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Triassic outliers in the Peak District, central England, and a stratigraphical revision of the Miocene Brassington Formation

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Abstract: The Miocene Brassington Formation of Derbyshire and Staffordshire in central England, as originally conceived, is preserved in sinkholes in the Lower Carboniferous/Mississippian Peak Limestone Group. However, contrary to the original Neogene age interpretation, most of the Brassington Formation is demonstrated herein to be of Triassic age, based upon gross lithofacies, material properties, palaeontology, palaeoclimatic considerations and palaeomagnetism. Specifically, the supposedly Miocene Kirkham and Bees Nest members of the Brassington Formation are reinterpreted as the Triassic Sherwood Sandstone and Mercia Mudstone groups respectively. The Brassington Formation is therefore emended to exclude the Kirkham and Bees Nest members, and to include the original Kenslow Member and the new Friden Member. The latter unit is a clay-dominated succession exposed at Kenslow Top Pit, near Friden, Derbyshire. Both the Kenslow and Friden members have yielded Middle–Late Miocene pollen and spores. Evidentially, both the Lower–Middle Triassic Sherwood Sandstone and Mercia Mudstone groups were originally deposited in the White Peak area of Derbyshire and Staffordshire before subsiding into karstic voids. Geological implications of this revised interpretation include that the Sherwood Sandstone Group formerly extended further northwards than was previously supposed, and was laid down in a more complex and extensive depositional

setting. The newly-discovered Sherwood Sandstone Group and Mercia Mudstone Group successions in the Peak District have implications for the interpretation of hydrological evolution and karstification in the subjacent Peak Limestone Group. Furthermore, the palynology of the emended Brassington Formation may help to determine altitude of deposition, and hence the understanding of Neogene uplift rates and interpretations of the drainage and landscape evolution of upland Britain.

Supplementary Material:

1. Introduction

Karst landscapes can play an important role in preserving parts of sedimentary successions that might otherwise have been lost due to erosion (Coxon 2005). Sinkholes allow sediments to subside below erosion surfaces, thereby enhancing the survival of contemporary or younger strata. Important examples of this within upland Britain are the 'pocket deposits' found in ~60 karst cavities in the Peak Limestone Group (Lower Carboniferous/Mississippian) of Derbyshire and Staffordshire. These preserved sediments were formalised by Boulter *et al*. (1971) as the Brassington Formation (Figs 1, 2) and regarded as a stratigraphically coherent, fining-upwards succession entirely of Neogene age. As originally defined, this unit largely comprises the sand-dominated Kirkham Member, locally overlain by the thinner, mud-dominated, Bees Nest and Kenslow members (Figs 2, 3; Table 1). A Neogene age was proposed for the entire formation based on the palynology of the uppermost bed, the Kenslow Member (Boulter 1970, 1971*a*, 1971*b*; Boulter & Chaloner 1970). The relatively sharp boundaries between the three members were interpreted by Boulter *et al*. (1971) and Walsh *et al*. (1972, 1980) as representing conformable transitions between these units. Consequently, a single depositional sequence was envisaged with consecutive fluvial, lacustrine and paludal palaeoenvironments.

Recent palaeontological studies (e.g. Pound *et al*. 2012*a*) have confirmed a Miocene age for the Kenslow Member. The underlying Kirkham and Bees Nest members are palaeontologically barren (Boulter *et al.* 1971). Earlier workers, for example Howe (1897) and Kent (1957) suggested a Triassic age for these lowermost units because of their resemblance to *in situ* Triassic strata within the wider region. Based on an assessment of the available evidence described herein, the present authors support and amplify these observations. We explain why the concept of the Brassington Formation as a genetically-related Neogene succession of Boulter *et al*. (1971) is flawed, and demonstrate that the Kirkham and Bees Nest members correlate with local Lower–Middle Triassic lithostratigraphical units; these are the Sherwood Sandstone and Mercia Mudstone groups respectively. This contribution provides a thorough stratigraphical revision of the Brassington Formation and discusses the geological implications of this action.

2. Geological background

2.1. Carboniferous geological setting, burial history and uplift

The area of the 'pocket deposits' is situated to the NE of the Midlands Microcraton on the Woo Dale Tilt Block (Smith *et al*. 2005). The Peak Limestone Group accumulated on this basement as extensive platform carbonate sediments deposited in a shallow shelf sea. They exhibit strong cyclicity that has been related to glacioeustacy and tectonic adjustments (Ford 1968, Manifold *et al*. 2020, Cózar *et al*. 2022). Platform growth ceased as it was drowned by the muds of the Middle Carboniferous Bowland Shale Formation, still evident around the platform margin (Gutteridge 2024) and by implication capping it (Ford 1999, Walsh *et al*. 2018). Platform marginal fault guided subsidence formed troughs, such as the Widmerpool Gulf to the south (Hennissen *et al*. 2017, fig. 1). During the Late Carboniferous the Bonsall Fault Terrace (Smith *et al*. 2005) became a focus for Variscan inversion, rifting and relative uplift on the SW side of the platform. Rifting was a focus for early dolomitisation of the platform carbonates (Breislin *et al*. 2020, 2023) and likely provided the structural guidance for the 'pocket deposits'(Ford & King 1968, Walsh *et al*. 2018). The UK-wide uplift at the Carboniferous–Permian transition (~305–290 Ma) exposed strata of this age to the erosion event that resulted in a significant sub-Triassic unconformity (Fig. 4).

Despite scant physical evidence, there appears to have been substantial Mesozoic cover over the northern England; Huddart (2002) estimated this to be 1–3 km thick. Studies of the burial history and thermal maturation of the Bowland Shale Formation in the East Midlands (e.g. Green *et al*. 2001, Andrews 2013, Lodhia *et al*. 2023) include one at Carsington, ~4 km SE of Brassington, which suggested 2200 m of post-Permian strata (Hao *et al*. 2021).

2.2. Triassic stratigraphy and sedimentation adjacent to the Peak District

2.2.1. Lithostratigraphy of the Sherwood Sandstone and Mercia Mudstone groups in the vicinity of the 'pocket deposits'

In the areas surrounding the Peak District, the Triassic is represented by the Sherwood Sandstone and Mercia Mudstone groups (Fig. 1; Wills 1970, Warrington *et al*. 1980). The former is an extensive varicoloured sandstone unit which is locally pebbly and fine-grained; the lowermost part is conglomeratic (Ambrose *et al*. 2014). Its weak cementation is prone to becoming friable upon weathering (Steel & Thompson 1983). The pebbles are dominated by smooth, well-rounded quartz and quartzite clasts derived from the Armorican Massif in NW France and the UK (Smith & Edwards 1991, Radley & Coram 2016, Burgess *et al*. 2024, fig. 7). Some of the pebbles exhibit faceting and/or pressure-pitting (Supplementary Material figs 1, 2; Warrington *et al*. 1980).

Within the Sherwood Sandstone Group, the Chester and Helsby Sandstone formations are most relevant to this contribution. The Chester Formation (formerly the Nottingham Castle Sandstone Formation) is Early Triassic (Olenekian) in age, conglomeratic at the base and generally fines upwards (Ambrose *et al*. 2014). Castle Rock, a reference section in central Nottingham (NGR SK 56927 39397), exposes up to 35 m of red-brown or grey, medium- to coarse-grained, pebbly, cross-bedded, fluvial/alluvial sandstone of this unit (Howard *et al*. 2008). The Helsby Sandstone Formation is of Middle Triassic (Anisian) age, and was previously mapped as the Hollington Formation in the Ashbourne area (Chisholm *et al*. 1988). This unit is lithologically and genetically comparable with the Chester Formation. The Helsby Sandstone Formation comprises beds of red, brown and grey pebbly sandstones with conglomeratic bases, interbedded with red and brown siltstones, and mudstones (Newell 2018). This unit is reported to thin over areas of contemporary high ground including Charnwood Forest, north Leicestershire (Scotney *et al.* 2012) and the White Peak (Newell 2018, fig. 15).

The Middle to Late Triassic (Anisian–Rhaetian) Mercia Mudstone Group is a thick, geographically extensive succession, that dominantly comprises brown, red, and green mudstones and subordinate siltstones. Of particular relevance here is the Tarporley Siltstone Formation (formerly the Sneinton Formation) of Anisian age, which comprises interbedded laminated and varicoloured micaceous mudstones, siltstones and fine-grained sandstones. It outcrops to the south of Brassington around Burton, Derby and Nottingham (Wills 1970, Carney *et al*. 2001). The Sherwood Sandstone Group–Tarporley Siltstone Formation transition is diachronous, and is demarcated where mudstone/siltstone is dominant over sandstone (Warrington *et al*. 1980, British Geological Survey 2025). Swinnerton (1935) observed that this transition is characterised by ventifacts.

2.2.2. Outcrop distribution

Permian strata thin westwards from the East Midlands Shelf, consequently the Sherwood Sandstone Group rests on a buried ridge of Lower Carboniferous strata near Ashbourne and immediately SW of Derby (Newell 2018, fig. 15). The Triassic outlier distribution reflects both the sub-Triassic topography and subsequent erosion histories. Outliers of Chester Formation occur around Hulland Ward, 4–6 km from Brassington (Fig. 1; British Geological Survey 1983). Relatively complete Triassic successions are present in the Cheshire Basin to the west, the Needwood Basin to the south and the East Midlands Shelf to the east (Warrington *et al*. 1980). The sub-Triassic unconformity is recognised at Nottingham where Lower Triassic rocks overlie Upper Carboniferous (upper Bashkirian to lower Moscovian) strata. Westwards, the Sherwood Sandstone Group overlie older (Bashkirian/Langsettian) Carboniferous rocks. This westerly trend indicates that Late Carboniferous uplift and Permian–Triassic denudation was greater in the west (Fig. 4).

