ages of passage development and sediment infill.

5. 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 (Figure 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 postdates 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 postdate the sediment fill. The samples from the 'Beyond a Choke' streamway were collected from three sites downstream of the junction with Gilwern Passage (Figure 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, whilst OD-12-14 was taken from flowstone approximately 2 m above the streamway (c. 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. The 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. Sub-samples of between 30-150 mg were obtained for ^{238}U-^{234}U-^{230}Th dating from individual growth layers comprised 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 in 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.

6. U-series results

Analytical data for all samples are provided in Table 3. Sample ages range from 1.8 $^{+0.1}_{-0.1}$ ka for stalagmite OD-12-09, 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 308-390 m asl approaching secular equilibrium (>500 ka) and the effective limit of the U–Th dating technique (see Figure 7). Inter-sample U concentrations are highly variable, ranging from 146 to 52,570 ng g^{-1}. U content also varied significantly on an intra-sample level, with stalagmite OD-12-05 (Second Inlet, Gilwern Passage) yielding concentrations between 8,721-52,570 ng g^{-1}. In some cases, the degree of intra-sample 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 2 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 (see Figure S1 in Supplementary Information). 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 age's decreases as samples approach the line of secular equilibrium. This apparent for the oldest finite U–Th ages for samples OD-96-13, OD-12-02 and OD-12-05, as age errors being substantially greater than 2%. Given the age and high U concentrations' of these samples (from 2,677-52,570 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.

7. Age of deposition

Two strands of evidence suggest that the relict sediments are of considerable antiquity and significantly predate the last Devensian (MIS 2) glaciation. Firstly, 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 prior to 230 ka, predominantly between 350-255 ka (corresponding to the onset of MIS 6 and termination of MIS 9, see Figure 8). However, a number of the 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 >>500 ka. The oldest reliably dated sample from Gilwern Passage (Second Inlet) yielded a corrected age of $524.6^{+29.4}_{-23.5}$ 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^{+61}_{-42} 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; that a closed system can have experienced no loss of parent and/or daughter isotopes. In spite of 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 prior to 525 ka, and thus predates 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 $347.1^{+6.5}_{-6.0}$ ka and $339.9^{+6.5}_{-6.0}$ 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 $313.2^{+4.7}_{-5.6}$ ka, $257.6^{+3.0}_{-3.0}$ ka and $109.2^{+0.6}_{-0.6}$ ka, respectively. These dates demonstrate that the present-day streamway had formed and a >6 m deep vadose trench had developed prior to the onset of MIS 9. To incise a canyon this deep assuming a fairly typical vadose incision rate of ~5 cm per ka would require 120 ka. Consequently, the sediment influx in the relict high level passages must have occurred a considerable time before MIS 9, most likely during the Anglian glaciation (MIS 12) between 478-424 ka. The only speleothem (OD-12-08) unequivocally growing on top of a deeply eroded sediment bank yielded an age of $6.2^{+0.1}_{-0.1}$ ka, which demonstrates that much of the sediment was flushed out prior to the early to mid-Holocene.

8. 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 (Böse *et al.*, 2012; Lee *et al.*, 2012; Lee *et al.*, 2011; Thierens *et al.*, 2012; Toucanne *et al.*, 2009), it is highly likely that the region was glaciated on other occasions, despite there being is little evidence for them in 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 to 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 (Figure 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 (Figure 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 c. 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 [51.76816ºN, 3.08770ºW; 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 prior to 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 prior to 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 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 c. 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 (Figure 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 resurgences. The deposition of the laminated silts above the cross-bedded sands suggests that the cave was partially or wholly inundated for a period of time 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 pre-existing 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, 1988) including Agen Allwedd where a similar sand and laminated silt sequence is seen (Bull, 1976). Simms and Hunt (2007) 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 1988) 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 prior to the Anglian glaciation, with relatively little modification in subsequent glacial advances.

9. 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 a number of 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 prior to 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 prior to ~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 pre-existing inlets. As the level of glacial ice in the neighbouring Usk valley was significantly lower, this meltwater was able to flow north or northeast 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 c. 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.

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Figure captions

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.

Figure 2. Schematic evolution of the Ogof Draenen system. (A.) Initial conduits develop southeast 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 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 northwestern 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, whilst 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 Figure 1. A colour version is available online.

Figure 4. Desiccated, cracked laminated silts overlying fine-grained silty sand, draped over breakdown, Upstream Passage. Photo M J Simms.

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 indicate flow to the left ('upstream'). Height of face shown is about 3 m. Photo M J Simms.

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

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).

Figure 8. Phases of speleothem growth versus passage elevations plotted against the LR04 benthic δ^{18}O stack (Lisiecki and Raymo, 2005). Circular plots denote a single U-series age, whilst rectangular plots include 2 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.

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. A colour version of this figure is available online.

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).

Tables

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

Table 1. Major cave systems of South Wales

Lithology (Mean %)	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

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 Measure outcrop (CM). 'Total Sandstone' is a combination of the Twrch Formation and Devonian sandstone. Glacial till samples were collected from Forgeside, near Blaenavon [51.77243ºN, 3.09258ºW], whilst the Coal Measures sample was taken from a tributary feeding the River Clydach at [51.80598ºN, 3.13908ºW]. Data from Pash (2003).

Table 3. U and Th concentrations, measured isotope activity ratios and detritally-corrected U–Th ages. Reported errors are 2σ.

