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Woodeaton Quarry: review of the stratigraphy and discovery of a new, rich Middle Jurassic microvertebrate horizon

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ABSTRACT

The geology and stratigraphy of Woodeaton Quarry in Oxfordshire, United Kingdom, is reviewed in context of previous studies and its regional setting. This is supplemented by additional field observations made between 2013 and 2016. The upper and lower boundaries of the White Limestone Formation are discussed and clarified and a new rich terrestrial microvertebrate horizon within the Bladon Member (White Limestone Formation) is described. A preliminary assessment of the palaeontology of the microvertebrate horizon is provided and the importance of microvertebrate sites for a full understanding of dinosaur and mammalian evolution is highlighted.

1. Introduction

Microvertebrate sites are sites which contain an abundance of vertebrate remains (usually teeth and bone fragments) where >75% of the identifiable specimens are smaller than 50 mm in maximum dimension (Eberth et al., 2007). Important Bathonian (Middle Jurassic) microvertebrate sites were discovered in the 1970's by E.F. Freeman who described mammalian remains from Kirtlington in Oxfordshire (Freeman, 1976a, 1979; Kermack et al., 1987) and Watton Cliff in Dorset (Freeman, 1976b). Since these initial discoveries further Bathonian sites have been described, with Evans and Milner (1994) recording sixteen localities producing terrestrial microvertebrates, mostly in the English Cotswolds. These assemblages have produced a mixture of marine (possibly reworked), aquatic / semi-aquatic and terrestrial taxa. Vertebrate remains are typically fragmentary small post cranial elements, isolated teeth and scales. Taxa recorded in these and subsequent studies are represented by mammals (cladotherians, docodonts, eutriconodonts, haramiyids, morganucodontids, multituberculates and pseudotribosphenids), dinosaurs (theropods and ornithischians), pterosaurs, frogs, turtles, albanerpetontids, salamanders, lizards, crocodiles and bony fish, sharks and rays (Evans et al., 2006; Evans and Milner, 1994; Metcalf et al., 1992; Metcalf and Walker, 1994; Underwood and Ward, 2004; Wills et al., 2014). Although these sites are predominantly known for their micro-remains, macro vertebrate fossils are also present from many of these localities (e.g. Benton et al., 1995; Benton and Spencer, 1995; Clark et al., 1995; Metcalf et al., 1992; Owen, 1838; Palmer, 1973; Palmer, 1979; Upchurch and Martin, 2003).

The Middle Jurassic is a key phase in terrestrial vertebrate evolution and diversification. All three dinosaur clades show major radiations in the Lower and Middle Jurassic with statistically significant upward trends in diversification of both theropods and sauropodomorphs (Barrett and Upchurch, 2005; Day et al., 2002; Mannion, 2010; Upchurch et al., 2011). The Middle Jurassic also saw the origin of major new mammal groups as well as peak rates of ecomorphological diversity in these groups (Close et al., 2015). Similar radiations have been noted for squamates and lissamphibians (REF).

Here we review and update the stratigraphy, sedimentology and geological setting of Woodeaton Quarry near Oxford (Fig. 1, SP533123) (Bathonian, Great Oolite Group), including the discovery of a new horizon rich in microvertebrate remains. The material described herein was collected between 2013 and 2016 by a team comprised of curators, researchers, students and volunteers from the Natural History Museum, London and Birkbeck College, University of London. The initial work was undertaken to recover a representative sample from each bed before sections became inaccessible and to verify the stratigraphy, as the quarry was scheduled to be landfilled and partly made into a nature reserve. A previous visit by the Natural History Museum in 2002 had recovered the partial remains of a small sauropod from the Rutland Formation (Great Oolite Group) which is currently being described.