2.2.3. Triassic palaeogeography and depositional environments

Sherwood Sandstone Group facies represent continental aeolian and fluvial sedimentation (Medici *et al*. 2015). The regional palaeocurrent was towards the NW, although a mean direction of NW–SE was reported for Styrrup Quarry, Nottinghamshire (Ambrose *et al*. 2014, Wakefield *et al*. 2015). The Mercia Mudstone Group largely represents arid continental conditions, with intermittent marine-influenced playa lacustrine settings (Warrington *et al*. 1980, Wilson 1993, Howard *et al*. 2008, Jones *et al*. 2025). The top of the Sherwood Sandstone Group was envisaged as a wind-deflated desert pavement which was subsequently buried by the Mercia Mudstone Group. Swinnerton (1935) interpreted the Sherwood Sandstone Group–Mercia Mudstone Group transition as a sustained hiatus; this has been construed as a manifestation of the Hardegsen unconformity of the central European and

North Sea basins (Smith & Warrington 1971). At Budleigh Salterton in Devon, this hiatus is associated with a clay-rich horizon, interpreted as a 'reg' palaeosol formed by prolonged pedogenesis under arid conditions (Wright *et al*. 1991).

Prior to the Hardegsen unconformity, deposition of the Chester Formation is attributed to the Budleighensis river system which drained periodically towards the NW into the Staffordshire, Cheshire and Irish Sea basins, or NE towards the East Midlands Shelf of the Southern North Sea (endorheic) Basin (Aitkenhead *et al*. 2002). This bifurcation resulted from asynchronous avulsion events. NE drainage lay between the southern flank of the Pennines and the northern spur of the Charnwood Massif, and thence onto the East Midlands Shelf and into the Southern North Sea Basin (Warrington & Ivimey-Cook 1992, Newell 2018). Although onlapped by the Mercia Mudstone Group during the Middle to Late Triassic, the Budleighensis river never overflowed the Charnwood Massif (Carney *et al*. 2001). Evidence from the outliers of the Chester Formation south of Carsington (Fig. 1, Chisholm *et al*. 1988) indicates that the Sherwood Sandstone Group spread north onto the south Pennines west of Derby. To the south, post-Hardesgen unconformity deposition of the Helsby Formation was partly fault-controlled (Carney *et al*. 2001). Deposition was consistently N and NW through the Needwood, Stafford, Cheshire and Irish Sea basins, spilling onto the Pennines around Ashbourne (Chisholm *et al*. 1988), where fluvial sediments intercalated with coeval aeolian sands (Newell 2018). Contemporaneously, the East Midlands Shelf experienced a prolonged period of aeolian deflation and ventifact concentration (Warrington & Ivimey-Cook 1992) and the Chester Formation is overlain by the westwards-onlapping Tarporley Siltstone Formation with a deflation unconformity at the boundary (Howard *et al*. 2009).

2.3. Post-Triassic structural evolution

Jurassic extensional tectonics episodically extended across the East Midlands, potentially contributing to the evolution of the sinkholes hosting the 'pocket deposits' (Smith *et al*. 2005), and regional Mesozoic subsidence accommodated any post-Permian strata. Late Cretaceous epicontinental seas were relatively shallow, starved of terrigenous sediment, and associated with the onset of a prolonged period of uplift that continued to the Paleocene (King 2006, Gale & Lovell 2018, Püttmann & Mutterlose 2021). This regionally discrete uplift reflected differences in rheological crustal properties (Green *et al*. 2001), possibly resulting from the development of the Iceland Plume and the onset of seafloor spreading between Europe and Greenland, coeval with the Alpine orogeny. Although, Green *et al*. (2001) noted that this pre-dated their apatite fission track uplift dates, Smith *et al*. (2005) proposed regional basin inversion. Westaway (2009, 2020) postulated a lower crustal flow model supported by detailed reviews of the geomorphological indicators of lithospheric buoyancy in central and northern England. This accounts for uplift of ~300–400 m since the Miocene, and by >100 m since the Middle Pleistocene.

2.4. The Cenozoic

Superimposed on the uplift history, the warm and wet climatic conditions of the Paleocene and Eocene (e.g. Kender *et al*. 2012) likely facilitated ongoing weathering of exposed rock. There is no evidence of strata of this age in the Pennines. Isolated, terrestrially-derived Miocene sediments recorded in the Brassington-Friden area, Anglesey and SW England were described as palaeogeographical outliers by King *et al*. (2016), in stark contrast to the extensive coeval successions offshore (Cope *et al*. 1992). Post-Miocene erosion precludes determination of the full thickness of the Miocene in the White Peak. Accommodation space may have been limited to paludal depocentres within subsidence hollows.

Glacial deposits are scarce in the White Peak where the bedrock comprises limestones. The area was probably subject to direct action of southerly-moving glaciers during the main expansion of MIS12 ice and earlier (Lee *et al.* 2011). By contrast, during MIS2-4, ice was limited to the perimeter of the Peak District thus periglacial conditions prevailed. Surviving glacial deposits, including till, and rafted sediments, are preserved in the ‘pockets’ (Jones *et al*. 2016).

3. The Brassington Formation

As proposed by Boulter *et al.* (1971). the Brassington Formation was a sand- and clay-dominated succession up to ~70 m thick, and entirely of Neogene age. Its type section is at Bees Nest Pit, ~1 km east of Brassington village (Figs 2, 3; Supplementary Material fig. 3). The Brassington Formation was subdivided into the Kirkham, Bees Nest and Kenslow members by Boulter *et al.* (1971) (Table 1). Only the Kenslow Member has been biostratigraphically dated (Boulter 1970; Boulter 1971*a, b*; Boulter & Chaloner 1970; Pound *et al*. 2012*a*; Pound & Riding 2016). Formalisation of the Brassington Formation followed on from the work of Yorke (1954, 1960, 1961) and Ford & King (1968, 1969), and was referenced in the maps and sheet memoirs produced by the British Geological Survey (Frost & Smart 1979, Aitkenhead *et al*. 1985, Chisholm *et al*. 1988). Further contributions on this unit include Ford (1972), Wilson (1979) and Walsh *et al.* (1972, 1980, 2018).

The sinkholes preserving these sediments are steep-sided, of differing shapes and volumes, and largely in the dolomitised Bee Low Limestone Formation (Asbian). They occur in three clusters, mainly at elevations of between 320 m and 275 m. These are centred around Friden and Brassington in Derbyshire, an area ~24 km long and ~6 km wide trending WNW–ESE, and a smaller area in the Weaver Hills, south of Waterhouses, Staffordshire (Fig. 1, Walsh *et al.* 2018, figs 1, 2). The Friden and Brassington 'pockets' appear to be related to the alignment of fault-controlled dolomitisation (Fig. 1; Breislin *et al*. 2023). Many of the 'pockets' have not been mapped in detail, and many others undoubtedly remain undiscovered (Jones & Banks 2014, Riding 2021, fig. 13) as indicated by local occurrences of pebbly soils, topographical hollows, and areas of broom and gorse bushes (Supplementary Material fig. 1).

Ford & King (1968, 1969) and Walsh *et al.* (1972, 1980, fig. 15) postulated that the sand-dominated Kirkham Member was derived from the Neogene erosion of southward-retreating scarps of the Sherwood Sandstone Group. These sediments supposedly formed a decametre-scale alluvial/fluvial sand sheet (Supplementary Material fig. 4). The overlying Bees Nest and Kenslow members are, by contrast, metre-scale clay-dominated units, interpreted respectively as an alluvial siliciclastic sheet and lacustrine/paludal clays deposited locally in small hollows. Commonly, sediments in the 'pockets' are underlain by an insoluble chert-clay residue derived from the host limestone. Blocks of dolomitised limestone derived from roof-collapse and subsided autochthonous masses of the Bowland Shale Formation are also present (Ford & King 1969, Walsh *et al.* 2018). Furthermore, many of the 'pockets' are capped by Pleistocene till and/or head (Supplementary Material table 1). Brecciated mineral accumulations, typically baryte slab breccias, sporadically occur in some of the 'pockets'. (Supplementary Material fig. 5). Reported examples include Golconda Mine ~2 km NE of Brassington (NGR SK 2488 5517, Fig. 1) (Ford & Jones 2007, pl. 9). Fragments of baryte and galena are also present in some underground alluvial red sands derived from the Sherwood Sandstone Group (Ford & Worley 2016, Worley 1978, Ford & Jones 2007, pl. 8). This material represents glacial meltwater flows and is not included in Supplementary Material table 1.

Typically, the Brassington Formation forms sag-synclinal structures with localised small- and moderate-scale faulting and steep dips at the margins, especially of the larger 'pockets' (Fig. 3; Walsh *et al*. 2018, figs 9, 12). A large mass of vertically-dipping Bees Nest Member at Bees Nest Pit is depicted in Supplementary Material fig. 6; this foundered block indicates significant movement along a subvertical linear fault. Minor (metre-scale) faulting locally affects both the Kirkham and Bees Nest members at Bees Nest Pit (e.g. Ijtaba 1973, pl. 2) with local fracturing of cemented parts of the Kirkham Member. These structural features may represent the reactivation of pre-Triassic faults in addition to the subsidence/collapse process.

4. The age controversy

The chronostratigraphy of the Brassington Formation has proved contentious, with proposed ages ranging from Carboniferous to Pleistocene (Table 2). Early workers like Brown (1867) invoked hybrid 'middle' Carboniferous and Triassic ages, while Brodie (1886) suggested a possible Paleogene age. Later researchers including Howe (1897), Arnold-Bemrose (1910), Barke *et al*. (1920) and Fearnsides (1932) favoured a Triassic age based on lithological similarities. Yorke (1954, 1960, 1961), Edwards & Trotter (1954) and other geological surveyors, and Kent (1957) also supported a Triassic age based mainly on lithological similarities. A more detailed commentary on this topic is provided as Supplementary Material appendix 1.

Chaloner (1961) reported Neogene plant macrofossils and pollen from the uppermost clays of the Brassington Formation. Ford & King (1968, 1969) concluded that the Kirkham Member comprised eroded Triassic sand deposited during the Neogene. Consequently, Boulter *et al*. (1971) established the Brassington Formation as entirely of Neogene age based on palynological data from the Kenslow Member. Recent research has refined the age of the Kenslow Member as Middle–Late Miocene (Serravalian–Tortonian) (Pound *et al*. 2012*a*, 2019; Pound & Riding 2016). The identification of a major unconformity below the Kenslow Member has contributed to a more objective chronostratigraphical interpretation (Supplementary Material fig. 7).