Lab ID	Sample ID	Location code	Distance from base (mm)	^{238}U (ng/g)	±	^{232}Th (ng/g)	±	(^{230}Th/^{232}Th)$_{Act}$	±	(^{230}Th/^{238}U)$_{Act}$ *	±	(^{234}U/^{238}U)$_{Act}$	±	Age (ka) †‡	+	-	(^{234}U/^{238}U)$_{Int}$	+	-
BIG-UTh-M224	OD-96-06.003	GBS	3	20930	130	1.783	0.015	64870	260	1.8087	0.0057	2.0435	0.0032	174.7	1.3	1.2	2.7085	0.0060	0.0060
BIG-UTh-M255	OD-96-06.006	GBS	6	20210	150	1.940	0.017	58280	260	1.8304	0.0063	2.0140	0.0031	185.3	1.6	1.5	2.7109	0.0070	0.0070
BIG-UTh-M256	OD-96-06.024	GBS	24	24700	180	2.571	0.024	56310	250	1.9175	0.0064	2.1291	0.0032	179.7	1.4	1.4	2.8751	0.0070	0.0070
BIG-UTh-M257	OD-96-06.039	GBS	39	18930	150	6.371	0.052	16252	26	1.7903	0.0054	2.0483	0.0032	170.2	1.2	1.2	2.6947	0.0055	0.0056
BIG-UTh-M223	OD-96-06.040	GBS	40	19670	160	3.36	0.11	33490	960	1.8738	0.0059	2.0783	0.0035	181.0	1.4	1.4	2.7972	0.0067	0.0065
BIG-UTh-M226	OD-96-13.004	BBJ	4	22660	200	171.3	1.5	426.82	0.61	1.0557	0.0033	1.0405	0.0018	680	224	110	1.28	0.24	0.07
BIG-UTh-M225	OD-96-13.007	BBJ	7	30140	200	2.963	0.089	33000	1000	1.0610	0.0033	1.0466	0.0016	584	118	57	1.242	0.098	0.033
BIG-UTh-M258	OD-96-13.012	BBJ	12	26370	230	16.10	0.15	5308.2	7.9	1.0603	0.0034	1.0431	0.0018	728	212	144	1.34	0.27	0.11
BIG-UTh-M228	OD-12-01.003	WOW	3	1158.7	7.9	22.73	0.15	175.08	0.27	1.1236	0.0034	1.0979	0.0017	488	32	27	1.390	0.033	0.024
BIG-UTh-M071	OD-12-01.004	WOW	4	3012	32	0.7075	0.0088	15140	98	1.1652	0.0043	1.0894	0.0020	N/A	-----	-----	-----	-----	-----
BIG-UTh-M245	OD-12-01.006	WOW	6	4865	32	0.9448	0.0083	20122	86	1.2803	0.0041	1.0900	0.0016	N/A	-----	-----	-----	-----	-----
BIG-UTh-M072	OD-12-01.043	WOW	43	964.7	8.5	4.239	0.039	813.3	2.5	1.1709	0.0055	1.1062	0.0023	N/A	-----	-----	-----	-----	-----
BIG-UTh-M227	OD-12-01.044	WOW	44	4442	36	15.47	0.13	1032.9	1.5	1.1790	0.0036	1.1229	0.0018	N/A	-----	-----	-----	-----	-----
BIG-UTh-M246	OD-12-01.045	WOW	45	1307	10	12.683	0.097	398.35	0.70	1.2667	0.0038	1.1552	0.0018	N/A	-----	-----	-----	-----	-----
BIG-UTh-M247	OD-12-02.000	WOW	0	4034	30	2.275	0.016	5820.7	9.5	1.0742	0.0034	1.0495	0.0017	N/A	-----	-----	-----	-----	-----
BIG-UTh-M073	OD-12-02.003	WOW	3	2677	29	0.917	0.012	9981	76	1.1198	0.0062	1.0507	0.0019	N/A	-----	-----	-----	-----	-----
BIG-UTh-M074	OD-12-02.057	WOW	57	4540	49	4.179	0.044	3733.7	8.3	1.1261	0.0050	1.0812	0.0019	N/A	-----	-----	-----	-----	-----
BIG-UTh-M248	OD-12-02.058	WOW	58	11082	74	2.654	0.018	14681	23	1.1504	0.0035	1.1051	0.0017	823	144	190	2.07	0.55	0.45
BIG-UTh-M230	OD-12-03A.001	GBS	1	184.4	1.1	4.861	0.031	230.47	0.47	1.9906	0.0067	1.9127	0.0035	267.0	4.0	3.9	2.953	0.019	0.018
BIG-UTh-M236	OD-12-03A.017	GBS	17	1049.1	1.8	24.688	0.051	247.98	0.41	1.9121	0.0054	1.8604	0.0028	259.7	3.2	3.2	2.802	0.013	0.013
BIG-UTh-M231	OD-12-03A.051	GBS	51	191.5	1.3	2.949	0.026	1434.7	8.4	7.2284	0.0387	2.0335	0.0031	N/A	-----	-----	-----	-----	-----
BIG-UTh-M260	OD-12-03B.007	GBS	7	38460	280	6.860	0.058	23900	100	1.3973	0.0049	1.4550	0.0023	236.9	2.8	2.7	1.8879	0.0063	0.0064
BIG-UTh-M261	OD-12-03B.062	GBS	62	43870	300	9.784	0.069	19333	28	1.4127	0.0048	1.4717	0.0022	235.3	2.7	2.6	1.9163	0.0063	0.0064
BIG-UTh-M244	OD-12-04.003	GBS	3	826.2	7.9	58.61	0.58	98.68	0.14	2.2936	0.0066	2.2162	0.0034	248.5	6.2	6.0	3.499	0.032	0.030
BIG-UTh-M262	OD-12-04.009	GBS	9	12833	92	3.361	0.032	25570	120	2.1942	0.0067	2.1556	0.0037	239.8	2.4	2.4	3.274	0.013	0.012
BIG-UTh-M268	OD-12-04.011	GBS	11	14240	110	6.227	0.046	15290	24	2.1914	0.0074	2.1534	0.0038	239.7	2.5	2.6	3.269	0.015	0.014
BIG-UTh-M243	OD-12-04.016	GBS	16	13303	97	3.092	0.021	29616	51	2.2525	0.0066	2.2098	0.0036	239.0	2.3	2.2	3.375	0.013	0.013
BIG-UTh-M267	OD-12-04.016	GBS	16	12174	77	8.229	0.051	10144	17	2.2435	0.0077	2.2097	0.0038	236.4	2.5	2.5	3.358	0.014	0.014
BIG-UTh-M249	OD-12-05.000	SI	0	8721	70	4.595	0.037	10853	16	1.8709	0.0056	1.5987	0.0026	N/A	-----	-----	-----	-----	-----
BIG-UTh-M271	OD-12-05.001	SI	1	26800	190	49.61	0.33	2945.5	4.3	1.7865	0.0056	1.5705	0.0026	524.6	29.4	23.5	3.51	0.21	0.16
BIG-UTh-M251	OD-12-05.003	SI	3	28300	230	4.188	0.033	36966	57	1.7924	0.0058	1.5777	0.0026	509.6	25.4	20.9	3.43	0.18	0.14
BIG-UTh-M250	OD-12-05.033	SI	33	30780	220	8.214	0.061	20553	34	1.7970	0.0056	1.5973	0.0027	449.7	15.0	13.7	3.125	0.089	0.077
BIG-UTh-M270	OD-12-05.036	SI	36	52570	410	0.8787	0.0087	313100	1700	1.7149	0.0067	1.5988	0.0030	334.5	7.1	6.8	2.539	0.029	0.028
BIG-UTh-M269	OD-12-05.039	SI	39	24550	170	0.8140	0.0082	158000	1000	1.7168	0.0067	1.6012	0.0027	333.4	7.1	6.7	2.540	0.029	0.027
BIG-UTh-M252	OD-12-05.051	SI	51	29200	200	59.69	0.44	2457.3	4.0	1.6458	0.0056	1.5249	0.0025	361.8	8.2	7.7	2.458	0.031	0.028
BIG-UTh-M232	OD-12-06.004	SI	4	17620	120	0.6694	0.0062	132940	800	1.6553	0.0060	1.5782	0.0030	306.2	5.6	5.3	2.372	0.019	0.018
BIG-UTh-M238	OD-12-06.005	SI	5	46325	83	10.545	0.021	22401	33	1.6707	0.0053	1.5695	0.0025	328.0	5.6	5.4	2.437	0.021	0.019
BIG-UTh-M237	OD-12-06.040	SI	40	42440	76	58.74	0.11	3773.5	5.5	1.7112	0.0052	1.6030	0.0026	326.3	5.5	5.3	2.515	0.021	0.020
BIG-UTh-M233	OD-12-06.043	SI	43	13897	92	74.41	0.51	982.7	1.4	1.7241	0.0055	1.6253	0.0027	314.0	5.1	5.0	2.519	0.019	0.018
BIG-UTh-M263	OD-12-07.023	GBS	23	440.8	2.8	1.0011	0.0074	2515.0	5.1	1.8718	0.0067	1.7098	0.0030	348.1	7.0	6.8	2.897	0.036	0.034
BIG-UTh-M241	OD-12-07.041	GBS	41	544.4	4.0	1.847	0.013	1684.3	2.9	1.8723	0.0056	1.7080	0.0029	350.7	6.5	6.1	2.907	0.031	0.028
BIG-UTh-M240	OD-12-08.105	UP	105	283.2	2.0	7.062	0.048	19.950	0.081	0.1631	0.0008	2.8136	0.0045	6.2	0.1	0.1	2.8578	0.0076	0.0077
BIG-UTh-M239	OD-12-08.006	UP	6	227.5	1.5	5.736	0.040	6.179	0.073	0.0510	0.0006	2.7532	0.0044	1.8	0.1	0.1	2.7737	0.0074	0.0073
BIG-UTh-M274	OD-12-09.003	GBS	3	146.4	1.8	2.368	0.035	340.8	3.2	1.8057	0.0149	1.5346	0.0055	N/A	-----	-----	-----	-----	-----
BIG-UTh-M275	OD-12-09.011	GBS	11	252.7	2.1	2.372	0.025	578.6	3.8	1.7791	0.0094	1.5315	0.0031	N/A	-----	-----	-----	-----	-----
BIG-UTh-M276	OD-12-09.033	GBS	33	264.9	1.9	0.8172	0.0078	1599.1	8.5	1.6166	0.0063	1.4416	0.0025	578	61	42	3.26	0.41	0.25
BIG-UTh-M277	OD-12-10.013	BACS	13	8244	56	5.80	0.18	9350	290	2.1546	0.0138	2.0132	0.0033	286.8	6.9	6.5	3.277	0.042	0.039
BIG-UTh-M278	OD-12-10.025	BACS	25	26000	240	25.70	0.73	7040	200	2.2783	0.0076	2.0270	0.0035	347.1	6.5	6.0	3.736	0.046	0.043
BIG-UTh-M279	OD-12-10.031	BACS	31	12320	110	9.25	0.10	9175	42	2.2569	0.0080	2.0185	0.0035	339.9	6.5	6.0	3.658	0.046	0.041
BIG-UTh-M280	OD-12-11.007	BACS	7	8919	76	27.19	0.23	2165.8	3.3	2.1632	0.0069	1.9783	0.0034	313.2	4.7	4.6	3.370	0.028	0.027
BIG-UTh-M281	OD-12-11.017	BACS	17	23280	160	3.442	0.031	42690	270	2.0650	0.0097	1.9375	0.0037	287.8	5.4	5.1	3.112	0.029	0.027
BIG-UTh-M283	OD-12-13.008	BACS	8	1433.1	9.2	4.149	0.028	2392.1	4.5	2.2692	0.0078	2.1723	0.0038	257.6	3.0	3.0	3.427	0.018	0.017
BIG-UTh-M284	OD-12-13.009	BACS	9	1214.8	8.9	829.8	6.1	9.636	0.017	2.1568	0.0065	2.0774	0.0039	250.6	95.4	50.7	3.66	0.59	0.27
BIG-UTh-M285	OD-12-14.008	BACS	8	20050	140	138.18	0.95	872.0	1.3	1.9694	0.0063	2.8501	0.0045	109.2	0.6	0.6	3.5222	0.0060	0.0059
BIG-UTh-M286	OD-12-14.019	BACS	19	431.6	3.9	0.455	0.093	6000	1000	2.0804	0.0068	2.7406	0.0049	127.1	0.8	0.8	3.4921	0.0065	0.0065
BIG-UTh-M287	OD-12-14.029	BACS	29	357.3	2.8	91.51	0.69	24.039	0.058	2.0174	0.0069	2.6195	0.0047	128.5	6.6	6.1	3.495	0.063	0.060

$_{Act}$ Denotes activity ratio.

* (^{230}Th/^{238}U)$_A$ = $1-e^{-\lambda 230T}+(\delta^{234}U_{measured}/1000)[\lambda_{230}/(\lambda_{230}-\lambda_{234})](1-e^{-(\lambda 230-\lambda 234)T})$, where *T* is the age in years. $\lambda_{230} = 9.1705\times10^{-6}$ ($\pm1.38\times10^{-8}$) yr^{-1} (Cheng *et al.*, 2013), $\lambda_{234} = 2.82206\times10^{-6}$ ($\pm3.02\times10^{-9}$) yr^{-1} (Cheng *et al.*, 2013), $\lambda_{238} = 1.55125\times10^{-10}$ ($\pm1.66\times10^{-13}$) yr^{-1} (Jaffey *et al.*, 1971).

† Thousands of years before 2013.

‡ Corrected for detrital Th contamination using the bulk Earth value of 0.746 ± 0.2 for initial (^{230}Th/^{232}Th)$_{Act}$. The degree of detrital ^{230}Th contamination is indicated by the measured (^{230}Th/^{232}Th) activity ratio.

$_{Int}$ Denotes initial activity ratio.

N/A indicates that no finite age solutions could be calculated based on the sample activity ratios.

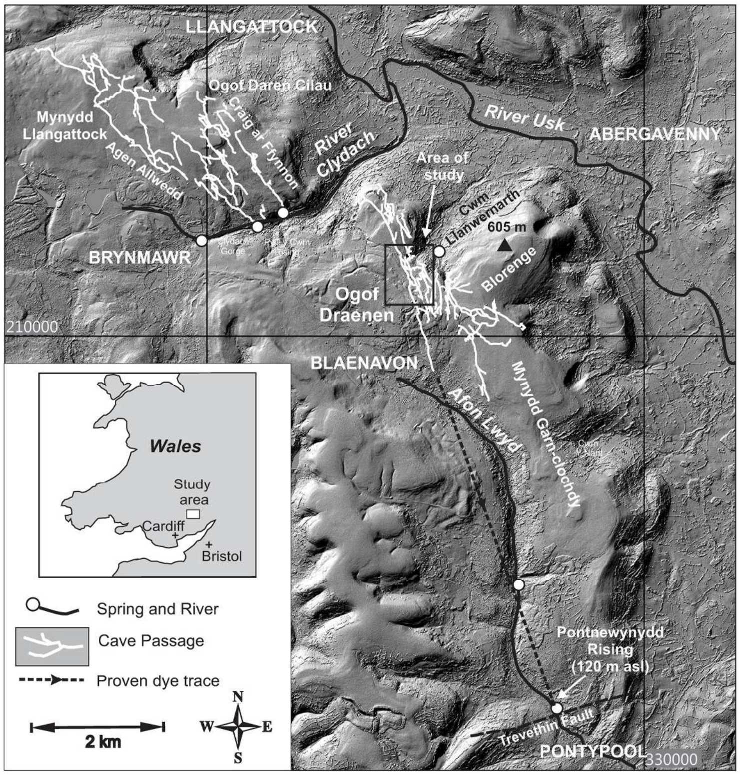

Figure 1. NEXTMap® hill-shaded surface model image of the north-eastern part of the South Wales coalfield and the Usk valley, showing the location of Ogof Draenen and the Mynydd Llangattock cave systems. NEXTMap® Britain elevation data from Intermap Technologies.
203x158mm (300 x 300 DPI)

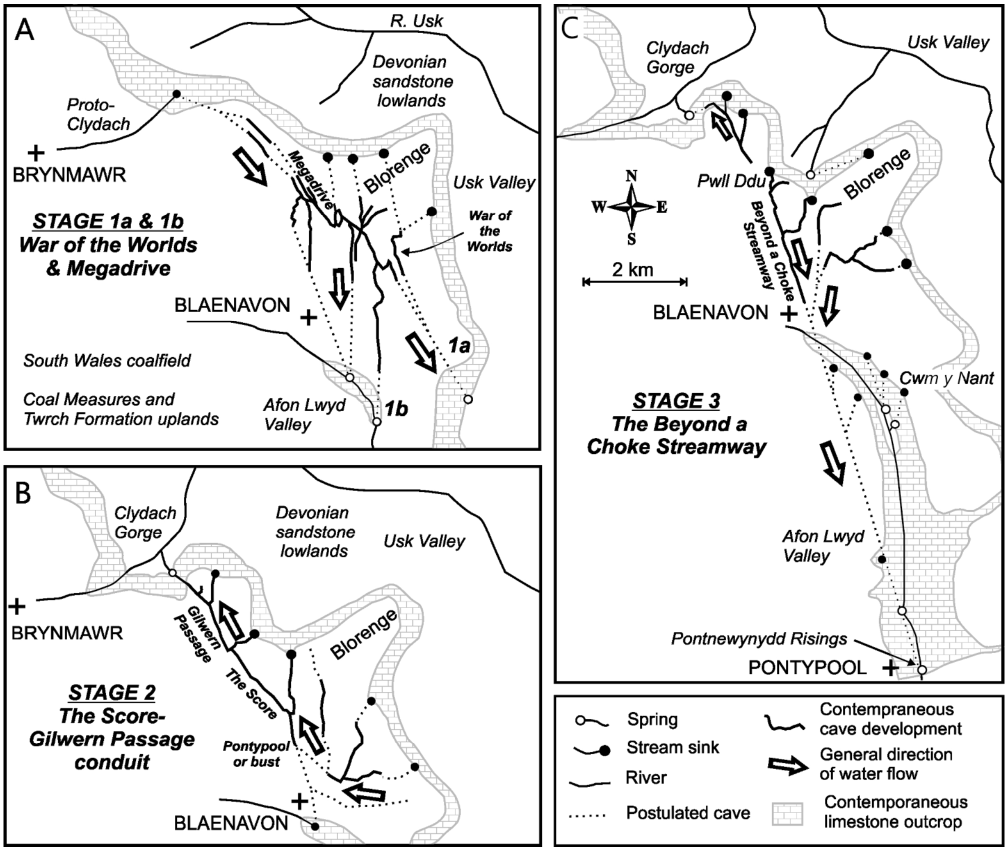

Figure 2. Schematic evolution of the Ogof Draenen system. A. Initial conduits develop southeast to springs in the Usk valley, subsequently captured to the south by new springs in the Afon Lwyd valley. B. Incision in the Clydach Gorge allows the north-draining 'The Score-Gilwern Passage' conduit to develop. C. Renewed incision in the Afon Lwyd allows drainage to revert to the south, creating the Beyond a Choke streamway. More details are in Farrant and Simms, 2011.
208x175mm (300 x 300 DPI)