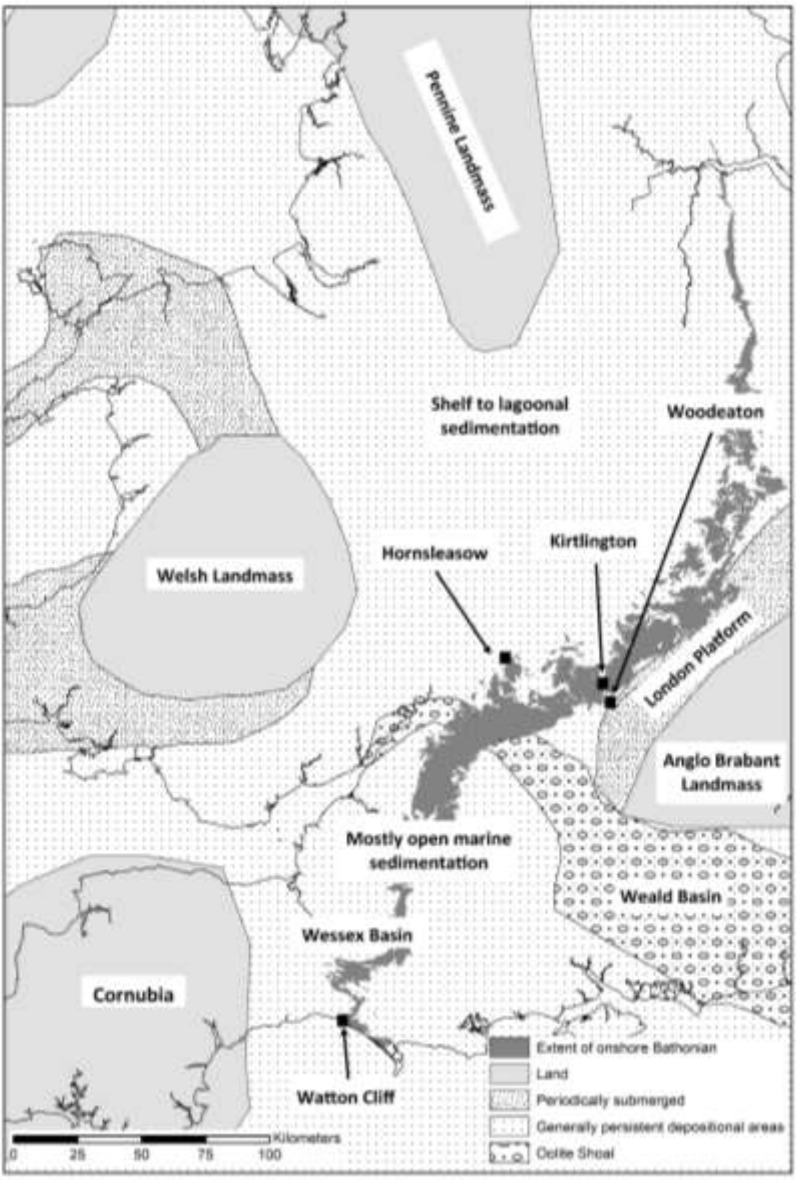


Fig. 1. Middle Jurassic palaeogeography and depositional regimes of southern England. After Barron et al. (2012) and Underwood (2004).

