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Reply to Walkden, Fraser and Simms (2021): The age and formation mechanisms of Late Triassic fissure deposits, Gloucestershire, England: Comments on Mussini, G., Whiteside, D. I., Hildebrandt C. and Benton M.J.

David I. Whiteside*, Michael J. Benton

School of Earth Sciences, University of Bristol, Bristol, BS8 1RJ, UK

The Walkden et al. (2021) comments particularly refer to previous papers involving Whiteside and Benton as authors, rather than Mussini et al. (2020). With the agreement of G. Mussini and C. Hildebrandt, the response, given here, is provided by David I. Whiteside and Michael J. Benton.

In this response, we deal with each key point in the comments by Walkden et al. (2021) and provide suggestions for future research, if their point of view is to be considered valid. We provide a more detailed point by point consideration of their comments in the Supplementary document.

We specifically consider here the Late Triassic vertebrate-bearing fissure fills of the Bristol region; these were formed by solution or by a combination of solution influenced by tectonic activity. This region of the UK is characterised by a two-phase sedimentary geological succession, where the extensive Carboniferous and older rocks were uplifted and then karstified and overlain unconformably by a Mesozoic rock sequence. The key question is whether this karstification, fissuring, infill and overlay happened over a long time-span, from Carnian to Norian (232–206 Ma) in the Late Triassic (the Walkden et al. view) or generally over a short time span, largely associated with the Rhaetian Transgression, lasting from *c.* 206–201 Ma (our view)?

1. Karstification in the Carnian?

Whiteside (1983), coining the term 'Pluvial episode' in the Carnian (this thesis was read and cited by Simms 1990) and Whiteside & Marshall (2008) did consider the possibility that the earliest Tytherington fissure speleogenesis could have occurred in the Carnian. However, we have found no unequivocally dateable (with fossils compared to UK strata) Norian or Carnian sediments at Tytherington despite continual searching for nearly 40 years up to the Mussini et al. (2020) publication. If, as suggested by Walkden et al. (2021), many of the phreatic voids were formed in the Carnian (*e.g.* fissure 2 at Ex 17) then *c.* 20 million years passed without any demonstrated Carnian or Norian sediment fill. Instead, as shown by Mussini et al. (2020), a deep-lying fill of a large phreatic void can be entirely ascribed to the Rhaetian, particularly the Westbury Formation (WF).

The statement by Whiteside and Marshall (2008), referenced by Walkden et al. (2021, section 5.2.5), referred to *solutional* carbonate karst of the type at Tytherington with phreatic caverns near the limestone surface and dolines which are not *formed* in deserts. This accords with Webb and White (2013, p 403), who remark that karst features in hot deserts are 'not because the karst features have formed in the desert environment; in every well-documented case they were developed in earlier wetter periods or by hypogene processes.'

2. Topographic height of the Cromhall fissures

We confirm that the entrance of the western fissures lay well above the 'cover' sequence of Walkden and Fraser (1993), based on the 1993 Cromhall Quarry map (Fig. 1), which was a detailed survey by the then owners (Amey Roadstone Corporation). The O.S. digimap (Fig. 1A) also shows the 75 m contour at the edge of the cliff (including fissure sites 3–7) in the western face of Cromhall Quarry. The spot height of 80.4 m at the entrance of fissure 2 (Fig. 1 B) is about 6 m above the top of the cover sequence (and 10 m above its base) dated as basal WF from coeval marine fish fossils by Walkden and Fraser (1993, p. 590). The cavern and other voids described by Robinson (1957, fig. 5) from this locality are an extension (now destroyed) of site 2 (O'Brien et al., 2018, fig. 2a). Our description of *Euestheria brodieana*, a characteristic late Rhaetian conchostracan (Boomer et al., 1999; Kozur and Weems, 2010) which was found by Robinson (1957) in those deposits, is therefore entirely consistent with the relative heights of the cover sequence and fissure entrance. Even in comparison to the newly conjectured 75 m WF base level of Walkden et al. (2021), the fissure site 2 entrance is about 5 m above. The topographic evidence substantiates the view of Morton et al. (2017) that the fissure deposits with *Clevosaurus hudsoni* are plausibly late Rhaetian in age.