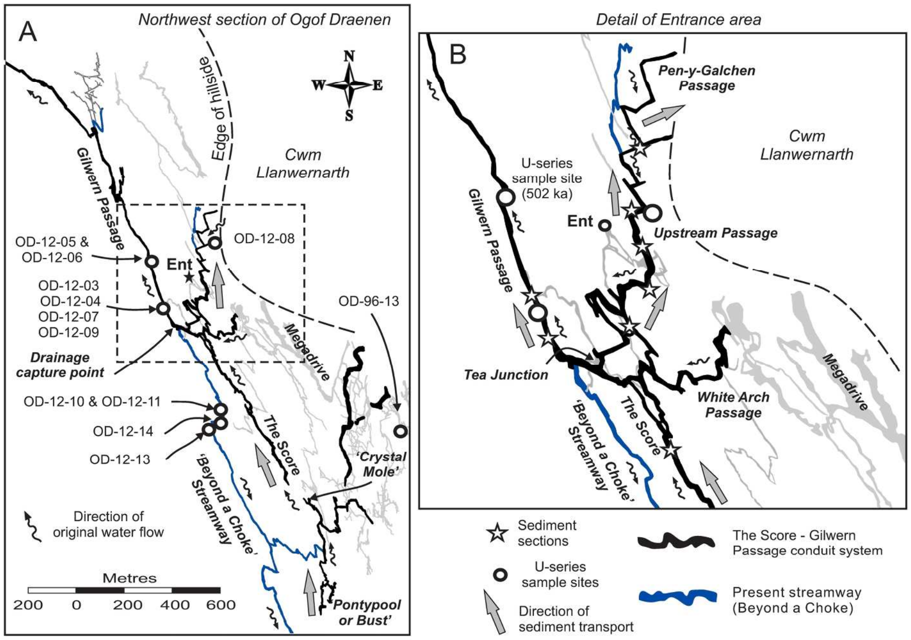

Figure 3. Outline centre-line survey of Ogof Draenen, adapted from surveys by Stevens, (1997). (A.) Outline survey of the northwestern part of the cave. (B.) Inset of area around the cave entrance (Ent). The black passages are those developed during the 'The Score-Gilwern Passage' conduit phase of development, whilst the 'Beyond a Choke' streamway 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 Figure 2. A colour version is available online.

201x133mm (300 x 300 DPI)

Figure 4. Desiccated, cracked laminated silts overlying fine-grained silty sand, draped over breakdown, Upstream Passage. Photo M J Simms.
82x59mm (300 x 300 DPI)

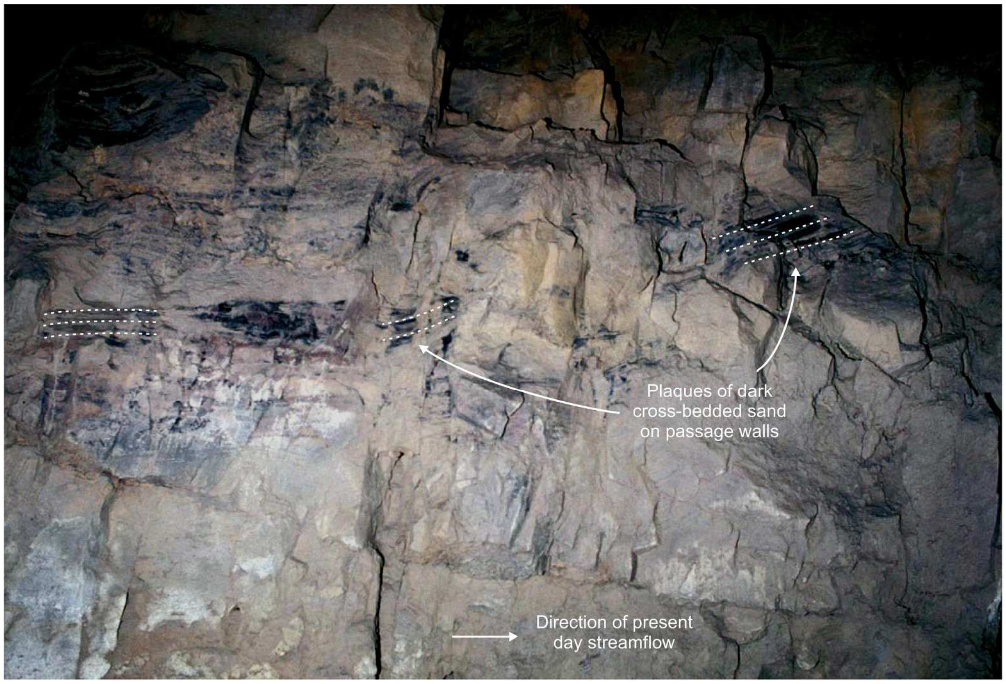

Figure 5. Cemented remnants of cross-bedded carbonaceous sand preserved on the bedrock wall several metres above the floor of Upstream Passage. Cross bedding picked out by darker lamina indicate flow to the left (‘upstream’). Height of face shown is about 3 m. Photo M J Simms.
184x124mm (300 x 300 DPI)

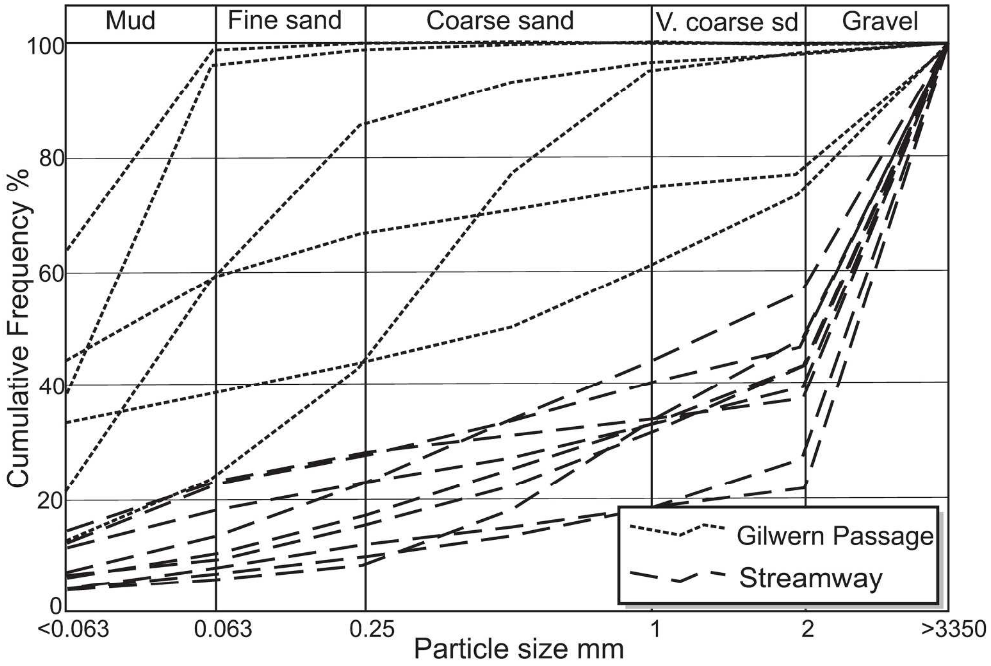

Figure 6. Cumulative frequency plots for the streamway and Gilwern Passage sediments.
184x126mm (300 x 300 DPI)

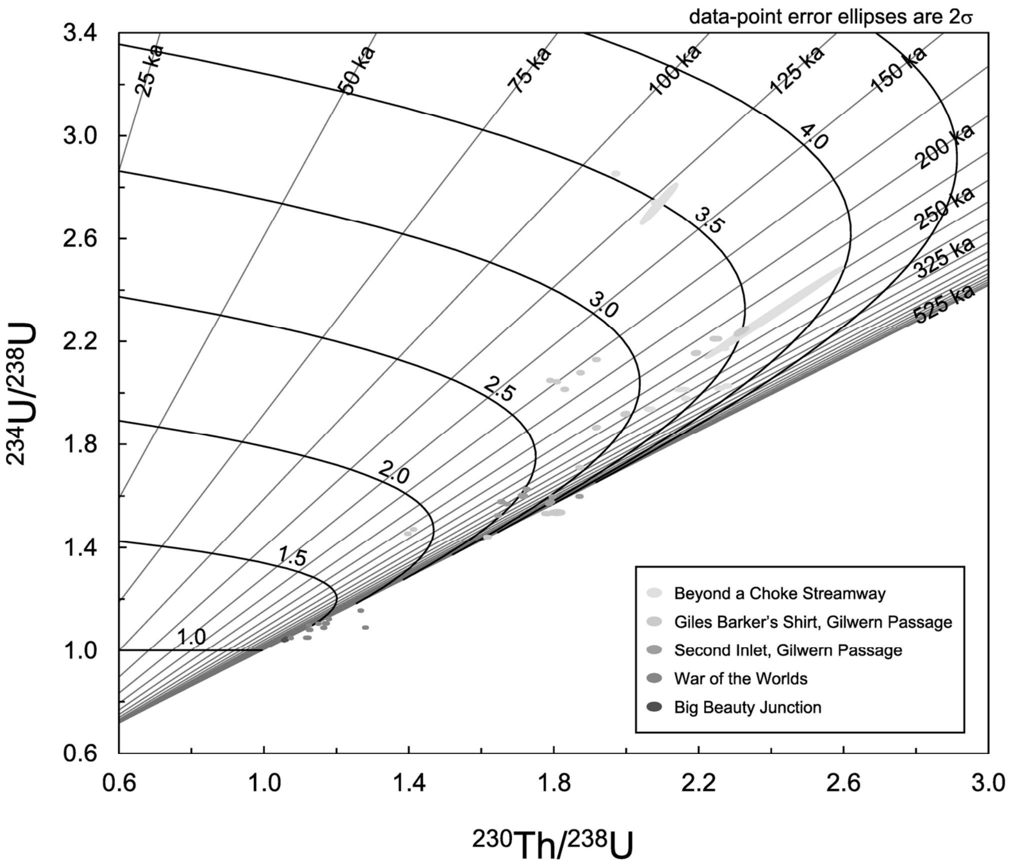

Figure 7. Corrected 230Th/238U-234U/238U activity ratios for Ogof Draenen speleothem samples analysed in this study, excluding OD-12-08. Sub-vertical grey lines are isochrons of constant age (given in thousands of years [ka] before present [2013]); curved blue lines depict the evolution of 234U/238U with time in a closed system (no loss or gain of parent/daughter isotopes).
154x131mm (300 x 300 DPI)