2. Previous work on geology and stratigraphy at Woodeaton

2.1. Regional geology

The Middle Jurassic in Britain has been the subject of extensive research stretching back well into the 19th Century with a large volume of literature on the subject (e.g., Arkell, 1931, 1933, 1947; Barron et al., 2012; Bradshaw, 1978; Bradshaw et al., 1992; Cope et al., 1992; Cope et al., 1980; Cox and Sumbler, 2002; Cripps, 1986; Hull, 1857, 1859; Judd, 1875; Murchison, 1834; Palmer, 1979; Phillips, 1871; Richardson, 1929, 1933; Richardson et al., 1946; Sumbler, 1984; Torrens, 1969; Woodward, 1894; Wyatt, 2011). The onshore Aalenian, Bajocian and Bathonian (Middle Jurassic) strata form a sequence of sediments up to 1300 m in thickness comprising mostly marine mudstones and carbonates in southern England with increasingly arenaceous and non-marine sediments in the East Midlands, Yorkshire and Scotland. Sedimentation throughout this period was controlled by rifted basins with intervening structural highs. The highs formed areas of low lying land, with surrounding seas dominated by shallow marine to paralic depositional areas in central England and the development of a carbonate ramp succession in the south of England. Woodeaton Quarry is situated on the ramp formed by the Cotswold Shelf (Fig. 1), and lay on, or to the north of, the oolite barrier system during the Bathonian. The ramp is characterised by a series of facies belts, representing increasing marine influence, that prograded basinwards with time (Wyatt, 1996; Wyatt, 2011) and include an oolite barrier which played an important role in controlling regional depositional environments. Open marine conditions with deeper water sedimentation prevailed to the south of the oolites with near shore marine, lagoonal and coastal plain environments to the north (Barron et al., 2012; Hesselbo, 2008; Palmer, 1979; Palmer and Jenkyns, 1975; Underwood, 2004; Wyatt, 1996). Localised fluctuations in relative sea level during the Bathonian resulted in a number of regressive units occurring throughout the succession. The units are represented by shallowing-up depositional sequences of sediment, often capped by hardgrounds (Bradshaw, 1978; Cripps, 1986; Horton et al., 1995; Palmer, 1979; Sumbler, 1984; Wyatt, 1996).

The lithostratigraphy (Fig. 2) has grown in complexity over the years with many named units often having no formal boundary definitions and lacking correlation with their lateral equivalents. The term White Limestone was first used for a defined interval by Woodward (1894), but was only formally defined and subdivided into its constituent members by Palmer (1979). Additional amendments were made by Sumbler (1984), Sumbler et al. (2000) and Barron et al. (2012) who revised the stratigraphic framework for the Middle Jurassic, updating and revising the definitions and formalising the unit names where appropriate.

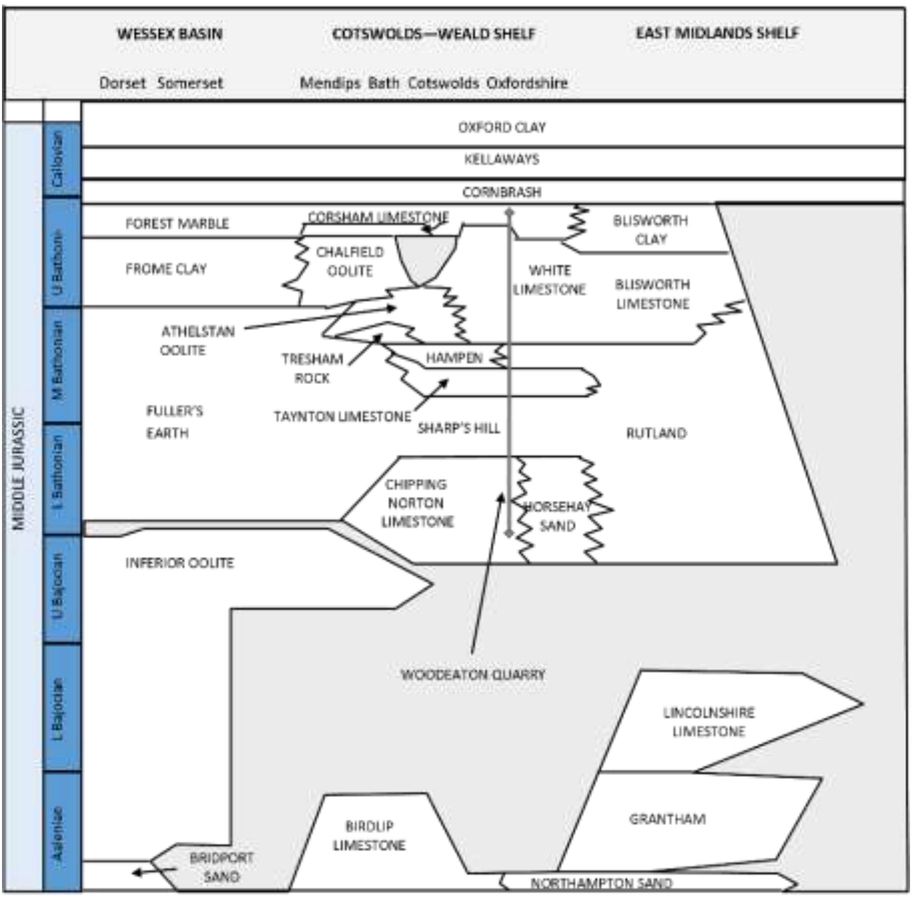


Fig. 2. Lithostratigraphy of the Great Oolite Group after Barron et al. (2012). The vertical grey line indicates the extent of the deposits represented at Woodeaton Quarry.