5. Evidence for the Triassic age of the Kirkham and Bees Nest members

This section documents nine lines of geological evidence pertaining to the Triassic age of the Kirkham and Bees Nest members of the Brassington Formation of Boulter *et al*. (1971); these are listed in Supplementary Material table 2.

5.1. The sub-Triassic unconformity

A major stratigraphical break immediately south of the Peak District brings Triassic strata into contact with a range of Carboniferous lithostratigraphical units (Fig. 4). NE of Derby, the Triassic Sherwood Sandstone Group overlies the Millstone Grit Group and the Pennine Lower Coal Measures Formation (uppermost Mississippian and Pennsylvanian). Westwards, between Derby and Ashbourne, Early Triassic strata rest on the Mississippian Widmerpool and Bowland Shale formations (British Geological Survey 2014). Further west, on the eastern edge of the Weaver Hills, the Sherwood Sandstone Group is in direct contact with the Mississippian Peak Limestone Group (British Geological Survey 1983). A 'pocket deposit' at Sallymoor (SK 083 464) includes material closely resembling local Triassic bedrock and blocks of red and yellow pebbly sandstone/sand of Triassic aspect which are typical of several 'pockets' within the western cluster (Chisholm *et al*. 1988) (Fig. 1, Supplementary Material table 3).

If projected northwestwards from Derby, the base of the Sherwood Sandstone Group would lie immediately above the eroded surface of the Peak Limestone Group near Wirksworth and Brassington (Fig. 4). This suggests that the Peak Limestone Group was formerly overlain by Triassic strata within what is now the southern cluster of 'pocket deposits' (Figs 1, 4). Detached masses of the Bowland Shale Formation in the 'pockets' implies that a thin layer of this unit was present above the Peak Limestone Group between the Late Carboniferous and the earliest Triassic (Walsh *et al*. 1972, 2018). Secondary staining ('reddening') of Carboniferous strata attributed to weathering of the sub-Triassic surface, or to downward percolation of iron-bearing solutions from a former Triassic cover. occurs at numerous localities south of the Peak District (Fig. 4, Stevenson & Gaunt 1971, Frost & Smart 1979, Chisholm *et al*. 1988). The juxtaposition of Triassic strata above Lower Carboniferous limestones and mudstones accords with the lithostratigraphical sequences within the larger 'pockets' (Supplementary Material table 1).

5.2. Lithological characteristics of the Kirkham Member

The Kirkham Member of Boulter *et al*. (1971) has been recorded in all the known 'pockets', and is mostly an unlithified cream/white, medium- to coarse-grained sand with angular/subangular particles (Fig. 5). It is frequently pebbly and contains occasional green and red clay/silt intraclasts and stringers. Locally, the Kirkham Member is weakly- to relatively well-lithified (Supplementary Material fig. 8). The vertical thickness is variable because this parameter is primarily controlled by the depth of each 'pocket'. For example, Boulter *et al*. (1971) and Ijtaba (1973) recorded 35.31 m at the type section at Bees Nest Pit (Supplementary Material table 4). Walsh *et al*. (2018, table 1) mentioned thicknesses of ~40–50 m elsewhere.

Masses of lithified pebbly medium- to coarse-grained coherent sandstone are generally yellow, red-brown and grey in colour, whereas, weakly-lithified and unconsolidated sand with well-rounded quartzite and quartz pebbles is largely cream/white in colour but locally is red to red/brown (Supplementary Material fig. 9, Aitkenhead *et al*. 1985). The cream/white deposits appear to have been bleached, perhaps by hypogene fluids and/or exposure to strong sunlight. Typically, the grains are coated by thin pellicles of kaolinite which is indicative of intense alteration, presumably of feldspar (Walsh *et al*. 1972, 1980, 2018). Together with sustained weathering, this may also account for the weak or absent cementation. The silica and kaolinite content, and largely uncemented characteristics were the principal reasons the Kirkham Member was quarried for refractory brick manufacture (Supplementary Material appendix 2, Boswell 1918). The Kirkham Member displays many features that typify the Sherwood Sandstone Group of the English Midlands. These include the absence of fossils, colour, weak cementation, particle morphology, sedimentary structures, grain and pebble composition, lithology, overall palaeocurrent flow direction, overall sedimentology, and texture. Pebbles from the Kirkham Member and the Sherwood Sandstone Group are closely comparable (Supplementary Material fig. 2).

An example of cemented sandstone in the Kirkham Member is exposed alongside the old access track at the west side of Bees Nest Pit, near Brassington (NGR SK 24108 54574; Supplementary Material fig. 8). This comprises 5–6 m of well- to moderately-well consolidated yellow-brown sandstone. Here, the lowermost part, a partially lithified conglomerate referred to as Bed 7 of the Kirkham Member (Ijtaba 1973, fig. 3; Walsh *et al*.

1980, fig. 2) at Bees Nest Pit closely resembles the pebble beds at the base of the Chester Formation.

Because the cemented sandstone masses in the Kirkham Member (Supplementary Material fig. 8) closely resemble the Chester and Helsby Sandstone formations, these parts of the Kirkham Member of Boulter *et al.* (1971) are referred to the Sherwood Sandstone Group. Similarly, the weakly-lithified sands within the Kirkham Member are laterally contiguous with the cemented masses, and are also lithologically similar. Hence, the latter facies is also assigned to the Sherwood Sandstone Group. The contention of Ford & King (1969, p. 60) and Walsh *et al.* (1972, p. 522) that the cemented masses represent localised secondary re-cementation of Triassic erosion debris during the Miocene is considered to be highly unlikely. We propose that these are relicts of *in situ*, incompletely weathered, Sherwood Sandstone Group which have subsided into the 'pockets'.

5.3. Lithological characteristics of the Bees Nest Member

The Bees Nest Member of Boulter *et al*. (1971) is represented by 6–9 m of lithified varicoloured, largely red and green mudstones and siltstones, and is only present in the centres of the larger 'pockets' (Walsh *et al*. 2018). Thicknesses of ~30 m and up to 40 m at Kenslow Top Pit reported by Ijtaba (1973, p. 25) and Aitkenhead *et al*. (1985, p. 107) respectively are considered herein to be apparent thicknesses and substantial overestimates of the true stratigraphical thickness of the steeply inclined foundered strata. Currently, the only known exposures of the Bees Nest Member are in Bees Nest Pit, (Fig. 6; NGR SK 24100 54580 and NGR SK 24170 54537) and at Spencer's Pit (NGR SK 21508 54147) ~1 km ENE and ~1.75 km W of Brassington respectively. This unit was previously exposed in other silica sand pits including Kenslow Top and Kirkham's pits, but these sections are no longer exposed. At the type section in Bees Nest Pit, the exposed Bees Nest Member comprises 6.17 m of interbedded unfossiliferous red, brown, grey, and green mudstones and siltstones, with occasional fine-grained sandstones (Figs 3, 6; Supplementary Material fig. 10). Some of the sandy beds are pebbly, and the pebbles are well-rounded quartz and quartzite pebbles. The pebbles are reminiscent of those in the Sherwood Sandstone Group.

The Bees Nest Member is lithologically very similar to the Middle to Late Triassic Mercia Mudstone Group. Specifically, the Bees Nest Member preserved at Bees Nest and Spencer's pits closely resembles the Tarporley Siltstone Formation. Due to the occurrence of pebbles in the Bees Nest Member, this unit strongly resembles the lowermost Tarporley Siltstone Formation of the Nottingham area, specifically the Woodthorpe Member (Howard *et al*. 2008). In summary, because the Bees Nest Member closely resembles the Tarporley Siltstone Formation east and south of Brassington, these two units are interpreted herein to be equivalent. This means that the representative units of the Sherwood Sandstone and Mercia Mudstone groups (i.e. the Kirkham and Bees Nest members respectively) in the 'pocket deposits' are thus preserved in their expected stratigraphical order (Warrington *et al.* 1980).

5.4. The transition between the Kirkham and Bees Nest members at the type section

Significant parts of the Kirkham, Bees Nest and Kenslow members of the Brassington Formation of Boulter *et al*. (1971) are still visible at the type section (Figs 3, 5–7), although the exposures have deteriorated since quarrying ceased. Records of the geology at Bees Nest Pit were made when the succession was better exposed than at present (e.g. Yorke 1954, 1960, 1961; Walsh *et al*. 1972, 1980; Ijtaba 1973), and collectively comprise a valuable geological archive. A log of the type section presented by Boulter *et al*. (1971, fig. 1), supplemented with additional lithological detail (Ijtaba 1973) is a composite of several exposures on the southern, eastern and northern sides of the pit. Each lithological unit is numbered consecutively upwards from the base of the 42.55 m thick succession (Fig. 2, Supplementary Material table 4).

Between the Kirkham and Bees Nest members, there is a transition zone of at least 3 m within which this boundary could have been placed. Whereas the Bees Nest Member largely comprises thin units of red or green silty clay, the lowermost 0.53 m is pebbly. Conversely, below Bed 12 (pebbly sand) of the underlying Kirkham Member, four thin clay/silt units (beds 8–11) are present within a predominantly sandy succession. This situation is analogous to the boundary between the Sherwood Sandstone and Mercia Mudstone groups in the Triassic successions of the East Midlands.

5.5. Wind-etched pebbles at the Kirkham Member/Bees Nest Member transition

At the Kirkham Member–Bees Nest Member transition, matrix-supported pebbles exhibit markedly etched surface textures with mesoscale flutes, grooves and pits (Fig. 8, Supplementary Material fig. 11), interpreted as ventifacts from wind action in unvegetated environments (Viles & Bourke 2007, Durand & Bourquin 2013). This contrasts with smooth-surfaced pebbles elsewhere in the Kirkham Member (Supplementary Material fig. 2).