0

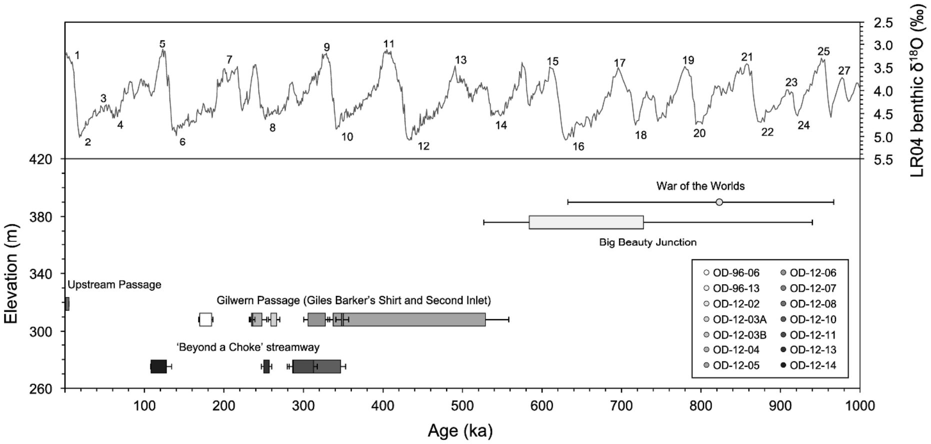

Figure 8. Phases of speleothem growth versus passage elevations plotted against the LR04 benthic δ18O stack (Lisiecki and Raymo, 2005). Circular plots denote a single U-series age, whilst rectangular plots include 2 or more U-series age determinations. Upper and lower limits for each speleothem growth phase are given by the 2σ age errors for the youngest and oldest stratigraphic ages for each speleothem.
305x303mm (300 x 300 DPI)

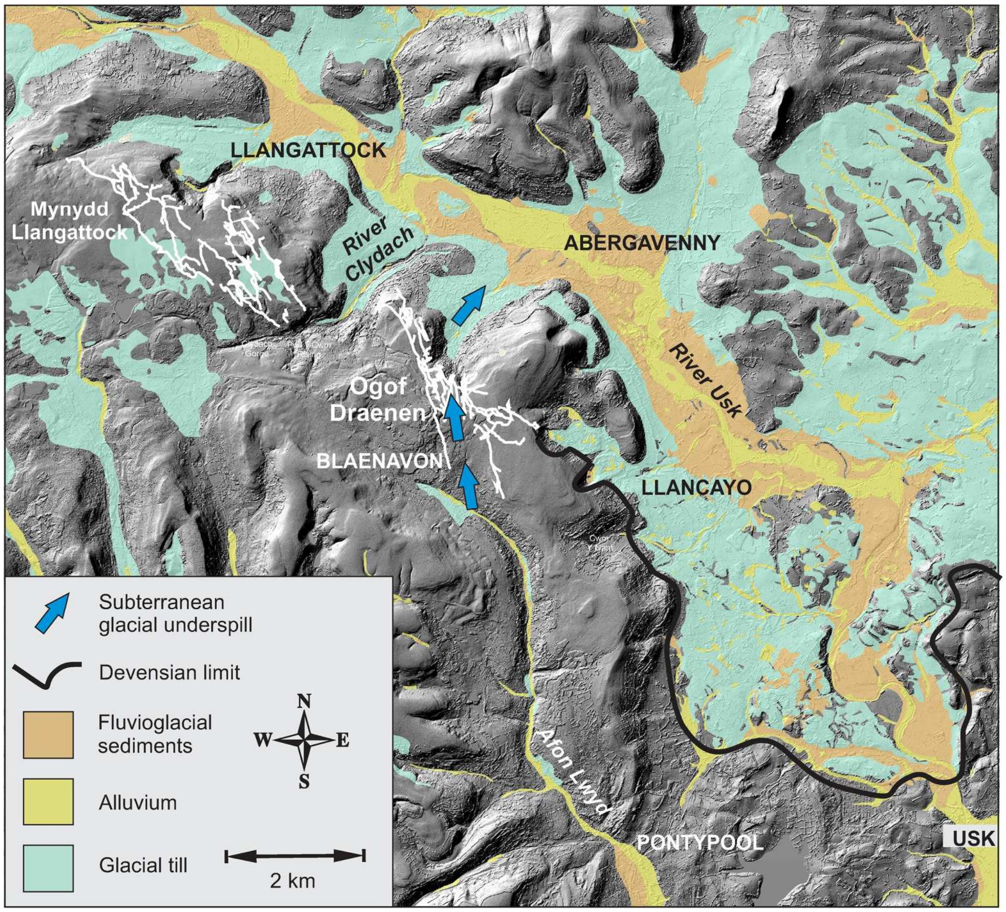

Figure 9. Superficial deposits in the Blaenavon area, showing the distribution of assumed Devensian age till, fluvioglacial deposits and post-glacial alluvium, and the limit of the Devensian ice sheet. Mapping based on NEXTMap® Britain elevation data from Intermap Technologies and superficial geological 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. A colour version of this figure is available online.
183x166mm (300 x 300 DPI)

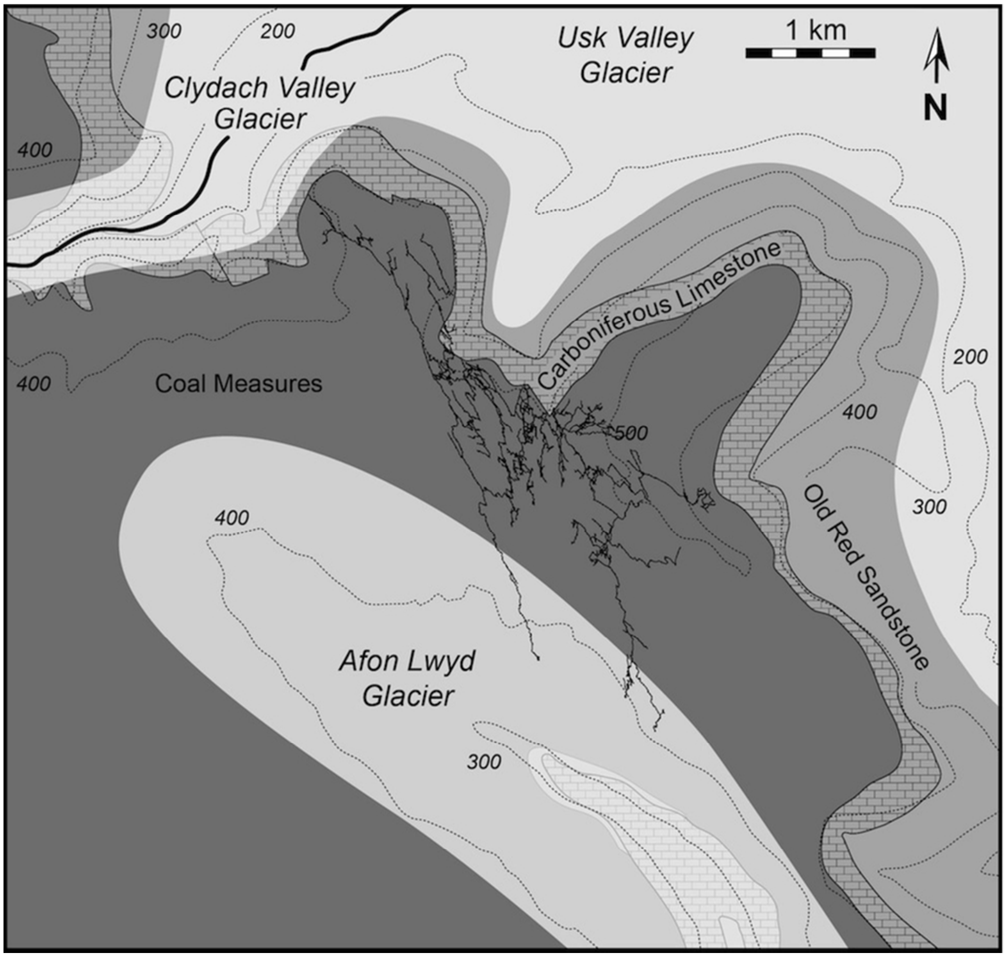

Figure 10. Proposed glacial setting during periods of subterranean glacial under-spill through Ogof Draenen during MIS 12 (Anglian glaciation). (A.) Plan view with the Afon Lwyd glacier feeding meltwater into the southern end of Ogof Draenen. (B.) Schematic cross section between the Afon Lwyd valley to the west (left) and the Cwm Llanwenarth valley to the east (right).
78x74mm (300 x 300 DPI)

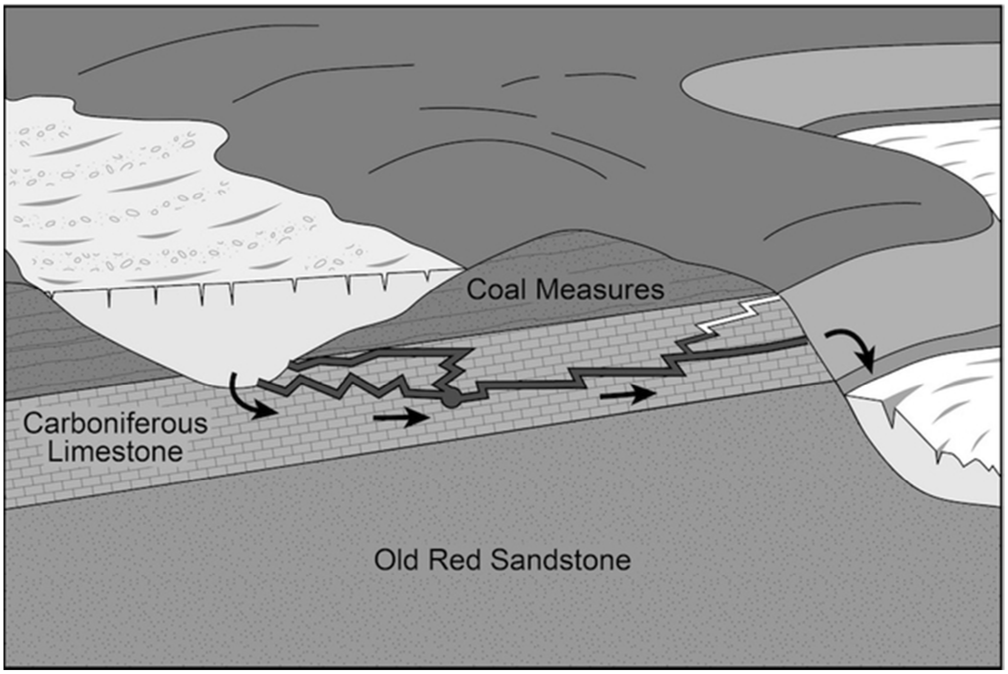

Figure 10. Proposed glacial setting during periods of subterranean glacial under-spill through Ogof Draenen during MIS 12 (Anglian glaciation). (A.) Plan view with the Afon Lwyd glacier feeding meltwater into the southern end of Ogof Draenen. (B.) Schematic cross section between the Afon Lwyd valley to the west (left) and the Cwm Llanwenarth valley to the east (right).
55x36mm (300 x 300 DPI)

SPELEOGENETIC EVIDENCE FROM OGOF DRAENEN FOR A PRE-DEVENSIAN GLACIATION IN THE BRECON BEACONS, SOUTH WALES, UK

Andrew R. Farrant [1], Christopher J. M. Smith [2, 3], Stephen R. Noble [4], Michael J. Simms [5],
David A. Richards [2, 3]

Supplementary Information

U-series dating methods

Sub-samples of calcite weighing between 30-150 mg were removed from speleothem samples using a Well Model 3421 precision vertical diamond-wire saw equipped with a 0.35 mm diameter cutting wire. Where possible, calcite wafers were obtained from individual growth layers comprised of clean, dense crystalline calcite, in order to minimise the contributions of detrital ^{230}Th contamination or areas potentially affected open system behaviour resulting from leaching of U or Rn diffusion (Lyons *et al.*, 1989; Richards *et al.*, 1998). Cutting debris was removed from samples by repeated ultrasonication in ultra-pure deionised (Milli-Q) water, followed by rising in 2% HCl.