* Corresponding author.
E-mail address: david.whiteside@bristol.ac.uk (D.I. Whiteside).

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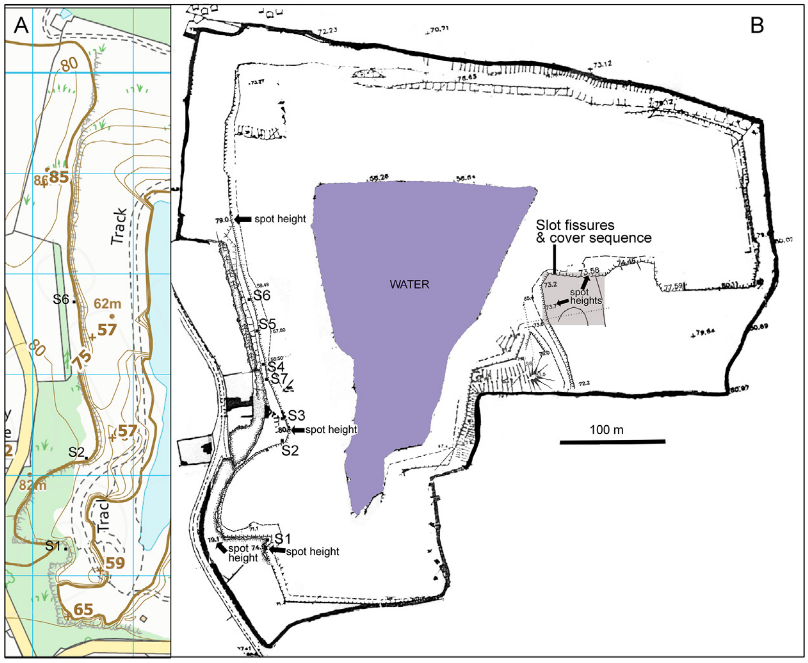

Fig. 1. Maps of Cromhall Quarry. (A) OS map digimap © 2020 showing western fissure areas, labelled S2 etc., with adjacent 75 m and 80 m contours. (B) Simplified 1993 Quarry map based on one compiled by the quarry company with spot heights indicated (from a scan of the map). Positions of fissures and cover derived from Walkden and Fraser (1993).

3. The Cromhall fish faunas

Mussini et al. (2020) reported that 'Durdham Down, Cromhall and Woodleaze faunas all have coeval marine fossils, giving consistent evidence of a marine transgression event'. As Walkden and Fraser (1993, p. 586) had cited coeval marine fish at Cromhall, this is not a surprising statement. Mussini et al. (2020) did not say (Walkden et al. 2021, section 3(1)) that coeval fish faunas are found 'throughout the faunas recovered at Cromhall', one of several imprecise statements by Walkden et al. (2021).

Behan et al. (2012) did not assess the suggested coeval fish from site 4 (BRSMG CC 6087) reported four years earlier by Whiteside and Marshall (2008), failing even to cite that paper. Walkden et al. (2021) dismiss these fossils, but apparently have not seen them. Whiteside et al. (2016) did not dismiss Behan et al. (2012), rather we simply presented counter evidence.

4. Fissure styles and modern analogues

We have stated (Whiteside et al., 2016, p. 263) that the material properties of the massive Black Rock Subgroup limestones likely constrained the morphology of the types of voids at Cromhall and Tytherington. We use the modern Bahamian islands as guides for phenomena that we might expect on a carbonate island in the Late Triassic, and we do not consider (or have ever said) that the properties of the much younger and more porous Bahamian Limestone are the same as the Carboniferous Limestone. Whiteside and Marshall (2008) discussed a range of phreatic and vadose voids at Tytherington in the Late Triassic. Our figures (*e.g.* Mussini et al., 2020, fig. 2A) show conduits that follow and cut across the bedding planes of the Black Rock Limestone, but also make clear that we consider that mixed freshwater/seawater dissolution is likely for some voids such as fissure 2 Ex 17. As described by Mussini et al. (2020), this cavern terminates followed by a narrow fissure at Ex20 m; east and south east of this cavern only narrow slot-type fissures were noted at this level or the levels immediately above and below in research from 1976– 2012.