The Great Oolite Group is a complex sequence of mudstones and limestones, up to 200 m thick onshore with the White Limestone Formation having a thickness of up to 30 m locally (Norton et al., 2004). The gently shelving nature of the structural highs, coupled with minor fluctuations in sea level, caused major changes in shoreline positions and local depositional environments. As a result of this, many of the units are thin, diachronous, laterally impersistent and show rapid lateral and vertical facies changes and non-sequences (Barron et al., 2012; Cox and Sumbler, 2002). Depositional types range from silicate mud of deep water marine conditions, carbonate muds on the shelf foreslope, oolitic and peletic carbonate sands on the very shallow marine shelf and mixed carbonate deposition in protected shallow marine lagoons (Barron et al., 2012; Palmer, 1979; Palmer and Jenkyns, 1975). Non-sequences and hardgrounds are relatively common with karstic weathering surfaces, palaeosol development and influxes of terrigenous sediment containing abundant plant and woody material indicating pauses in marine sedimentation and occasional local emergence prior to the onset of fully marine conditions in the overlying Forest Marble Formation.

2.2. Local geology

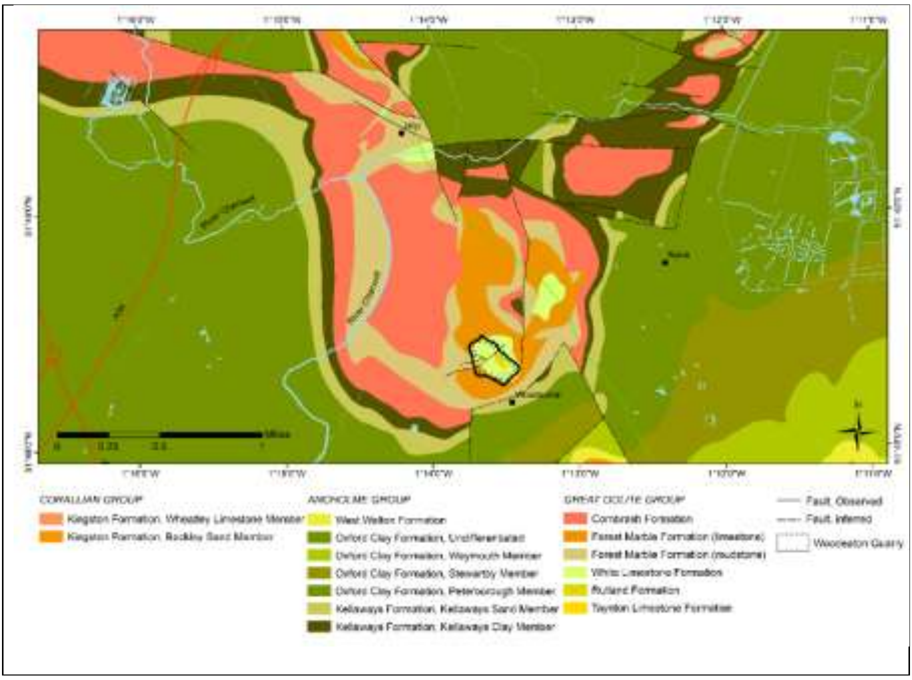


Fig. 3. Location and geological setting of Woodeaton Quarry, Oxfordshire. Licence number 2017/024 ED British Geological Survey (c) NERC. All rights reserved.