Prior to spiking, individual wafers were weighed and dissolved in concentrated HNO_3. Samples were typically spiked with between 20-60 mg of OUBB conc. ^{229}Th-^{236}U spike (^{229}Th/^{236}U = 2.462). Details of the spike calibration are described in Hoffmann *et al.*, (2007). Spiked samples were then weighed again to calculate total spike mass. Sample-spike equilibration was ensured by refluxing the sample solutions at 100ºC for 3 hours. After equilibrating, sample solutions were dried at 105ºC, re-dissolved in 1 ml H_2O_2 and 1 ml concentrated HNO_3 and refluxed at 160ºC to destroy organics. Sample solutions were dried down at 105ºC and re-dissolved in 6 ml 3N HNO_3, ready for extraction chromatography.

U and Th were purified by extraction chromatography using a modified version of the method described in Potter *et al.*, (2005). U and Th separation was achieved by a single column pass through Eichrom UTEVA (100-150 μm) anion exchange resin. The UTEVA resin was conditioned with 3 N HNO_3 and the samples loaded in 6 ml 3N HNO_3. Sample matrix components were eluted with 9 ml 3N HNO_3 and discarded. Elution of Th and U fractions was provoked by switching from HNO_3 to HCl. Th and U were collected in separate 15 ml Teflon vials and eluted using 3 ml 3N HCl and 8 ml 0.1N HCl + 0.3N HF, respectively. After collection, 0.5 ml H_2O_2 and 0.5 ml 15.7 ml HNO_3 was added to each sample solution and refluxed at 160ºC for 24 hours to destroy any remaining organics. Purified U and Th fractions were then dried and taken up in 2 ml 2 % HCl ready for isotopic analysis.

Samples solutions were analysed on a ThermoFinnigan Neptune MC-ICP-MS coupled to a Cetac Aridus induction system, equipped with a PFA spray chamber and heated desolvating membrane. Standard-sample bracketing protocols were adopted from Hoffmann *et al.*, (2007) to correct for mass fractionation and Faraday cup to SEM gain. The Neptune collector system comprises eight movable Faraday cups and a single fixed centre cup or SEM. During analysis the axial beam can be deflected into either the central Faraday cup or the SEM. The spectrometer is fitted with MasCom multipliers which show significantly smaller intensity effects compared with previous generation ETP multipliers. Situated in front of the multipliers is an energy and angular filtering device or retarding potential quadrupole (RPQ) designed to improve abundance sensitivity. With increased abundance sensitivity it is possible to monitor the contribution of the signal peak tails of major U-series isotopes (e.g. ^{238}U and ^{232}Th) on the minor isotopes (e.g. ^{234}U, ^{236}U, ^{229}Th and ^{230}Th).

U measurements were bracketed using the NBL-112a standard and Th measurements by an in-house ^{229}Th-^{230}Th-^{232}Th Th standard (TEDDi). U–Th activity ratios were calculated using the ^{238}U half-life reported in Jaffey *et al.*, (1971), the ^{232}Th half-life given in Holden (1990) and the ^{230}Th and ^{234}U half-lives reported in Cheng *et al.*, (2013). Uncertainties for all analytical variables listed in Hoffmann *et al.*, (2007) were propagated using a Monte Carlo procedure to determine the final error for reported isotope activity ratios, and are quoted at 95 % confidence, unless otherwise stated.

The corrected activity ratios and sample ages for speleothem samples from the Ogof Draenen cave system are shown in a series of ^{230}Th/^{238}U vs ^{234}U/^{238}U activity ratio diagrams, below.

Measured versus corrected $^{230}Th/^{238}U$ versus $^{234}U/^{238}U$ activity ratios

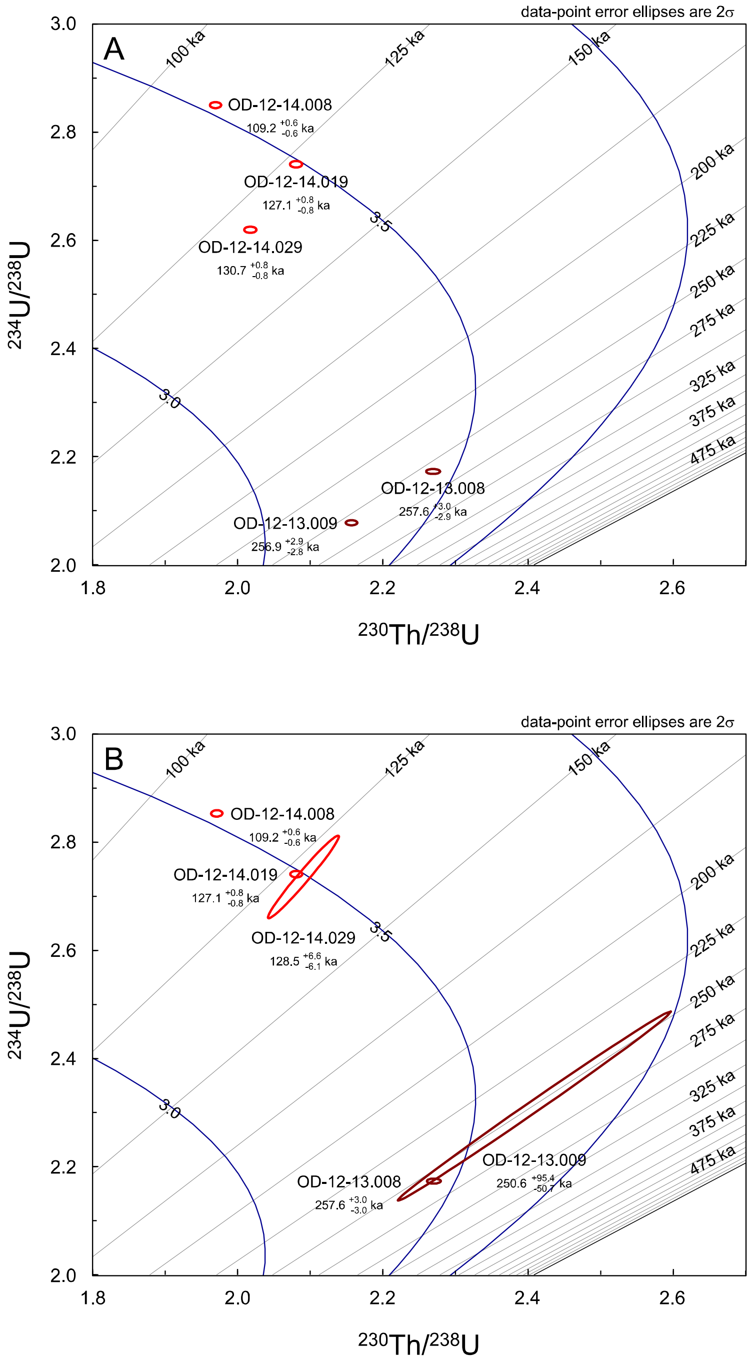

Figure S1. (A.) Measured and (B.) corrected $^{230}Th/^{238}U$-$^{234}U/^{238}U$ activity ratios for stalagmites OD-12-13 and OD-12-14 from the 'Beyond a Choke' streamway. Note sub-samples OD-12-13.009 and OD-12-14.029, which have low ($<10^2$) $^{230}Th/^{232}Th$ ratios (see Table 3), indicating the presence of high levels of ^{232}Th and detrital ^{230}Th. Correcting the isotopic composition of these sub-samples against the mean bulk earth $^{230}Th/^{232}Th$ ratio

(0.746 ± 0.2) increases the dimensions of the error ellipses on the on the ^{230}Th/^{238}U axis, resulting in increased age errors.

Corrected ^{230}Th/^{238}U versus ^{234}U/^{238}U activity ratios for Ogof Draenen speleothems

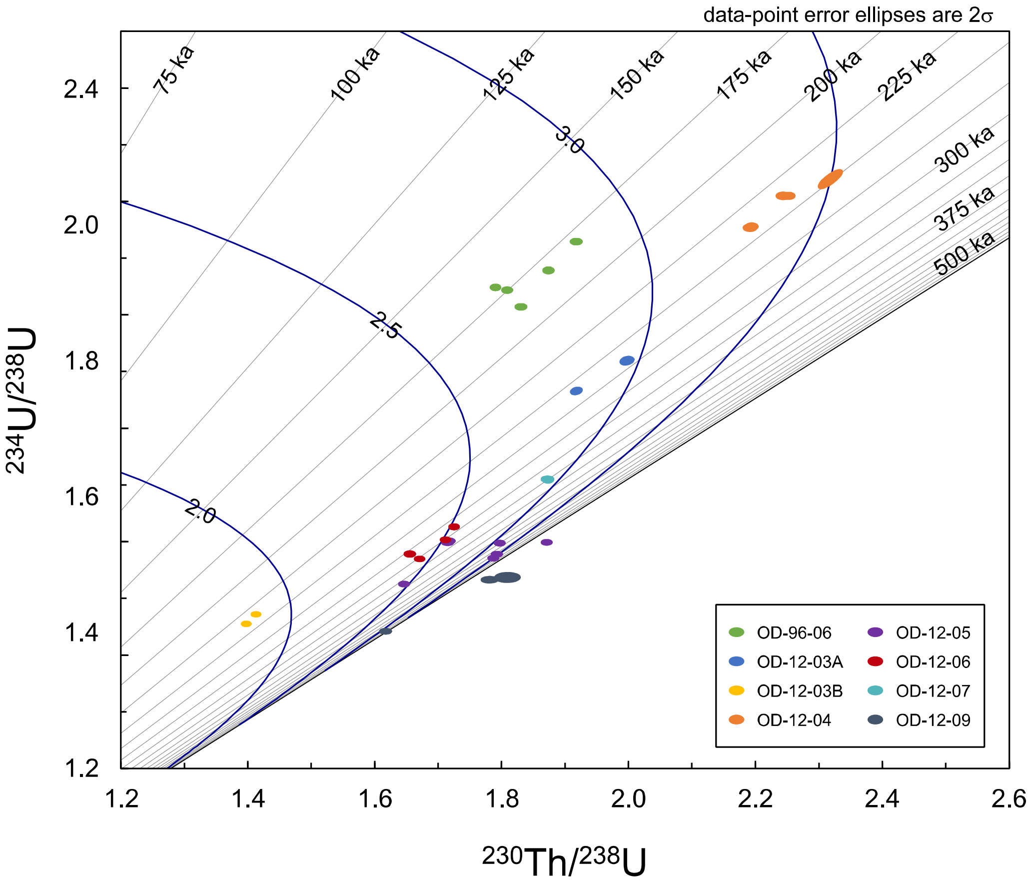

Figure S2. Corrected ^{230}Th/^{238}U-^{234}U/^{238}U activity ratios for speleothems from Gilwern Passage, including Giles Barker's Shirt (OD-96-06, OD-12-03A, OD-12-03B, OD-12-04, OD-12-07, OD-12-09) and Second Inlet (OD-12-05, OD-12-06).