Three potential explanations for the occurrence of this zone of concentrated ventifacts at the Kirkham Member/Bees Nest Member transition are:

(i) *in situ* erosion by wind action during the Neogene;
(ii) derivation from ventifact-bearing Triassic source rocks with redeposition during the Neogene;
(iii) ventifacts formed at the Triassic land surface, and subsequently buried by younger Triassic sediments

Given the evidence for a forest-dominated landscape and a humid climate during the Miocene (Pound and Riding 2016, McCoy *et al*. 2022), the first possibility can be discounted. The second is also highly unlikely owing to the well-preserved wind-etched features. Because of the hot, arid climate during the Triassic, the third possibility appears to be by far the most plausible.

With the exception of Hughes (1952) and Yorke (1961), there are few recorded details of wind-worn pebbles from the Kirkham Member. Unpublished research by D.B. Thompson suggests that ventifacts are rare in the Kirkham Member. By contrast, these sculpted pebbles are common in the Triassic of the English Midlands. Examples have been reported from the Triassic close to the southern Pennines (e.g. Lamplugh *et al*. 1908, Swinnerton 1914, Thompson & Worsley 1967, Frost & Smart 1979, Howard *et al*. 2009). The distinctly wind-worn pebbles occur in a thin interval (beds 12–16 of Ijtaba 1973), straddling the contact (i.e. the base of bed 13) between the Kirkham and Bees Nest members (Fig. 2). This zone of exclusively wind-worn pebbles indicates a relict desert pavement, perhaps reminiscent of the upper surface of the Lower Triassic Budleigh Salterton Pebble Bed at Budleigh Salterton, Devon (Wright *et al*. 1991). Similarly, the concentration of ventifacts reported to overlie the Sherwood Sandstone Group at Sneinton, Nottingham (Supplementary material fig. 12; Swinnerton 1914, Howard *et al*. 2009) is probably an additional example of such a pavement, and is significant for being located much closer to the Brassington area. It seems probable that the relatively sharp lithostratigraphical change from the Kirkham Member to the Bees Nest Member represents the Triassic Hardegsen unconformity. Furthermore, for Triassic-derived ventifacts to be concentrated in this interval during the Neogene requires highly unusual circumstances: a source of Triassic wind-worn pebbles in the local area; erosion from the host rock; water transport with limited damage to the surface ornamentation (delicate micro-pitting in some cases); and the exclusion of Sherwood Sandstone Group pebbles without the surface textures. A control sample taken from Bed 7 of Boulter *et al*. (1971) stratigraphically lower in the Kirkham Member did not reveal sculpted pebbles. The pebbles in Bed 7 are typically smooth and well-rounded (Supplementary material fig. 2).

5.6. Material properties and engineering geology

Advances in the analysis of material properties since Walsh *et al*. (1972) and Ijtaba (1973) underpins the evidence-based comparison with more recent Triassic literature. The Kirkham Member is kaolinitic, thus matching the clay mineral character of the Sherwood Sandstone Group (Table 3; Ijtaba 1973, Bath *et al*. 1987). Similarly, the illite-rich Bees Nest Member is entirely consistent with the Mercia Mudstone Group (Table 3; Hobbs *et al*. 2002, Jones *et al*. 2025). Heavy mineral analysis shows both the Kirkham Member and the Sherwood Sandstone Group in Derbyshire are sparse in staurolite, and rich in tourmaline and zircon (Table 3; Ijtaba 1973, Jeans *et al*. 1993). Subsidence and possible contact with hypogene fluids (Banks *et al*. 2015) may have further reduced the mechanical strength of these units, as could exposure to hydrological weathering during the Quaternary, for example, resulting in the dissolution of any carbonate cement. The grading analyses of Ijtaba (1973) were also considered in the discussion of the lithostratigraphy herein. Pre-consolidation pressure tests of clays show significant differences between Kirkham (888 kN/m^2) and Kenslow (257 kN/m^2) members, far exceeding stress from their current separation, suggesting considerably different burial histories and geological ages (Table 4; Ijtaba 1973).

Wilson (1979) studied sand grain surface textures from the Kirkham Member. These match the equivalent features in the Chester Formation, with no evidence for subsequent fluvial action. This is contrary to the hypothesis of the Kirkham Member being the result of a second phase of riverine reworking of the Sherwood Sandstone Group of Walsh *et al*. (1972) (Table 4). Some of the pebbles exhibit small white pits which appear to be pressure solution features (Supplementary material fig. 2). These pits are interpreted as being developed during post-depositional sediment loading (Table 4), suggesting that there was a significant thickness of post-deposition strata, that has subsequently been removed by erosion. This supports the view that Bed 7 of the Kirkham Member represents *in situ* Triassic Sherwood Sandstone Group that subsequently subsided into dissolution cavities without further overland movement. This is because, were the pebbles derived from reworking of Triassic sandstones, the pressure solution marks would likely have been destroyed.

5.7. Palaeontology

In common with the Sherwood Sandstone Group (Holloway *et al.* 1989, Ambrose *et al.* 2014, Warrington & Pollard 2021) the Kirkham Member is apparently devoid of fossils including palynomorphs (Boulter *et al*. 1971, JBR personal observations). Similarly, the Bees Nest Member is macropalaeontologically barren, comparable with the Mercia Mudstone Group, which is extremely sparse in macrofossils (e.g. Howard *et al.* 2008, Gallois 2019). Six palynological samples analysed from the Bees Nest Member of Bees Nest Pit (Fig. 6) proved entirely devoid of palynomorphs, and contained only dark fragments of woody tissue. This depauperate nature is consistent with the Tarporley Siltstone Formation of the East Midlands (Howard *et al*. 2009, p. 113 and references therein, Hodgskiss *et al.* 2024).

Conversely, the Kenslow Member is extremely rich in macrobotanical, microbotanical and fungal fossils indicative of a Miocene age (Boulter 1971*a*; Pound & Riding 2016; O'Keefe *et al.* 2020; McCoy *et al.* 2022; Pound *et al.* 2019, 2022). The marked difference in the fossil contents of the Bees Nest and Kenslow members represents a depositional hiatus and disparate palaeoenvironmental conditions. If these two clay-rich units were both Miocene in age, as hypothesised by Ford & King (1968, 1969), Boulter *et al.* (1971) and Walsh *et al*. (1972), it is unlikely that they would exhibit such a marked difference in palaeontological content. For example, if the Kirkham Member represents reworking of the Triassic Sherwood Sandstone Group during the Miocene, and redeposited in a well-vegetated alluvial/fluvial setting with a pervasive, temperate climate, then it should contain abundant plant fossils, like the Kenslow Member.

5.8. Palaeoclimate

Clay mineralogy, colour, relative lack of fossils, mud flake intraclasts and sedimentology all indicate that the Triassic Sherwood Sandstone and Mercia Mudstone groups were deposited in a predominantly arid, monsoonal palaeoclimatic regime with intense seasonality (e.g. Parrish 1993, Sellwood & Valdes 2006, Preto *et al*. 2010). Furthermore, ventifacts are present, and bioturbation and palaeosols are absent in the Sherwood Sandstone

Group/Kirkham Member of the Brassington Formation of Boulter *et al*. (1971) (Fig. 2). These Triassic strata are interpreted as being deposited in an extreme greenhouse palaeoclimate (Radley & Coram 2016). The predominantly red colour with green/grey mottling and layering of the Bees Nest Member is consistent with a highly arid depositional setting, comparable to the Mercia Mudstone Group (Howard *et al*. 2008, Milroy *et al*. 2019).

In stark contrast, the European Miocene was relatively warm, wet and temperate, and sedimentary successions with proxies for hot and dry conditions are regionally unknown (Bruch *et al.* 2007; Pound *et al.* 2011, 2012*b*; Steinthorsdottir *et al.* 2021). The Kenslow Member was deposited in a low relief lacustrine/paludal environment under warmer and wetter conditions than present-day UK (Pound *et al*. 2012*a*, Pound & Riding 2016, Gibson *et al*. 2022, McCoy *et al*. 2022, Pound *et al*. 2022).

5.9. Palaeomagnetism

The palaeomagnetism of the cemented sandstone in the Kirkham Member and the Bees Nest Member at Bees Nest Pit was analysed by Conall Mac Niocaill (University of Oxford). Several core samples were taken in 2018 from a metre-scale mass of lithified former Kirkham Member on the west side of the access track to Bees Nest Pit (Supplementary Material fig. 8; NGR SK 24108 54574), and from the type section of the Bees Nest Member at Bees Nest Pit (Figs 3, 6; NGR SK 24100 54580). The shallow palaeomagnetic inclinations recorded from these members are consistent with a Triassic age, when what is now the UK lay at tropical latitudes (Warrington & Ivimey-Cook 1992). Steeper inclinations would be expected in Miocene deposits, when Europe was close to its present temperate latitude (Tauxe 2010).

6. Revised lithostratigraphy and regional implications

The evidence presented above requires that the Brassington Formation of Boulter *et al*. (1971) is redefined herein. Consequently, the Kirkham and Bees Nest members are discarded as redundant lithostratigraphical units, and formally referred to the Sherwood Sandstone Group (Chester and Helsby Sandstone formations) and the Mercia Mudstone Group (Tarporley Siltstone Formation) respectively (Table 1). The Brassington Formation is emended such that the Kenslow Member of Boulter *et al*. (1971) is retained, and a new Friden Member is proposed (Appendix and Supplementary Material appendix 3). This revision denotes a radical reduction of Peak District sites containing sediments attributable to the Brassington Formation. These are: Bees Nest Pit (Kenslow Member), Kirkham's Pit (Kenslow Member) and Kenslow Top Pit (Kenslow and Friden members). Other sites where organic deposits have been reported include Green Clay, Minninglow, Blake Moor, Heathcote and Sallymoor pits, and Hindlow Quarry. Although these are potential correlatives of the Kenslow Member, these deposits lack detailed analysis (Supplementary Material table 3).