5. Freshwater lens and marine-freshwater mixing

The hypothesis of a Tytherington palaeoisland freshwater lens following the onset of the Rhaetian transgression conforms to modern-day carbonate islands where such lenses are frequently formed on even very small islets (>270 m across). The Tytherington palaeo-island was substantially larger than this in the early Rhaetian, as shown by Walkden et al. (2021, section 5.2.4). Indeed, it would have been larger still at the onset of the Rhaetian Transgression towards the end of deposition of the upper Mercia Mudstone Group (MMG), and then reduced in size as the transgression progressed. A freshwater lens can be located very deep, even on a very small island, but the depth depends on factors controlling the hydraulic head, the density of marine waters and geology of the limestone, as well as flow within the lens. Nevertheless, an island such as Buariki, on Tarawa Atoll, only 1200 m across, has a lens of 29 m depth (Bailey et al., 2008) and there are other even smaller islands (*e.g.* Buota, *c* 650 m width) with lenses over 20 m deep. Since mixing zones form where the freshwater lens meets saline water, we regard our suggestion that fissure 2 at Ex 17 was developed in a mixing zone as entirely reasonable, especially as the fissure fill of over 6 m depth has a mixed terrestrial and littoral marine fauna. The glauconitic clay from this exposure, formed in euryhaline conditions (Whiteside and Robinson, 1983), conforms to this model.

A freshwater lens supported by surrounding saline waters provides a water table at or near the limestone surface. This provides the freshwater standing pools lasting a few weeks for the alga *Botryococcus* (found at Tytherington) to grow (Batten and Grenfell, 1996); it also provides the habitat for the conchostracan *Euestheria* present at both Cromhall and Tytherington. Without a lens, the surface water would quickly drain away, killing the organisms and transporting them to destruction.

Walkden et al. (2021) state that 'the mixing zone cannot account for many very specific features of (the Tytherington) cavities and their fills', implying that is our entire model. Our model (Mussini et al. 2020, Fig 2A) includes freshwater phreatic tubes within the lens and vadose voids such as dolines which are fully outlined in Whiteside and Marshall (2008). In addition to explaining the presence of phreatic caverns near the surface of the limestone at Tytherington and Cromhall, a freshwater lens provides accessible water to maintain a productive ecosystem, including a diversity of plants (found in the palynomorph assemblages at Tytherington) and therefore arthropods; both are likely food for the numerous Triassic reptiles. The fossil bones would not have had to be transported far before deposition, which accounts for the articulated specimens described by Fraser (1988) and O'Brien et al. (2018) and the abundant isolated bones. In contrast, the much drier environment that existed at times during the Norian would have supported a noticeably less productive ecological community.

6. Westbury-aged sediments and coeval fossils

Walkden et al. (2021) suggest that the grey Westbury conglomerate with graded bedding from Tytherington fissure 1 is a proxy for internal sediment distribution by seismic activity. Whiteside and Marshall (2008, fig. 7a, b) demonstrated that the undisturbed right-hand side of the fissure 1 deposit (with four graded beds) was palynologically dated entirely in the WF with a duration equivalent to beds 2–3 to 7–9 at Hampstead Farm Quarry. The disturbance to the fissure was from earth movements, but the main slumping was caused by seismic activity that widened the fissure and caused a block of Carboniferous Limestone to fall. This exposure was unique, limited to the 'Westbury' deposit, and later sequences in fissure 1, and where it probably joined fissure 2 (Whiteside and Marshall, 2008, fig. 2), consist of palynologically dated, layered Westbury-age sediments.