Woodeaton quarry (Fig. 3) is situated on a periclinal inlier of Great Oolite Group surrounded by Kellaways Formation and Oxford Clay Formation at the intersection of the Islip anticline with the Wheatley Fault Zone (Arkell, 1944; Horton et al., 1995; Wyatt, 2002). The area around Woodeaton has been extensively quarried in the past. Arkell (1947) notes that there were at least twenty-eight quarries in the Noke Hill area. Woodeaton Quarry, also known as Grove Quarry, is one of two original quarries situated in the vicinity of Woodeaton Village with Hope Farm Quarry long since closed (Cripps, 1986). The quarry formerly exposed one of the most complete sequences of the Middle to Late Bathonian in the UK from Chipping Norton Limestone Formation to the lower part of the Forest Marble Formation (Fig. 4).


A
C
W2
W1
B
W2
W1

Fig. 4. Northwest face at Woodeaton Quarry with approximate locations of logged sections. A, In 1991 showing exposure from the Rutland Formation through to the Forest Marble Formation. B, In 2017 with only the uppermost Bladon Member of the White Limestone Formation and the Forest Marble Formation visible. Contains British Geological Survey materials © NERC 1991.

Palmer (1973) provided the first detailed description of Woodeaton Quarry with subsequent descriptions in Cripps (1986), Horton et al. (1995), Palmer (1974), Palmer (1979), Palmer and Jenkyns (1975) and Wyatt (2002). The Rutland Formation, White Limestone Formation and lower part of the Forest Marble Formation are well known from long term exposures (e.g. Horton et al., 1995). Of these units, the Rutland Formation was least exposed and commonly rather degraded, to the extent that nearly half of its thickness, now known to contain three palaeosols, was grouped by Horton et al. (1995) into a single bed. Considerable lateral variation is seen in some of the units, but this is not mentioned in publications on the stratigraphy of the site. Renewed quarrying in 2002 greatly expanded the exposed succession, with units referred to the Chipping Norton Limestone, Sharps Hill, Charlbury and Taynton Limestone Formations being exposed. These lower units were rapidly obscured and no mention was made of them in later publications such as Guthrie et al. (2014). Of these lower units, only the uppermost part of the Taynton Limestone Formation was still exposed in 2014 – 2016, although grey marl with rhynchonellids, originating from the Charlbury Formation, was being used as a quarry lining in several places. The quarry is currently being used as a landfill site and as of 2017 the only remaining extant sections visible are from the White Limestone Formation (Ardley Member) through to the Forest Marble Formation.

3. Materials and methods

Accessible sections throughout the quarry were examined in the field and detailed stratigraphic and sedimentological data logged. All stratigraphic and sedimentological data was recorded on logging charts and later converted to digital format. Lithological descriptions consist of bed thickness, lithology, grain size, colour, trace and body fossils and any sedimentary structures. Also captured are field interpretations of facies and palaeoenvironments. Bulk sampling was carried out in both the Rutland Formation clays and in the clay and marl horizons of the Bladon Member (White Limestone Formation). An initial 1.6 tonnes of sediment was removed dried and sieved to 500 µm using a mechanical sieving machine (Ward, 1981). It was found that most of the dried sediments washed at a rate of between 3 and 10 kg per hour. The clay horizons in the Rutland disaggregated readily, the 500 µm residues comprising around 1 - 2% of the original sample weight. The oyster-rich horizons of the White Limestone disaggregated more slowly and yielded large volumes of oyster shards, reducing to approximately 10% of the original sample weight. The coarse fractions, between 6 and 12mm, which were mainly oyster shell, were dried and sorted by eye. The finer fractions, less than 6 mm, were decalcified in 7.5% formic acid buffered with 20% spent acid. An electronic pH meter was used to ensure that the pH did not drop below 3.2. An untreated archive sample of the fine fraction was saved. The decalcified residue was washed several times to remove any calcium formate residues, dried, graded and picked under a binocular microscope. The sorted fraction retained and archived.