The presence in the 'pockets' of subsided masses of Triassic sediment has significant implications. For example, it indicates that whilst there is no representation of Upper Carboniferous, Permian and lowermost Triassic strata, the Sherwood Sandstone Group formerly extended northwards at least as far as the Brassington-Friden area. This implies the existence of a more complex and laterally extensive fluvial palaeoenvironment during the Early–Middle Triassic. It also questions traditional views that the northwards-flowing 'Budleighensis' river system was deflected northwestwards and northeastwards by higher ground on reaching the southern Pennines (e.g. Radley & Coram 2016). Although limited in number, the Mercia Mudstone Group occurrences in the 'pockets' are among the first to be recorded in the southern Pennines. Triassic successions within the Peak District are less complete than in the adjacent basins. However, they offer the potential to add to existing information on palaeoenvironments and to knowledge of post-Carboniferous history, with associated implications for the interpretation of karst processes, the exhumation history of the carbonate platform and its hydrological evolution.

Miocene non-marine sediments are rare in Britain (King 2006). This has been attributed to a hiatus in deposition during uplift associated with the Alpine orogeny (Jackson 2008). Although the depositional context requires further analysis, the freshwater Brassington Formation, as revised herein, possibly accumulated in subsidence-related depressions reactivated by the Alpine uplift and associated faulting (Andrews 2013). It was suggested by Walsh *et al*. (1972, 2018) that these sediments formed close to sea level. If future palynological studies can establish the precise altitude of deposition, the potential exists to substantially refine our understanding of Neogene uplift rates for the Peak District. This would have additional applications for interpretations of the landscape and drainage evolution of upland Britain. Therefore, despite its limited occurrence, the emended Brassington Formation is a particularly significant onshore Miocene deposit in the UK, reinforcing the views expressed by Pound & Riding (2015).

7. Conclusions

This contribution fundamentally revises the stratigraphy of the 'pocket deposits' in the southern Pennines. All three members of the Brassington Formation of Boulter *et al*. (1971) were originally interpreted as being of Neogene age. The revision assigns the lower two units to the Triassic. The Kirkham Member comprises pebbly, unfossiliferous sandstone. Based on exposure analogues, absence of fossils, geotechnical properties, lithofacies, mineralogy, palaeomagnetism and sedimentology, this succession is referred to the Early–Middle Triassic Sherwood Sandstone Group, as several authors previously postulated. The overlying Bees Nest Member comprises unfossiliferous, varicoloured mudstones and siltstones. Evidence from clay mineralogy, lithology, palaeomagnetism and the transitional boundary indicates correlation with the Middle–Late Triassic Mercia Mudstone Group. This stratigraphical juxtaposition is entirely consistent with Triassic successions throughout southern Britain (Howard *et al*. 2008, Ambrose *et al*. 2014, Newell 2018). Only the uppermost Kenslow Member, and newly defined Friden Member (see Appendix), yield Miocene index fossils, and now constitute the revised Brassington Formation. Therefore, we contend that the concept of a fining-upwards, genetically-related, entirely Neogene Brassington Formation of Boulter *et al*. (1971) succession lacks empirical proof. Specifically, there is no *prima facie* evidence for a Neogene age for the Kirkham and Bees Nest members, and their gross lithofacial nature clearly indicates the preservation of a classic Triassic stratal succession.

This occurrence of the Sherwood Sandstone Group at the southern end of the Pennines adds to our understanding of Triassic palaeogeography, and the nature of the northward bifurcation of the 'Budleighensis' fluvial systems. Together with the first reported occurrence of the Mercia Mudstone Group in the White Peak, the stratigraphical revisions herein highlight that a more extensive Triassic cover was formerly present at the southern end of the Pennines, in addition to reaffirming the negligible presence of Miocene rocks throughout onshore UK. Nevertheless, more detailed analyses of the revised Miocene Brassington Formation potentially offers significant insights with respect to the complex uplift history of the Pennines.

In summary, the evidence presented herein overwhelmingly favours a Triassic, rather than Miocene, age for the Kirkham and Bees Nest members of the Brassington Formation of

Boulter *et al*. (1971), indicating relatively minor northerly palaeogeographical extensions of two of the most distinctive and extensive lithostratigraphical units in northern Europe.

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Appendix - A revised lithostratigraphy of the Brassington Formation

As outlined in the main text, this contribution fundamentally revises the Miocene Brassington Formation of Boulter *et al.* (1971) (Table 1). Specifically, the Kirkham and Bees Nest members of these authors are discarded as redundant lithostratigraphical units, which are referred to the Triassic Sherwood Sandstone Group and the Mercia Mudstone Group respectively. The Brassington Formation is emended herein such that the Kenslow Member of Boulter *et al*. (1971) is retained, and the overlying Friden Member is newly proposed. The full lithostratigraphical revision is presented in appendix 3 of the Supplementary Material. However, because the Friden Member is a lithostratigraphical novelty, this is unit is formally outlined below.

The Friden Member of the emended Brassington Formation (new unit)

Overview: The Friden Member is formally established herein. It is a clay and sand-dominated unit found only at the southern side of Kenslow Top Pit, and comprises a large glaciotectonic raft ~3 m thick within subglacial sediments (Fig. 9). It was originally described by Jones *et al.* (2016), and is their units B and C (Supplementary Material figs 13, 14 respectively). Pound *et al*. (2012*a*) recovered a Late Miocene (Tortonian) pollen flora from the Friden Member, which they misidentified as the Kenslow Member. The Friden Member is younger than the Kenslow Member based upon mapping at Kenslow Top Pit, the lithological dissimilarity to the Middle–Late Miocene Kenslow Member at the type section and pollen biostratigraphy (Pound *et al*. 2012*a*). It is therefore younger than the Kenslow Member, which is Middle–Late Miocene in age (Pound & Riding 2016), and is distinguished from the latter unit on clear lithological grounds.

Type section: The southern side of Kenslow Top Pit, near Friden, Derbyshire, UK (Fig. 9; NGR SK 18289 61420). There are no other exposures of the Friden Member, hence a separate reference section cannot be designated.

Lithology: Subglacially sheared, interbedded brown and grey clay, yellow-brown sand, and brown gravels. The beds are streaky and locally deformed due to cryoturbation/glaciotectonics, and there is local hydrofracturing (Jones *et al*. 2016, figs 3–6).

Upper boundary: The top of the Friden Member is defined by its upper boundary with Quaternary glaciogenic sediments, interpreted as subglacial fluvial deposits (unit D of Jones *et al*. 2016) at Kenslow Top Pit.

Lower boundary: The base of the Friden Member is defined by the boundary between units B and A of Jones *et al*. (2016); unit A was interpreted as locally-derived subglacial debris. The transition with the underlying Kenslow Member, has therefore not been observed.

Distribution and thickness: The Friden Member has only been recorded from the type section at the southern end of Kenslow Top Pit; it is up to ~3 m in thickness.

Genetic interpretation: The brown and grey clays are interpreted as lacustrine deposits. Periodically, substantial influxes of sand and gravel were transported into the lake, perhaps due to storm activity.

Age: Late Miocene (Tortonian) (Pound *et al*. 2012*a*).

Captions for Figures 1-9:

Fig. 1. The geology of the central and southern Peak District, central England illustrating major bedrock outcrops and the distribution of the 'pocket deposits'. Individual members of the former Brassington Formation are too small in area to be discernible at this scale. Note the concentration of the 'pockets' in the dolomitised limestone, and the NW-SE orientation of the two major clusters in Derbyshire. The western cluster is located south of Waterhouses, Staffordshire. Localities where pebbles characteristic of the Sherwood Sandstone Group occur in the topsoil are also indicated. Note the northwards overstep of the Triassic Sherwood Sandstone Group onto the Carboniferous strata immediately north of ~53°N. Credit – British Geological Survey. DiGMapGB-50 [SHAPE geospatial data], Scale 1:50000, Tiles: ew111,ew112,ew124,ew125, Updated: 30 November 2016, BGS, Using: EDINA Geology Digimap Service, <https://digimap.edina.ac.uk>, Downloaded: 2024-04-26 16:00:21.688. OS Open Roads [SHAPE geospatial data], Scale 1:25000, Tiles: sk, Updated: 9 October 2023, Ordnance Survey (GB), Using: EDINA Digimap Ordnance Survey Service, <https://digimap.edina.ac.uk>, Downloaded: 2024-04-26 16:15:07.883.

Fig. 2. A graphic log of the type section of the Brassington Formation of Boulter *et al*. (1971) at Bees Nest Pit, near Brassington with a key (A, B respectively), and a geological map of Bees Nest Pit (C). A – The type section is a composite of four successions measured and logged on the east side of the pit in the early 1970s by Itjaba (1973, p. 17, fig. 3). Twenty-four numbered beds were recognised (Supplementary Material table 4); the location of this composite section is indicated in C by four solid yellow lines. The ventifact-bearing interval (beds 12–16) is indicated. B – Lithological key. C – A sketch map of Bees Nest Pit during the early 1970s when quarrying operations were ongoing, and there was virtually full exposure of the different lithological units. A and B are adapted from Ijtaba (1973, fig. 3), and C is substantially modified after Boulter *et al*. (1971, fig. 1) and Walsh *et al*. (1972, fig. 2A). Abbreviations: BNM = Bees Nest Member; BSF = Bowland Shale Formation; B. Fm. = Brassington Formation; KM – Kenslow Member; MMG = Mercia Mudstone Group; P = plant fossils.

Fig. 3. The main part of the type section of the Brassington Formation of Boulter *et al*. (1971) at Bees Nest Pit, near Brassington. This is the northernmost solid yellow line in Fig. 2C. The

central northern face is pictured, looking northeastwards. The majority of the exposure is the Kirkham Member; now the Sherwood Sandstone Group, marked SSG. This is overlain by the Bees Nest Member, now the Mercia Mudstone Group (marked MMG), which dips steeply towards the left (i.e., northwestwards). The uppermost unit is the relatively unconsolidated Kenslow Member, marked KM. This unit tends to be washed downslope as is evident above the person on the left. Photograph by Peter T. Walsh taken during the mid-1970s, and reproduced with permission.