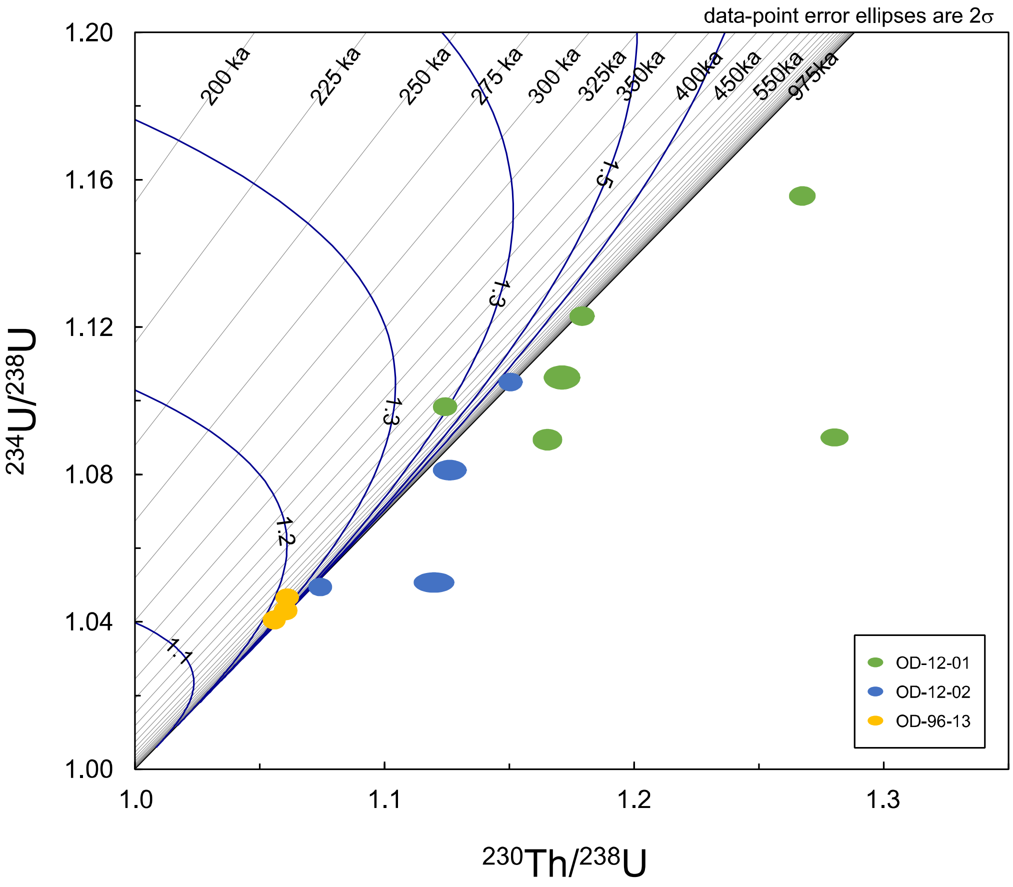

Figure S 3. Corrected $^{230}Th/^{238}U$-$^{234}U/^{238}U$ activity ratios for speleothems from War of the Worlds (OD-12-01, OD-12-02) and Big Beauty Junction (OD-96-13).

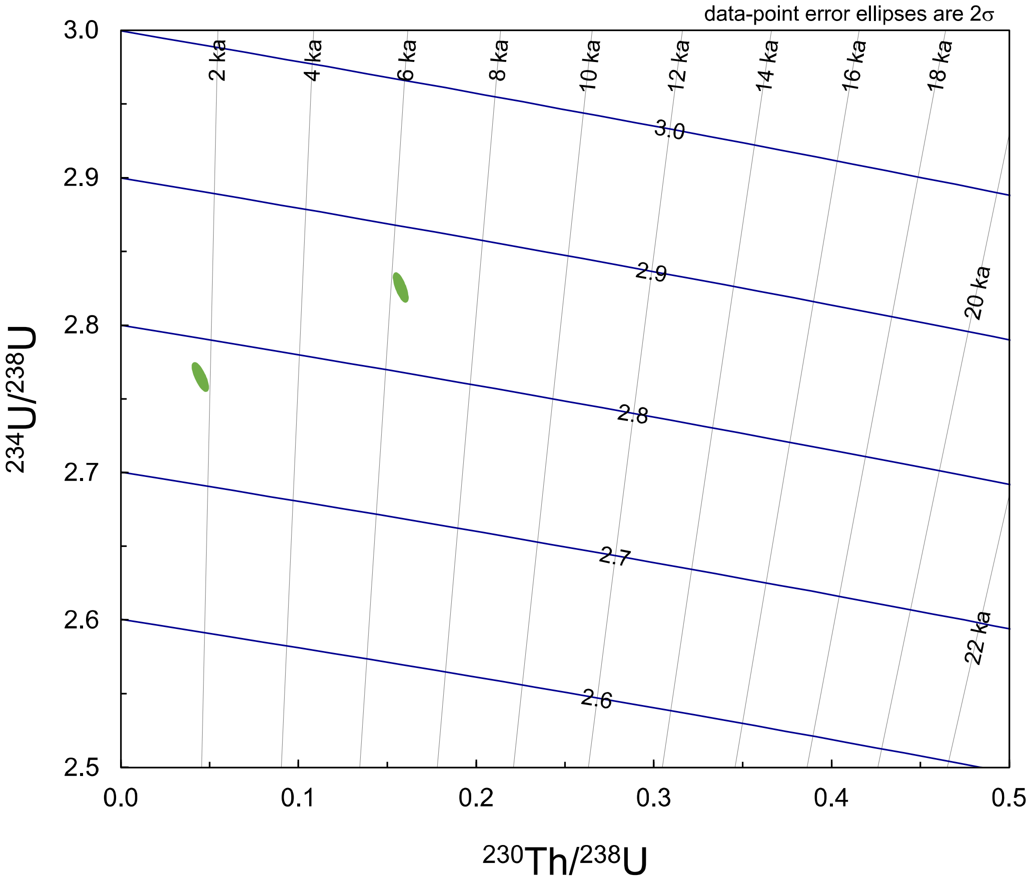

Figure S 4. Corrected $^{230}Th/^{238}U$-$^{234}U/^{238}U$ activity ratios for stalagmite OD-12-08 from Upstream Passage.

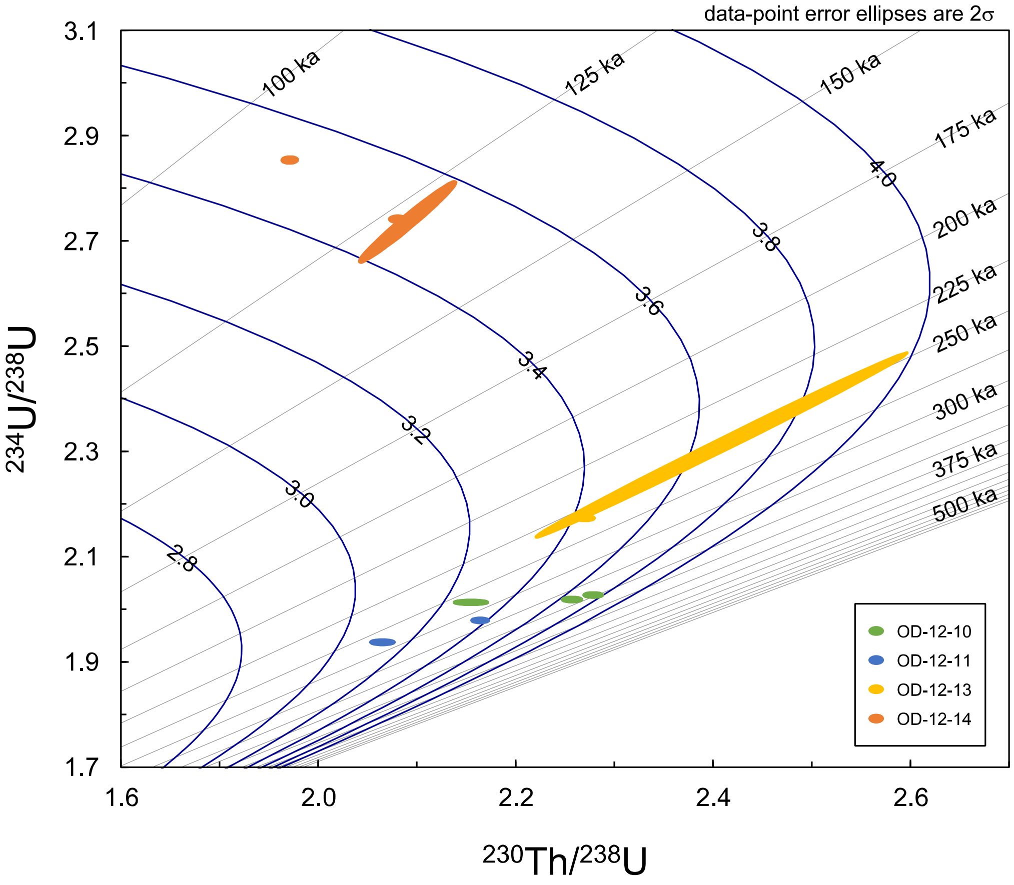

Figure S5. Corrected ^{230}Th/^{238}U-^{234}U/^{238}U activity ratios for speleothems from 'Beyond a Choke' streamway (OD-12-10, OD-12-11, OD-12-13, OD-12-14).