During the first stages of fieldwork a section along the western edge of the quarry was examined. This section exposed a sequence of limestones and clays of the Ardley and Bladon Members (Great Oolite Group, White Limestone Formation) through to the shelly detrital limestone of the Forest Marble Formation. One bed, a variably lithified clay to impure limestone horizon with abundant plant material (Bed 23, see section 4.1.6), produced substantial quantities of terrestrial microvertebrates. Bulk sampling thereafter concentrated on this unit with 2.4 tonnes of sediment collected and an additional 800 kg taken from the overlying bed. After screen-washing and drying, the concentrate was split into size fractions (500 µm – 1 mm, 1 mm – 2 mm, 2 mm-4 mm, > 4 mm) to create convenient sample sizes for picking. Approximately 30kg of concentrate from Bed 23 remained after screen-washing. Each size fraction was then picked for vertebrate remains under a binocular microscope and categorised to the lowest taxonomic level possible.

4 Results

4.1 Geology and stratigraphy of Woodeaton Quarry

Sedimentary logs resulting from this study are presented in Fig. 5.

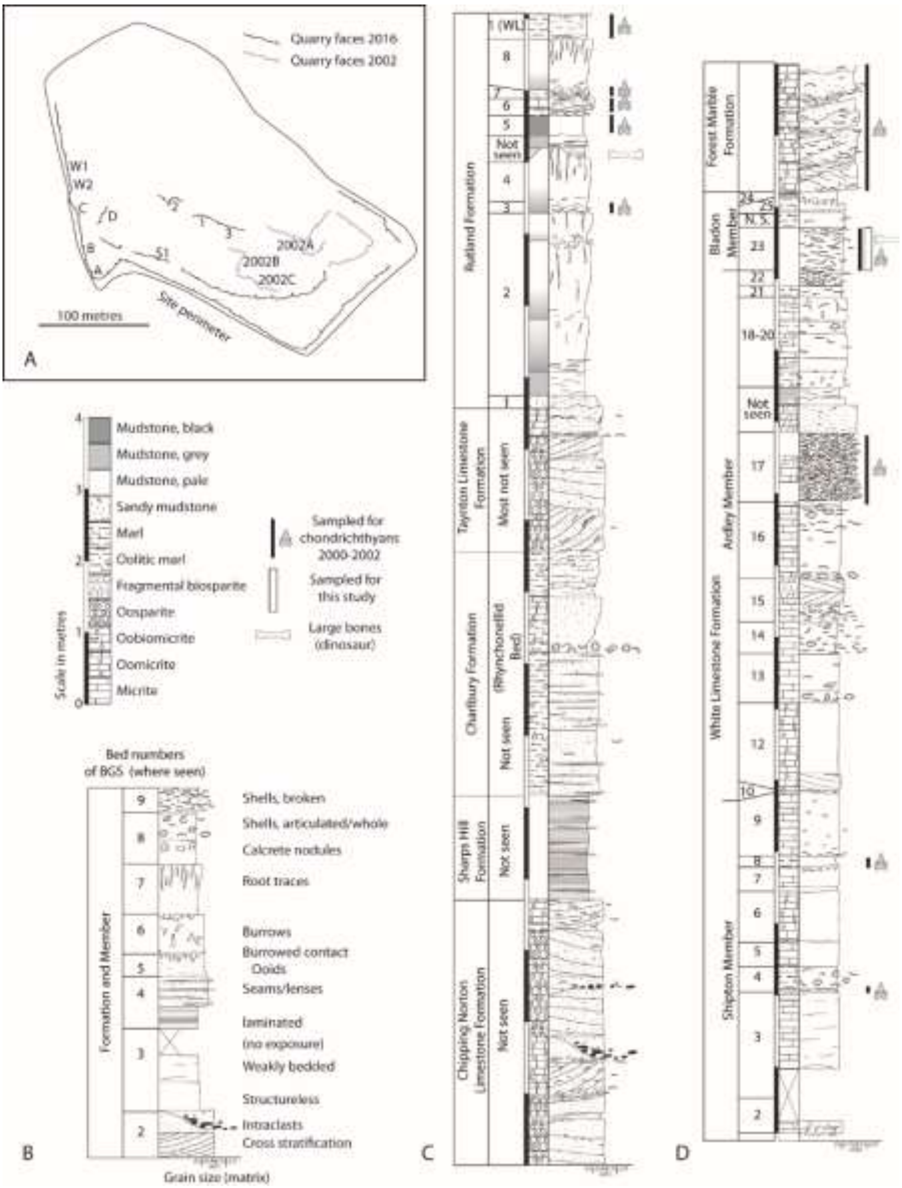


Fig. 5. A, location of described sections at Woodeaton Quarry. B, Composite stratigraphic log from the Chipping Norton Formation to the Forest Marble Formation showing sampling undertaken in

2000 – 2002 and for this study. Bed numbers referred to British Geological Survey numbering from Horton et al. (1995).

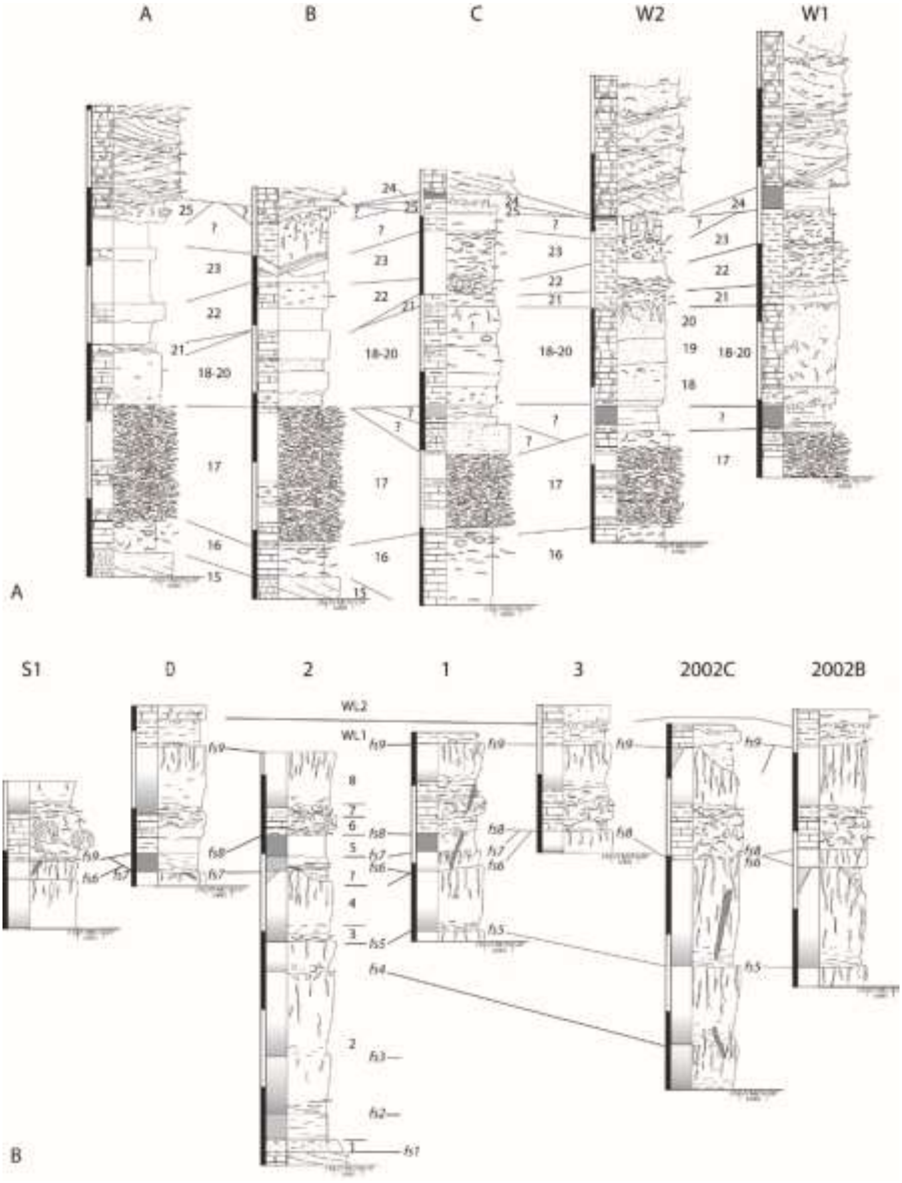


Fig. 6. Correlated stratigraphic logs. Section names refer to localities on Fig. 5A, bed numbers refer to Fig. 5B, fs – flooding surface. A, north – south section along eastern perimeter of quarry. B, east – west section.