Fig. 4. A cross section illustrating the Carboniferous Peak Limestone, Craven and Millstone Grit groups, and the Triassic Sherwood Sandstone Group (stippled) from Turnditch in the SE, to west of Wirksworth in the NW, a distance of ~10 km (see Fig. 1), to illustrate the sub-Triassic unconformity. The projection of this unconformity to the Peak District in the north clearly demonstrates that the occurrence of the Sherwood Sandstone and Mercia Mudstone groups in the Peak District is highly likely in gross geological terms. Specifically, assuming no major fault movement, if the gradient of the base of the Triassic is projected northwards to Wirksworth from the *in situ* outcrop at Turnditch, the Sherwood Sandstone Group can be placed directly on top of the Lower Carboniferous Peak Limestone Group at, or immediately above, the contemporary land surface. This places the Sherwood Sandstone Group onto the Peak District upland surface at about 300 m AOD. The projected sub-Triassic unconformity in the NW indicates the likely presence of the Bowland Shale Formation overlying the Peak Limestone Group to source the foundered shale blocks in some of the larger 'pockets'. For orientation, the village of Turnditch is ~12 km east of Ashbourne at NGR SK 293 463, and Yokecliffe Rake is a mineralised Mississippi Valley Type mineralised fault trending E-W to the west of Wirksworth centered on NGR SK 2679 5400. Considerably modified after Frost & Smart (1979, fig. 56). Abbreviation: MMG = Millstone Grit Group.

Fig. 5. A montage of four photographs of former working quarries illustrating the unlithified facies of the Kirkham Member, now the Sherwood Sandstone Group, around Brassington and Friden taken in the early 1970s (see also Walsh *et al*. 2018, figs 5, 6, 11). These are now largely obscured, and Kirkham's Pit (C) has been infilled. Photographs A, C and D are by Peter T. Walsh, and B was taken by Jack Shirley; all are used with permission. A – the NW corner of Bees Nest Pit, near Brassington taken from the SE corner (NGR SK 24159 54491).

B – the N side of Green Clay Pit, near Brassington taken from the southern side (NGR SK 23974 54703). C – the SE part of Kirkham's Pit, west of Brassington taken from the NW side (NGR SK 21729 54138). D – the NE part of Kenslow Top Pit, near Friden taken from near the access road looking towards the SW (NGR SK 18223 61507).

Fig. 6. The uppermost part of the Bees Nest Member, now the Mercia Mudstone Group, at Bees Nest Pit. This is the type section of the former Bees Nest Member, E of the main access ramp on the N side of the quarry. The outcrop on the right has been cleaned to show the beds of reddish-brown mudstones interbedded with green siltstones and pale-brown, fine-grained sandstones. This unit overlies the Kirkham Member/Sherwood Sandstone Group, and is overlain, with a sharp boundary, by the Kenslow Member. Photograph taken in September 2019 by Peter F. Jones; geological hammer for scale.

Fig. 7. The Kenslow Member of the Brassington Formation at the type section, the central-north of Bees Nest Pit, near Brassington. Abundant plant fossils are present, dominated by blackened and dark brown fragments of mummified wood (Mustoe 2018). Photograph taken during the late 1970s by Peter F. Jones; geological hammer for scale.

Fig. 8. A wind-etched pebble with flutes and grooves from the transition zone between the Kirkham and Bees Nest members (now the Sherwood Sandstone and Mercia Mudstone groups respectively) from the N side of Bees Nest Pit, near Brassington and interpreted as a ventifact. The length is 70 mm, and the breadth is 43 mm. This surface texture contrasts markedly with the pebbles from Bed 7 which are smooth and well-rounded (Supplementary Material fig. 2).

Fig. 9. The type section and only known outcrop of the Friden Member of the Brassington Formation at the S side of Kenslow Top Pit, near Friden (Appendix and Supplementary Material appendix 3). This was originally described by Jones *et al.* (2016) as units B and C. The base of the Friden Member is the base of the prominent grey clay (unit B) marked by the base of the cleaned section at the break of slope immediately above the field notebook. The

top of the Friden Member is the upper boundary of unit C, the streaky succession of interbedded brown clays and yellow sands; the geological hammer is in the centre of this unit. Unit B is underlain by locally-derived subglacial debris, and Unit C is overlain by lighter brown clays with gravels (head). Photograph taken in June 2015 by Peter F. Jones; geological hammer and spade for scale.

Captions for Tables 1-4:

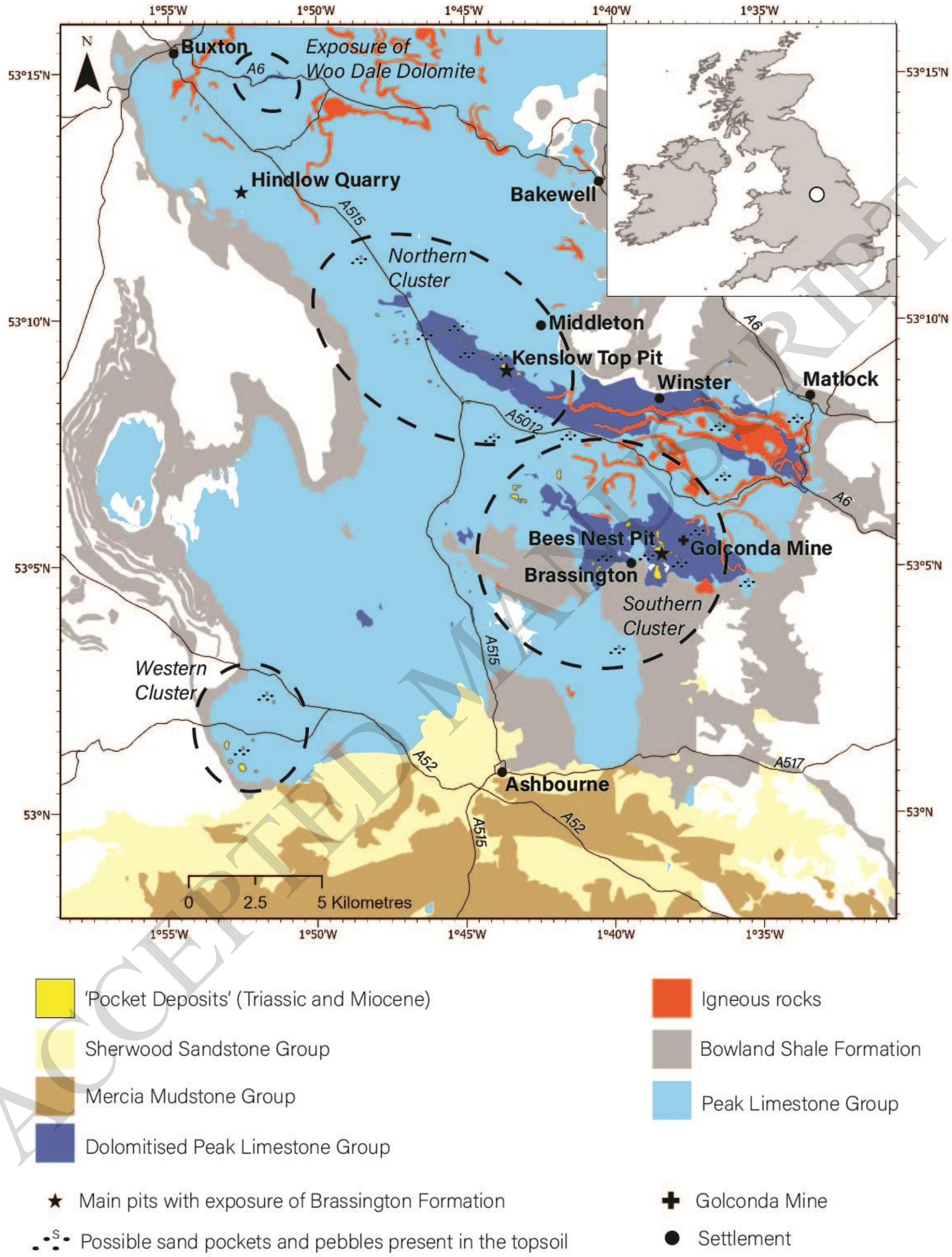
Table 1. The stratigraphy of the Brassington Formation as defined by Boulter *et al.* (1971) in the left-hand column, directly compared with the revised stratigraphical interpretations herein in the centre and right-hand columns.

Table 2. A selective summary of the age interpretations of the fills of the 'pocket deposits', and the evidential basis for these. The early works of Brown (1867), Brodie (1886) and Thomas *et al*. (1920) gave somewhat equivocal age assessments. By contrast, Howe (1897), Scott (1927) and Chaloner (1961) (in bold font) postulated Triassic, Carboniferous and Neogene ages respectively. The latter three studies were the first to indicate those ages, and therefore represent the principal breakthroughs on this topic. The title of Kent (1957) perceptively referred to the 'pocket deposits' as 'Triassic relics'. *Note that the work of Chaloner (1961) is based on the Kenslow Member only.

Table 3. A comparison of relevant studies on the clay mineralogy and the heavy minerals of the Brassington Formation of Boulter *et al*. (1971), and the Triassic Sherwood Sandstone and Mercia Mudstone groups. This indicates that the Kirkham and Bees Nest Members of the Brassington Formation are likely to be of Triassic age, and that the Kenslow Member is of Miocene age.

Table 4. A summary of sand grain surface texture analyses, pebble solution marks and pre-consolidation pressure tests on material from the Brassington Formation of Boulter *et al*. (1971). The top two rows (Part 1) summarise the work of Wilson (1979) on the surface textures of sand grains from the Kirkham Member. This indicates that these are closely

comparable to the Triassic Chester Formation of the Sherwood Sandstone Group. Below this (Part 2) is the observation that the surfaces of some quartz and quartzite/metaquartzite pebbles from Bed 7 of the Kirkham Member exhibit pressure solution marks indicative of considerable post-depositional sediment loading during the Mesozoic and Paleogene. This means that the Kirkham Member is far more likely to of Triassic, rather than Neogene, age. Part 3. documents data on pre-consolidation pressure tests of beds 10 and 24 of Boulter *et al*. (1971) and Ijtaba (1973). The differences noted are consistent with the Triassic Kirkham Member being deeply buried and consolidated below a younger Mesozoic cover, and then unroofed by erosion prior to the deposition of the Miocene Kenslow Member.