Overall, the Tytherington fissure fills are predominantly red-brown or red (see *e.g.* Whiteside and Marshall 2008, fig. 9) but include green sediments such as fissure 14 (Whiteside and Marshall 2008); in no case is there a cap of typical grey Westbury strata found above which might demonstrate a pre-PG age. This is contrary evidence to the models of Walkden et al. (2021) but conforms to our model. Rather than occurring in clasts, coeval marine fish and invertebrates are generally found individually as teeth or steinkerns together with terrestrial reptiles in overwhelmingly brown or reddish-brown (not 'grey' as stated by Walkden et al., 2021, section 1) sediment, as documented by Mussini et al. (2020) in fissure 2 Ex 17.

7. Evidence-based Rhaetian ages

Walkden et al. (2021) doubt our age-dating evidence for various fissure deposits. We have presented a dating and palaeoenvironmental model in a series of papers – Marshall and Whiteside (1980), Whiteside and Robinson (1983), Whiteside and Marshall (2008), Whiteside et al. (2016), Morton et al. (2017) and Mussini et al. (2020). These are based on all available palaeontological, geomorphological, topographical, mapping and sedimentological evidence. For example, all dateable Late Triassic rocks from Tytherington Quarry can be assigned to the Rhaetian and the great majority of these to age equivalence with the WF, based on palynomorphs, a variety of invertebrates, and fish fossils. The consequence of these biostratigraphically assigned ages at Tytherington, Cromhall and other penecontemporaneous fissures is to confirm that the greatest period of fissure formation was in the Rhaetian, and this began with the onset of the transgression.

In a new study, preliminarily summarised by Lovegrove (2019), we apply computational GIS methods to generate a detailed 3D map of the region, and this contradicts the suggestion by Walkden et al. (2021, section 5.2.4) that "any surviving island after the transgression would have been insignificant and short lived". In fact, the new GIS work shows that Tytherington and Cromhall were islands in the early Rhaetian, and the latter persisted into the late Rhaetian. Moreover, the Walkden et al. (2021) palaeogeographic analysis is equivocal because their baseline data is highly variable; for example, the closest 'boundary sampled' of the WF to Cromhall lies at 64 m (11 m below the conjectured sub-WF base) whilst the next nearest is 82 m (Walkden et al., 2021, table 1, locations 3 and 4), a difference in height of 18 m. Further, there is a lack of equivalence in the baselines chosen for Walkden et al. (2021) calculations e.g. location 11 is written as 'proven Rhaetian bone Bed', but location 10 is identified as the 'basal Rhaetian' and others such as location 12 as 'basal Penarth Group'. The BGS digimap © refers all three nearest locations (3–6) as 'undifferentiated mudstone of the WF and Cotham Mbr'. In any case, a sub-Westbury base is not basal Rhaetian, and this means that the approach cannot eliminate the postulated Tytherington and Cromhall Rhaetian palaeo-islands (with their tetrapods) from the start of the transgression.

8. Postulated Carnian and Norian ages

Walkden et al. (2021), and in previous publications, argue for a Norian or even Carnian date for the Cromhall fissure fills. They point to the (apparent) similarity of colour to sediments of the MMG. We would urge caution; determining the stratigraphic ages of sediments by texture and colour is speculative. In their commentary and model (*e.g.* Walkden et al., 2021, fig. 2) and in their earlier papers we can find no evidence of biostratigraphically useful fossils, nor even a comparative chemical analysis of the matrix that could at least provide some evidence for their claims. They do not consider the possibility that red and green sediments might also have covered the limestone islands in the Rhaetian. Yet, we have described the late Rhaetian-aged conchostracan *Euestheria brodieana* from a conspicuously red matrix at Cromhall; *Clevosaurus hudsoni* is also found in red matrix in the same deposit. They speculate that the substantial cavernous voids at Tytherington and Cromhall formed in the Carnian but provide no example of dated pre-Rhaetian sediments that subsequently filled the fissures. Walkden et al. (2021) mention the fish fauna from the cover and slot fissures of Cromhall, first described by Walkden and Fraser (1993), including *Lissodus*, *Gyrolepis*, *Birgeria*, *Palaeospinax (= Synechodus)*, *Polyacrodus* and a pholidophoriform. They suggested that the ichthyofauna is 'with some certainty' basal PG (Fraser, 1994, p. 219), but they now suggest it is 'pre-Rhaetian' (not pre-Westbury; Walkden et al., 2021, fig. 2).