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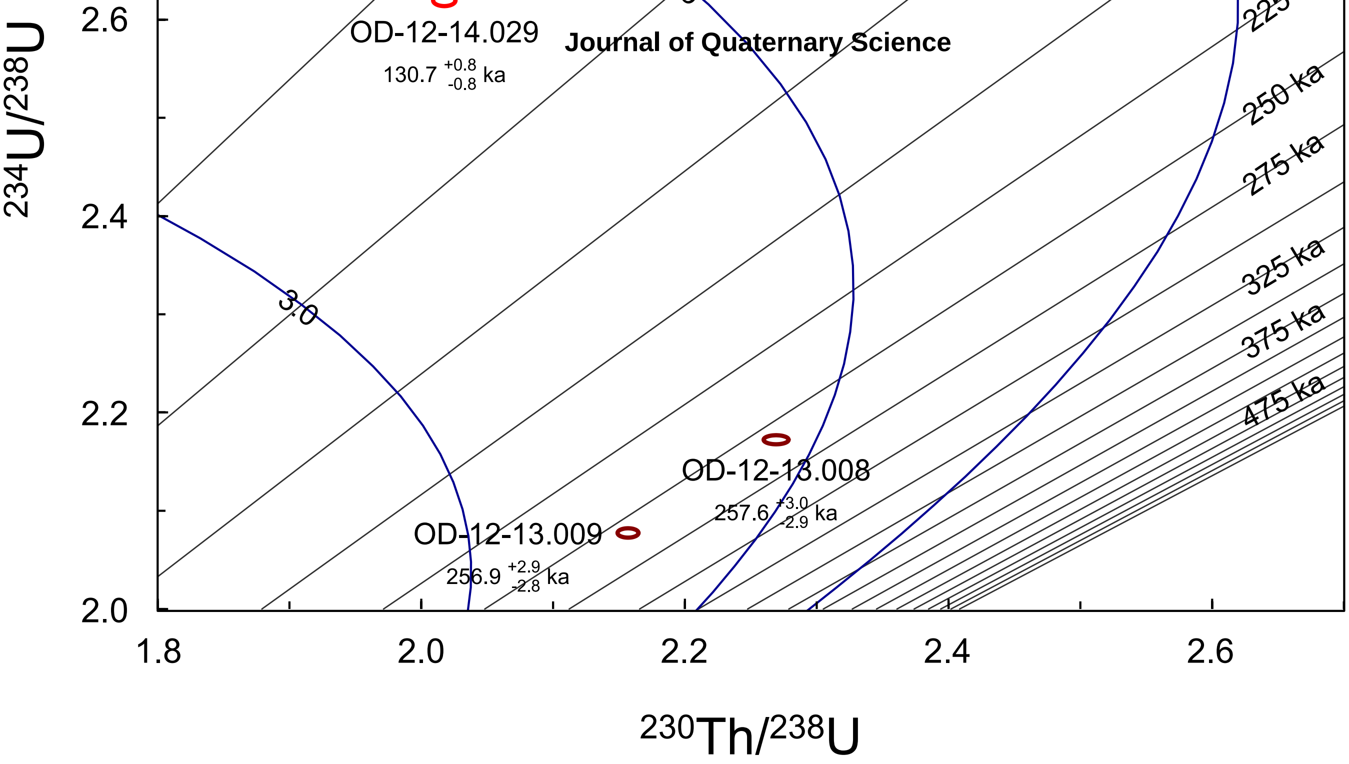
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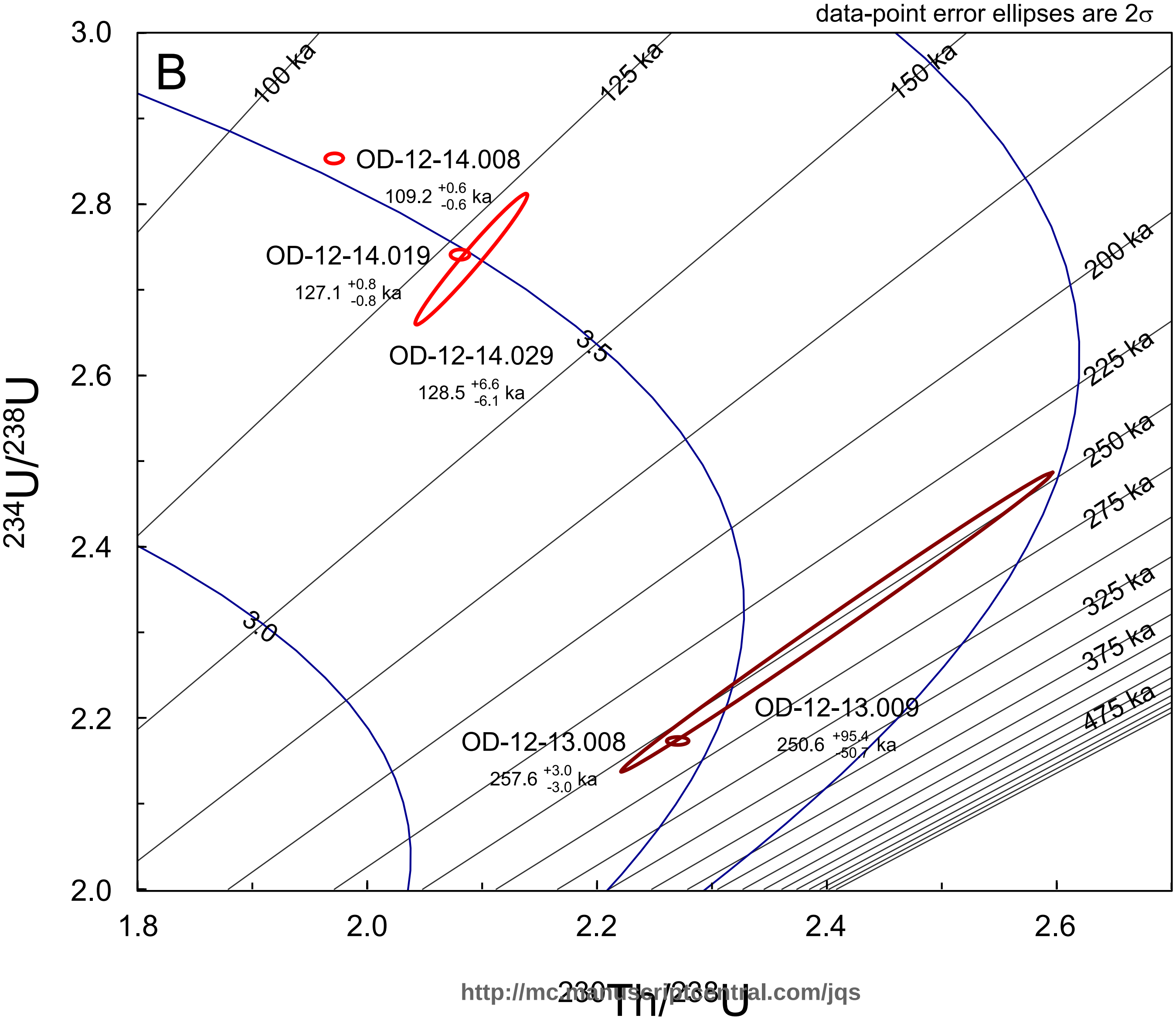
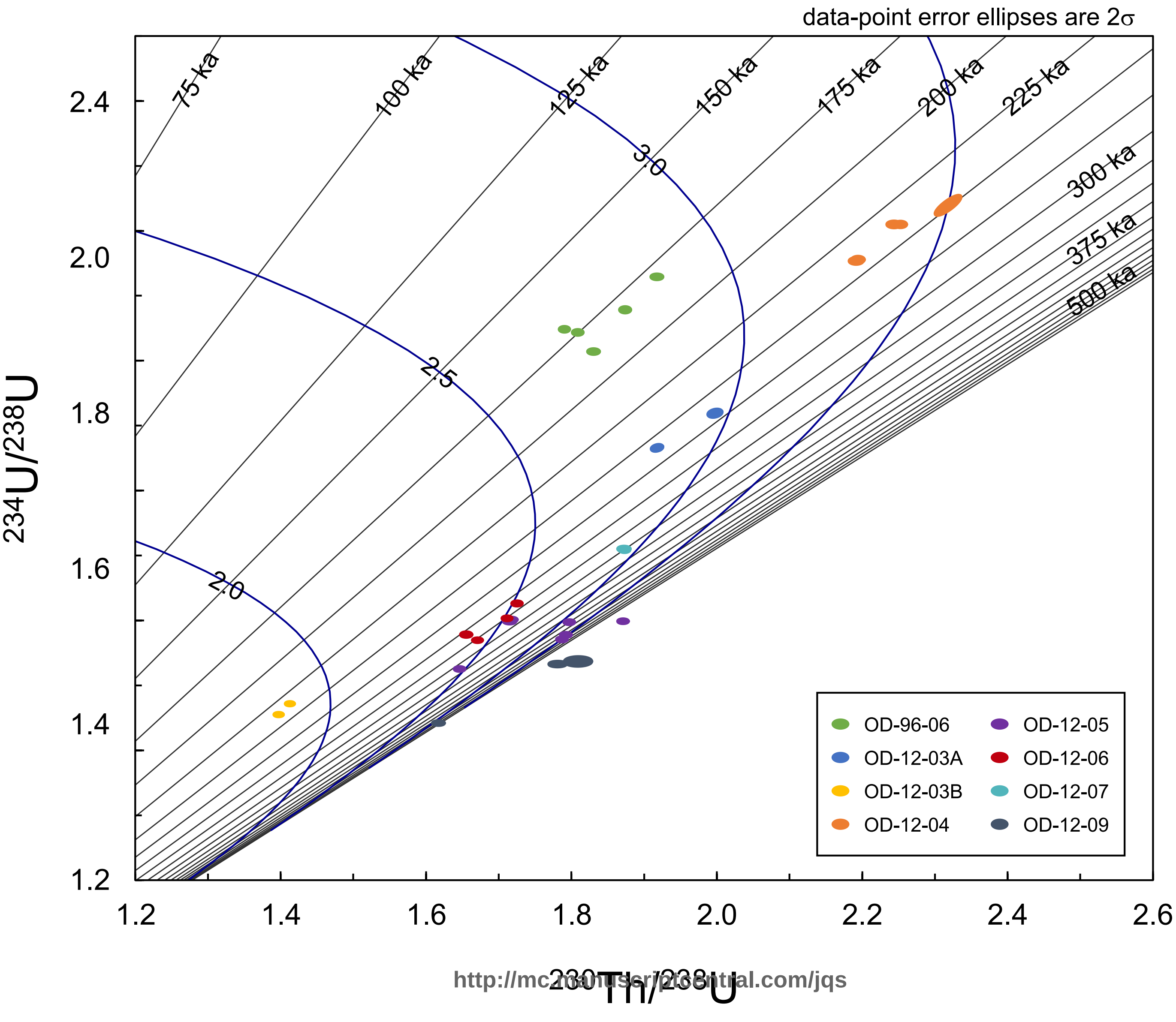
OD-12-13.008
257.6 +3.0 -2.9 ka
OD-12-13.009
256.9 +2.9 -2.8 ka
3.0
225
250 ka
275 ka
325 ka
375 ka
475 ka
2.6
2.4
2.2
2.0
1.8
2.0
2.2
2.4
2.6
234U/238U
230Th/238U