1°55'W
1°50'W
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1°40'W
1°35'W
53°15'N
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N
Buxton
A6
Exposure of
Woo Dale Dolomite
Hindlow Quarry
Bakewell
A515
Northern
Cluster
Middleton
A6
Kenslow Top Pit
Winster
Matlock
A5012
A6
Bees Nest Pit
Golconda Mine
Brassington
Southern
Cluster
A515
Western
Cluster
A52
Ashbourne
A517
A515
A52
0
2.5
5 Kilometres
'Pocket Deposits' (Triassic and Miocene)
Sherwood Sandstone Group
Mercia Mudstone Group
Dolomitised Peak Limestone Group
Igneous rocks
Bowland Shale Formation
Peak Limestone Group
Main pits with exposure of Brassington Formation
Possible sand pockets and pebbles present in the topsoil
Golconda Mine
Settlement

Figure 1

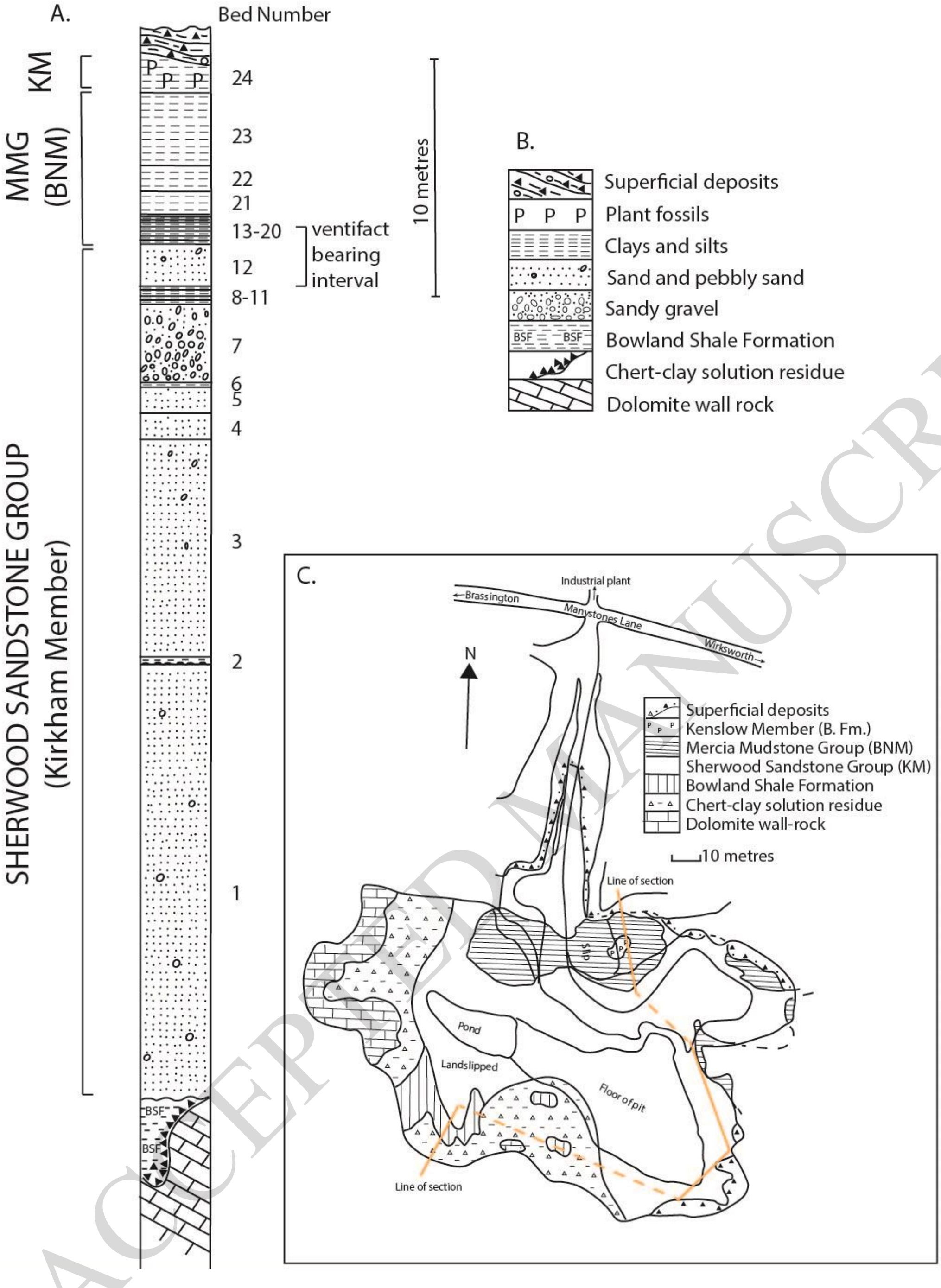
A.
Bed Number
KM
MMG (BNM)
SHERWOOD SANDSTONE GROUP (Kirkham Member)
24
23
22
21
13-20
12
8-11
7
6
5
4
3
2
1
ventifact bearing interval
10 metres
BSF
B.
Superficial deposits
Plant fossils
Clays and silts
Sand and pebbly sand
Sandy gravel
Bowland Shale Formation
Chert-clay solution residue
Dolomite wall rock
C.
Industrial plant
Brassington
Manystones Lane
Wirksworth
N
Superficial deposits
Kenslow Member (B. Fm.)
Mercia Mudstone Group (BNM)
Sherwood Sandstone Group (KM)
Bowland Shale Formation
Chert-clay solution residue
Dolomite wall-rock
10 metres
Line of section
Slip
Pond
Landslipped
Floor of pit
Line of section

Figure 2

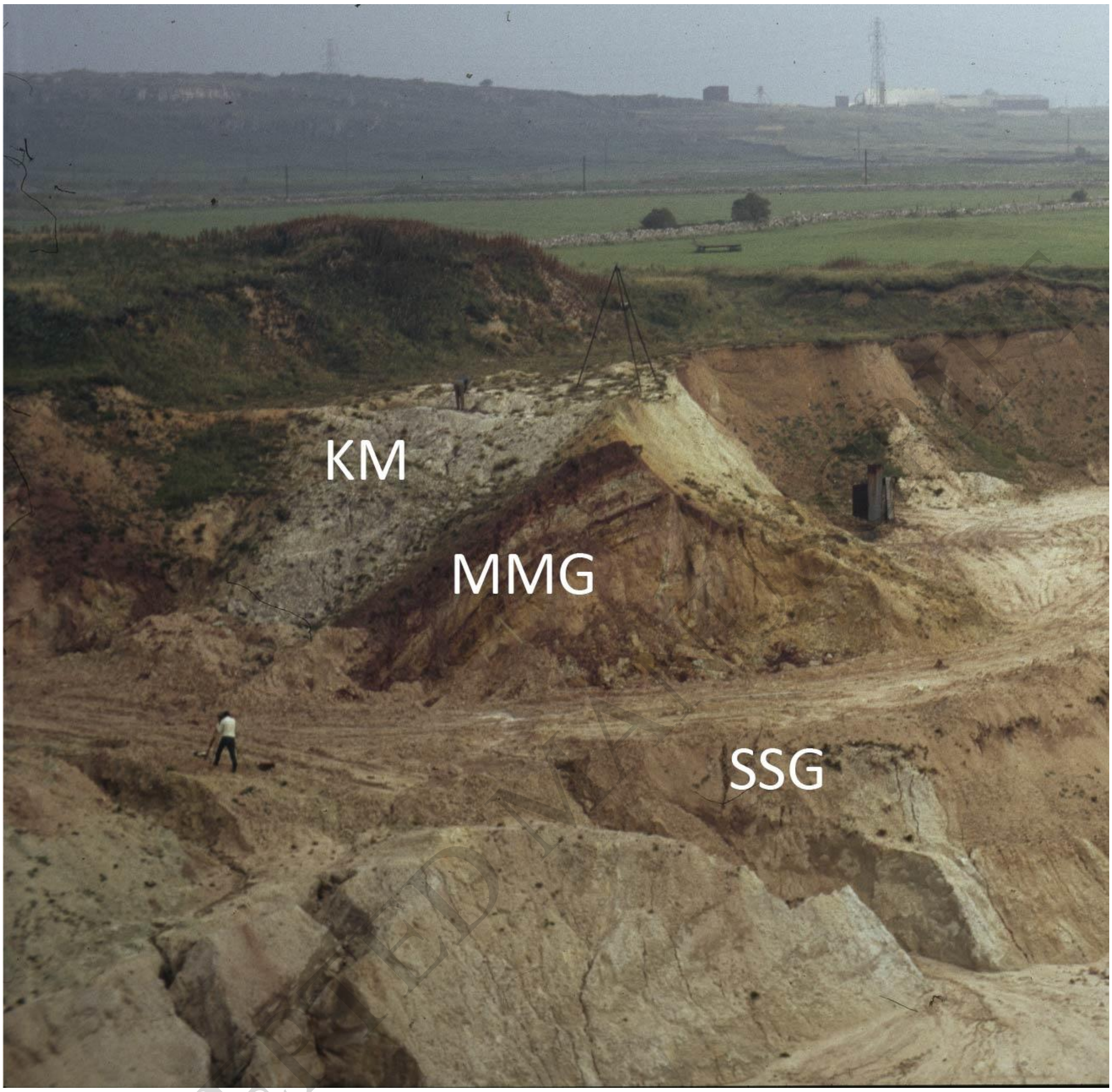

Figure 3

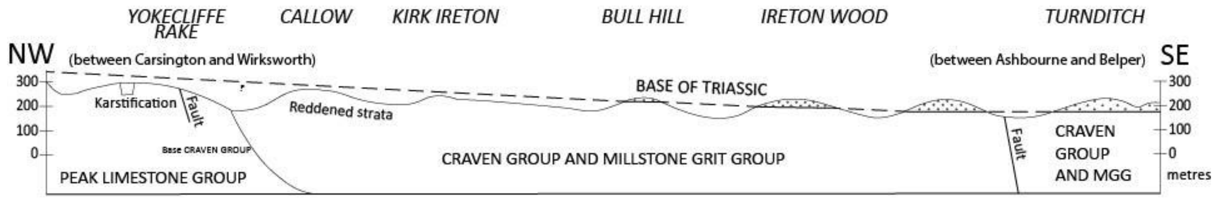
YOKECLIFFE RAKE
CALLOW
KIRK IRETON
BULL HILL
IRETON WOOD
TURNDITCH
NW
(between Carsington and Wirksworth)
(between Ashbourne and Belper)
SE
300
200
100
0
BASE OF TRIASSIC
Karstification
Fault
Reddened strata
Base CRAVEN GROUP
CRAVEN GROUP AND MILLSTONE GRIT GROUP
PEAK LIMESTONE GROUP
Fault
CRAVEN GROUP AND MGG
metres