There is little doubt that Carnian-Norian tetrapods would have lived on the limestone surface, but we find no evidence for their deposition in the Tytherington and Cromhall fissures. The postulated earliest fissure tetrapod assemblage from Ruthin Quarry, South Wales, dominated by procolophonids but also including archosaurs and a trilophosaur, as well as the sphenodontians *Planocephalosaurus* and *Diphydontosaurus*, is ascribed to the early Rhaetian, just after the beginning of the Rhaetian transgression by Skinner et al. (2020), based on coeval fish fossils. That fauna, although including some sphenodontian genera in common with those at Tytherington and Cromhall, is distinctively different, as it is dominated by an abundance and diversity of procolophonids not characteristic of those localities.

9. Orthodoxy

Perhaps our model of Late Triassic islands which probably had a freshwater lens is the 'new orthodoxy', but the question is not about orthodoxy or non-orthodoxy, but about what is right and wrong. We contrast our Rhaetian age model based on a wide range of evidence with the Carnian-Norian model argued by Walkden et al. (2021) based on conjecture.

10. Evidence

Walkden et al. (2021) note: 'Faunal dating based upon inaccurate or imprecise non-palaeontological evidence opens the way to circular reasoning.' We regret to suggest that this seems to be more a comment on their approach rather than ours. They also state, 'we confine ourselves here largely to geological argument and have no need to address wider palaeontological implications that can be addressed elsewhere'. We suggest that they re-examine their argument and that they must address the wider palaeontological issues.

We have rebutted the arguments by Walkden et al. (2021), and we suggest five areas of research to resolve the dating of Cromhall. We would be keen to collaborate with Walkden and colleagues on such analyses, particularly (2):

1 Walkden et al. (2021) state (and in many previous papers) that various red and green sediments at Cromhall are characteristic of the MMG and distinctly Norian in age. Walkden and colleagues ought to provide the lithological and chemical analysis data that demonstrate the conclusive similarities between the UK MMG and the Cromhall fissure-fill sediments. General similarities of colour and texture are hardly enough to make their case.
2 Walkden and colleagues could investigate the fish fauna of the Cromhall Quarry slot fissures and cover sequence, to discover if an assignment to the Rhaetian or Norian is likely, based on biostratigraphic criteria. This assemblage was described by Walkden and Fraser (1993, p. 585, 586) as a 'rich fish fauna . . . dominated by fish remains' and by Fraser (1994 p. 219) as 'abundant' although now (Walkden et al., 2021) the fauna is said to be 'sparse'. Either way, comparing the fauna quantitatively with a range of PG and MMG fossil fish assemblages already reported in the literature, such as those at Hampstead Farm Quarry (Mears et al., 2016), would be informative.
3 Walkden et al. (2021) state that the voids at Cromhall and Tytherington were substantially formed in the Carnian (such as fissure 2 Ex 17). We suggest that they calculate the amount of rainfall and recharge in the Carnian to create the phreatic caverns formed at Tytherington. The catchment area of Tytherington is reported as 2 km^2 (Simms and Ruffell 1990, p. 323), so this provides some background.
4 Walkden and colleagues could find some characteristic Carnian-Norian fossils in their substantial Cromhall fissures collections to match with fossils from dated UK continental strata.
5 Walkden and colleagues might also identify vadose and phreatic cave systems with tetrapod-bearing infills (similar to Cromhall/Tytherington) and which lie under definitive, Blue Anchor Formation, Rhaetian or at least proven basal WF strata in the Bristol region.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.pgeola.2020.12.001.

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