data-point error ellipses are 2σ
B
100 ka
125 ka
150 ka
200 ka
225 ka
250 ka
275 ka
325 ka
375 ka
475 ka
3.0
3.5
OD-12-14.008
109.2 +0.6 -0.6 ka
OD-12-14.019
127.1 +0.8 -0.8 ka
OD-12-14.029
128.5 +6.6 -6.1 ka
OD-12-13.009
250.6 +95.4 -50.7 ka
OD-12-13.008
257.6 +3.0 -3.0 ka
3.0
2.8
2.6
2.4
2.2
2.0
1.8
2.0
2.2
2.4
2.6
234U/238U
230Th/238U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125 ka
150 ka
175 ka
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225 ka
300 ka
375 ka
500 ka
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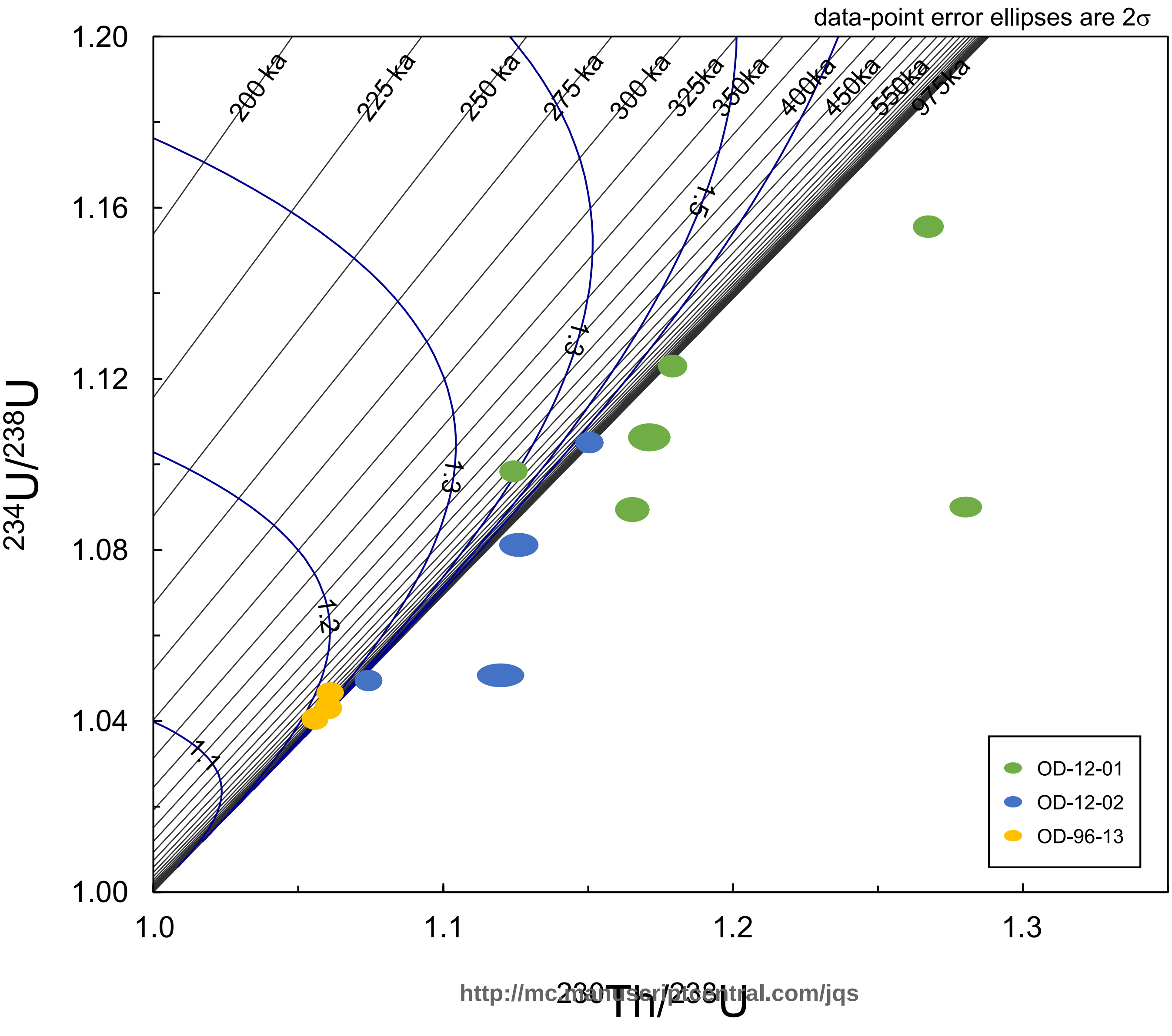
2.5
2.0
$^{234}U/^{238}U$
2.4
2.0
1.8
1.6
1.4
1.2
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
$^{230}Th/^{238}U$
OD-96-06
OD-12-03A
OD-12-03B
OD-12-04
OD-12-05
OD-12-06
OD-12-07
OD-12-09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200 ka
225 ka
250 ka
275 ka
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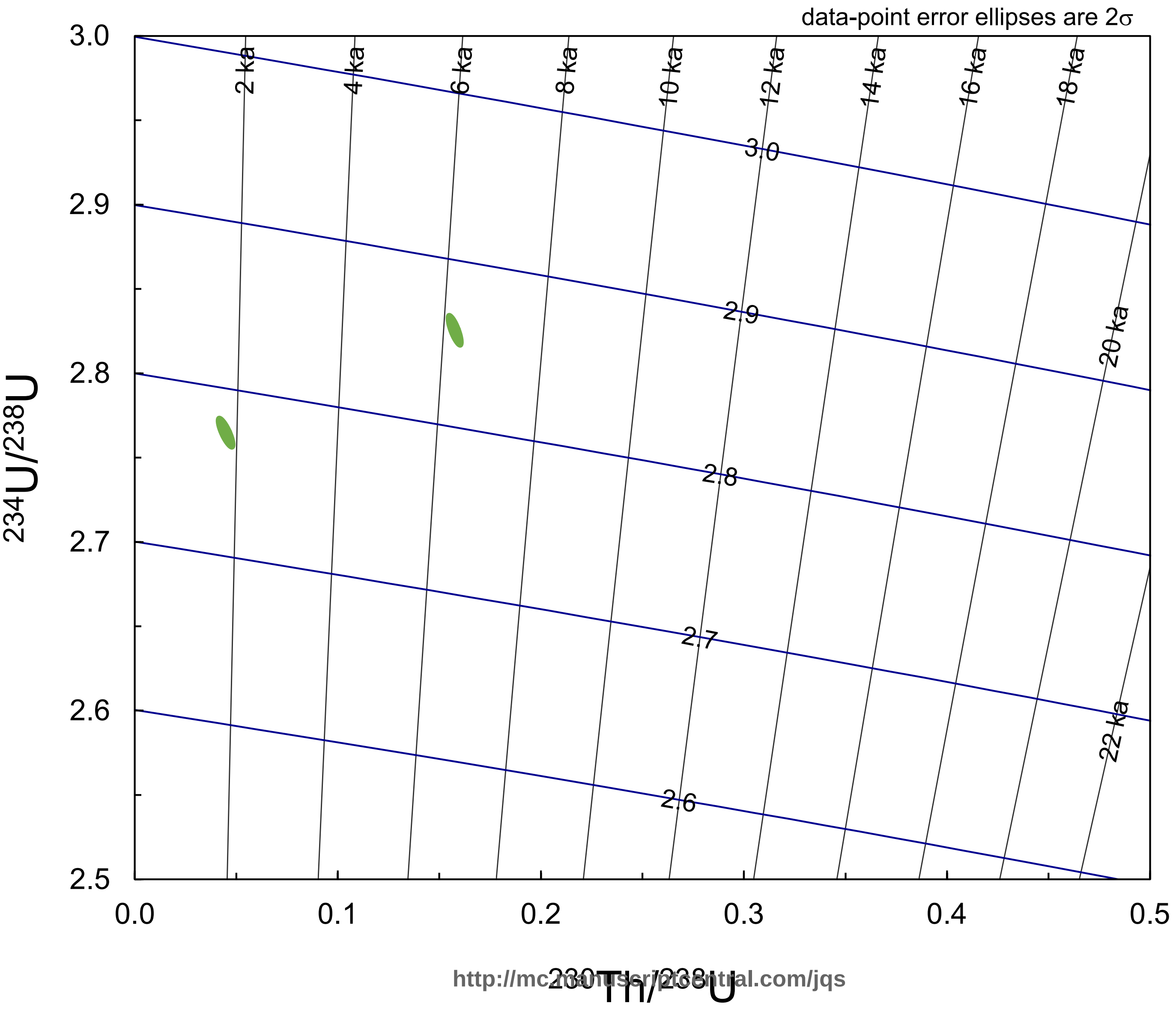
400ka
450ka
550ka
975ka
1.1
1.2
1.3
1.3
1.5
1.20
1.16
1.12
1.08
1.04
1.00
^{234}U/^{238}U
1.0
1.1
1.2
1.3
^{230}Th/^{238}U
OD-12-01
OD-12-02
OD-96-13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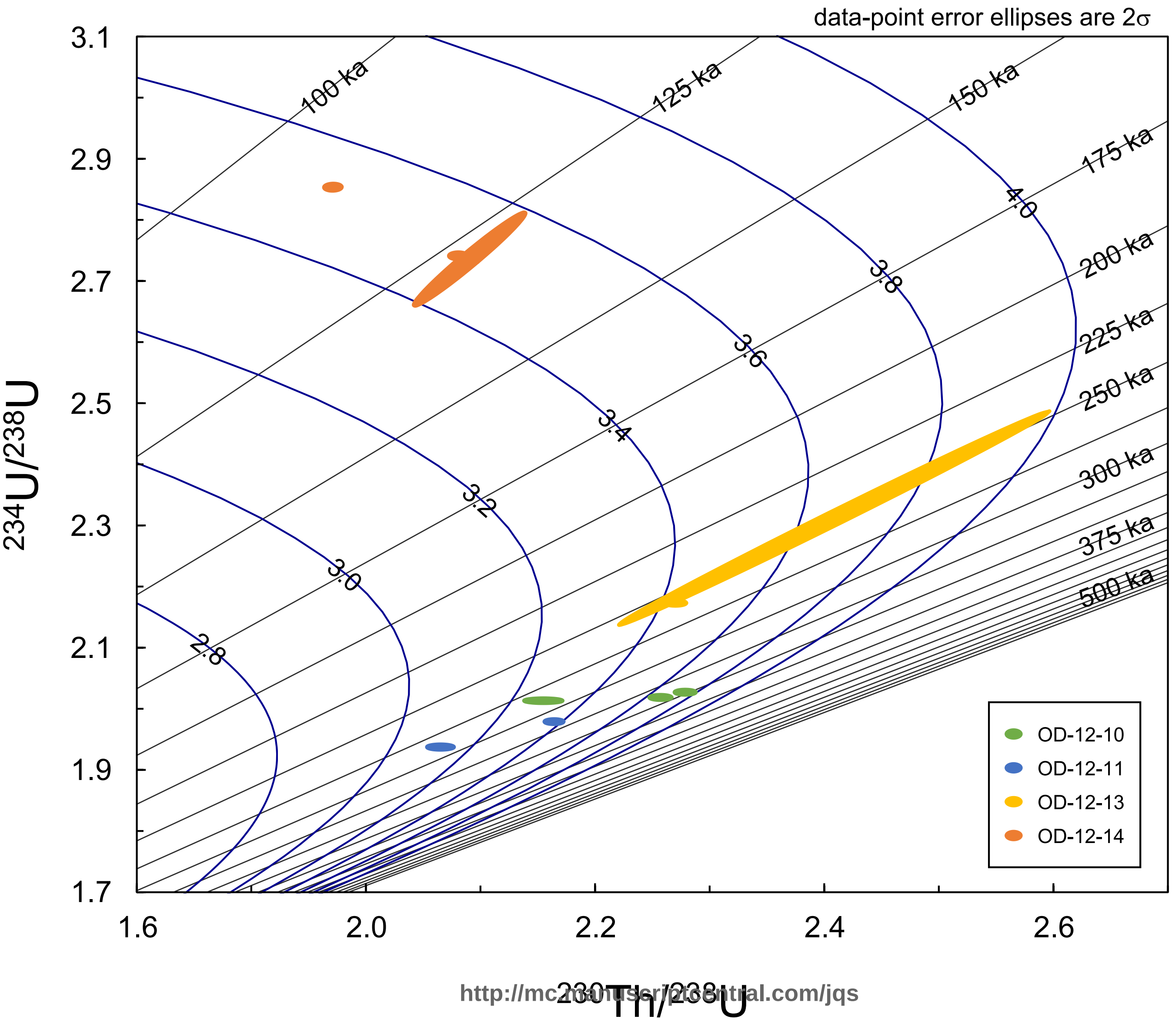
0.1
0.2
0.3
0.4
0.5
2 ka
4 ka
6 ka
8 ka
10 ka
12 ka
14 ka
16 ka
18 ka
20 ka
22 ka
3.0
2.9
2.8
2.7
2.6
234U/238U
230Th/238U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3.1
2.9
2.7
2.5
2.3
2.1
1.9
1.7
1.6
2.0
2.2
2.4
2.6
^{234}U/^{238}U
^{230}Th/^{238}U
100 ka
125 ka
150 ka
175 ka
200 ka
225 ka
250 ka
300 ka
375 ka
500 ka
2.8
3.0
3.2
3.4
3.6
3.8
4.0
● OD-12-10
● OD-12-11
● OD-12-13
● OD-12-14