Figure 4

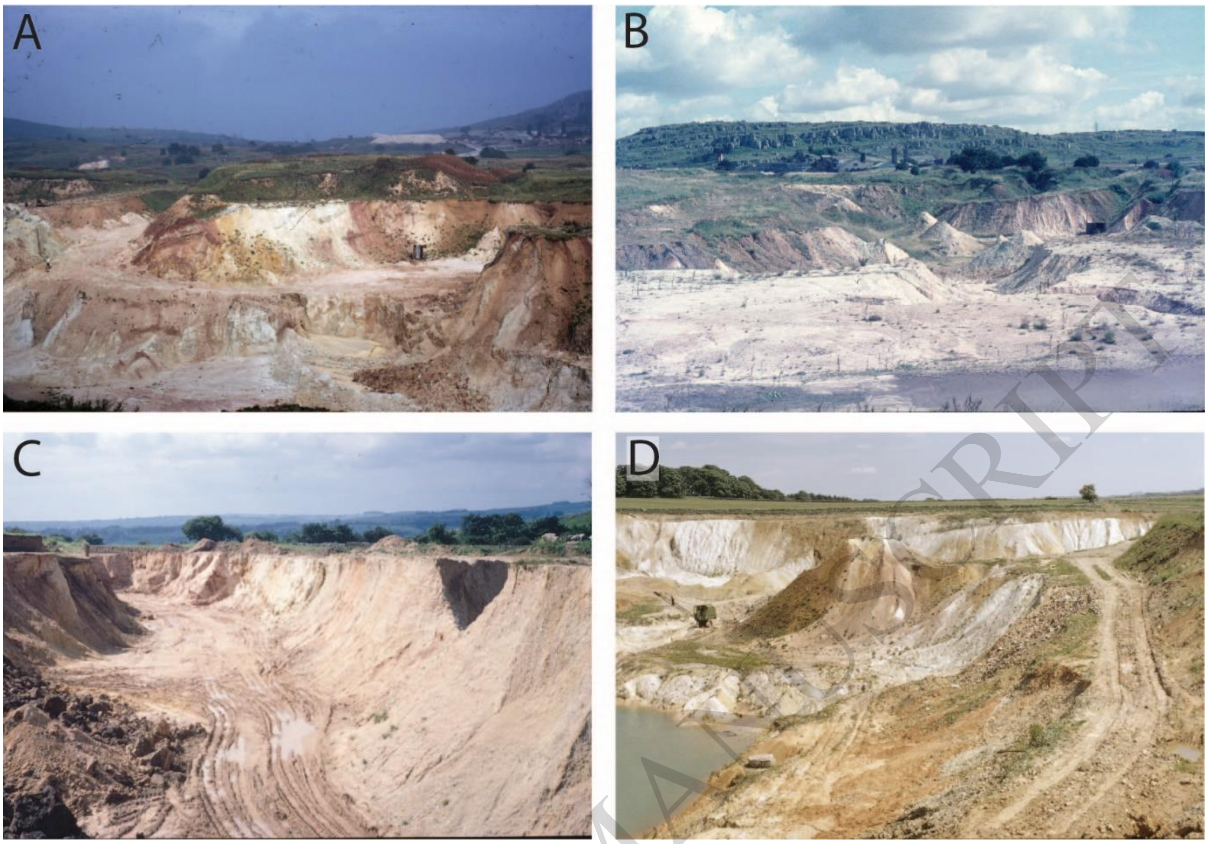

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Table 1

Stratigraphy of Boulter *et al.* (1971)	**Reinterpreted lithostratigraphy and chronostratigraphy herein**	
not recognised	Friden Member (Brassington Formation)	Late Miocene
Kenslow Member (Brassington Formation - Neogene)	Kenslow Member (Brassington Formation)	Middle–Late Miocene
Bees Nest Member (Brassington Formation - Neogene)	Mercia Mudstone Group (Tarporley Mudstone Formation)	Middle Triassic
Kirkham Member (Brassington Formation - Neogene)	Sherwood Sandstone Group (Chester and Helsby Sandstone formations)	Early–Middle Triassic

Table 2

Author(s) and year	**Age of the 'pocket deposit' fills**	**Evidence**
Brown (1867)	Carboniferous or Triassic	lithological similarity
Brodie (1886)	Triassic or Paleogene	lithological similarity
Howe (1897)	**Triassic**	**lithological similarity**
Thomas *et al.* (1920)	post-Triassic to Pleistocene	overall lithofacies
Scott (1927)	**Carboniferous**	**lithological similarity**
Kent (1957)	Triassic	lithological similarity
Chaloner (1961)	**Neogene**	**palaeobotany and palynology***
this paper	Triassic and Miocene	see the main text

Table 3

MINERAL SPECIES	MINERALOGICAL ANALYSES OF THE BRASSINGTON FORMATION	MINERALOGICAL ANALYSES OF TRIASSIC STRATA	STRATIGRAPHICAL INTERPRETATION
CLAY MINERALS (ANALYSED BY X-RAY DIFFRACTION)			
Gibbsite	Ijtaba (1973) studied the Kenslow Member (Bed 24), and found abundant gibbsite; this suggests humid, warm weathering of Miocene lacustrine clays during the Pliocene (Gasparini *et al*. 2022)	N/A	Miocene (Kenslow Member)
Illite	Ijtaba (1973) studied the Bees Nest Member, beds 19–21, and found this succession to be rich in illite	Hobbs *et al*. (2002) reported that the clay mineralogy of Mercia Mudstone Group units A and B of northeast England are illite-rich (see also Cripps & Taylor 1987 and Jones *et al.* 2025)	Triassic (Bees Nest Member)
Kaolinite	Ijtaba (1973) studied beds 2, 6 and 8 of the Kirkham Member and found them to be highly kaolinitic	Bath *et al*. (1987) investigated the diagenesis of the Sherwood Sandstone Group, and found K-	Triassic (Kirkham Member)

		feldspar and authigenic kaolinite to be present	
HEAVY MINERAL ANALYSES			
	Ijtaba (1973) from the Kirkham Member	**Jeans *et al*. (1993) - specific gravity >2.92; 64–250 µm**	
Anatase	Scarce or absent; euhedral bluish, dusky, yellowish tabular grains	Staurolite is common in the Sherwood Sandstone Group of Nottinghamshire, however it is sparse in Derbyshire. Jeans *et al*. (1993) suggested that heavy mineral analyses of the overlying Mercia Mudstone Group would be informative; their work indicated a lower tourmaline content with locally rapid changes in garnet and sphene concentrations.	
Brookite	Scarce or absent; brownish, dusky tabular grains not exhibiting extinction under crossed polars; these grains are absent in the Sherwood Sandstone Group (Chester Formation) that was sampled		
Garnet	Scarce or absent; colourless, fractured and isotropic grains		
Monazite	Scarce or absent; biaxial, light yellow rounded grains		
Rutile	Minor; red (ubiquitous) and yellow; rounded to subrounded; transverse striations on some grains		

Staurolite	Minor; straw yellow, marked pleochroism and with conchoidal surfaces on some grains		Triassic (Kirkham Member)
Titanite	Two grains observed from Bees Nest Pit		
Tourmaline	Abundant; blue, brown, green and yellow; angular to rounded; roundness increases with size; variable intensity of pleochroism		Triassic (Kirkham Member)
Zircon	Dominant; grain roundness increases with size; several grains with faint dusty zoning parallel to the crystal faces		Triassic (Kirkham Member)
Opaques	Haematite, ilmenite, leucoxene coating and magnetite		

Table 4

1. SAND GRAIN SURFACE TEXTURE ANALYSES		STRATIGRAPHICAL INTERPRETATION
Wilson (1979) examined nine sand samples from the Kirkham Member using a scanning electron microscope, and compared these with a sample of the Chester Formation of the Sherwood Sandstone Group from Hulland Quarry (NGR SK 280 455) 10 km south of Brassington	Wilson (1979) stated that the surface features of the grains from the 'pocket deposits' lack high-energy indicators of secondary subaqueous abrasion and high-energy chemical weathering; however they do exhibit evidence of chemical abrasion and mechanical fracturing	Triassic (Kirkham Member)
2. PEBBLES WITH PRESSURE SOLUTION MARKS		
Some pebbles from Bed 7 of the Kirkham Member exhibit pressure pitting, which strongly suggests significant overburden pressure		Triassic (Kirkham Member)
3. PRE-CONSOLIDATION PRESSURE TESTS		
Ijtaba (1973) found that the pre-consolidation pressure of Bed 10 of the Kirkham Member is 829 kN/m2	Ijtaba (1973) concluded that beds 10 and 24 are both normally consolidated clays, however there is a significant difference in the pre-consolidation pressures; Davis & Chandler (1973) also discussed the pre-consolidation	Bed 10 (Kirkham Member) is Triassic, and Bed 24 (Kenslow Member) is Miocene
Ijtaba (1973) found that the pre-consolidation pressure of the Kenslow Member (Bed 24) is 257 kN/m2		
Beds 10 and 24 are separated by 5–6 m of sediment (around 120 kN/m^2); the coefficients of volume compressibility (Mv) and coefficient of consolidation (Cv)		

values were not given by Ijtaba (1973)	pressures of weathered Mercia Mudstone Group material	