4.1.1 Chipping Norton Limestone Formation.

Up to 3.8 m of this unit was previously exposed during the working life of the quarry. The base was not seen but a spring line near the exposed base suggests that a contact with an underlying impervious unit (presumably Toarcian mudstones) is present not far below the exposure. The Chipping Norton Limestone Formation comprises yellow-orange, strongly cross stratified oolitic and bioclastic packstones and some grainstones. The cross stratification appears to be mostly in the form of trough sets, some reaching 1 m high. The majority of the unit is oolitic with only rare bioclasts, but some beds are composed primarily of small and fragmented bioclasts. One small channel contained large numbers of oval intraclasts, with rare intraclasts being present elsewhere in the unit.

4.1.2 Sharps Hill Formation.

This muddy unit was never well exposed, but where exposure occurs it reaches about 1.3 m in thickness. It comprises pale grey silty claystones with thin lenses and seams of calcareous siltstone. Lamination is apparent throughout, and the unit is virtually unfossiliferous.

4.1.3 Charlbury Formation.

The Charlbury Formation is about 3.5 m thick and largely comprises grey to yellowish impure limestone. The dominant lithology is a soft micrite with matrix supported ooids throughout. Thin lenses and seams of calcareous siltstone are present. Fossils are generally uncommon with scattered oysters and brachiopods, with the exception of a bed of marl crowded with well-preserved rhynchonellid brachiopods (*Kallirhynchia*). This is the *Rhynchonella* Bed recognized at other sites e.g. Boneham and Wyatt (1993).

4.1.4 Taynton Limestone Formation.

The majority of the 2 m thick Taynton Limestone Formation comprises strongly cross stratified cream coloured oolitic grainstones. The tabular cross sets are typically at a low angle and bioclasts are small and uncommon throughout. Towards the top of the formation, there is more matrix and bioclasts, typically broken oysters, are common. The top surface of the unit is irregular and orange-stained and appears karstic.

4.1.5 Rutland Formation.

The Rutland Formation here corresponds to the Hampen Marly Beds of Arkell et al. (1933) and Arkell (1947), the Hampen Marly Formation of Palmer (1979) and the Upper Estuarine Series of Bradshaw (1978). The term Hampen Marly Formation is now restricted to the more marine clay and limestone facies that occur to the west of the area (Horton et al., 1995). The Rutland Formation is a variable package of lagoonal to subaerial lagoon margin facies totalling about 5.2 m in thickness. Whilst the lower parts were only seen in two excavated sections in 2002 and 2014, the uppermost 2 m of the section was well exposed and shows considerable lateral variation. The bed numbering scheme of Horton et al. (1995) works for the upper part of the formation, but it does not take lateral variation into account and groups several distinct units together in the lower part. In addition, the uppermost unit of the Rutland Formation was included into the White Limestone Formation by Horton et al. (1995) despite being identical lithologically to some underlying beds.

The base of the Rutland Formation is an oolitic clay with clasts of limestone from the underlying Taynton Limestone formation. Above this, the Rutland Formation comprises a sequence of shallowing upwards cycles terminating in rooted palaeosols, with flooding surfaces terminating the rooted units. Above the basal flooding surface, eight additional surfaces were recognized (fs 2-8, see Fig. 6), but not all were seen in all sections due to erosional downcutting at some of the flooding levels. Where complete, each of the cycles in the lower to mid part of the formation, comprises a basal dark mudstone with small aragonitic shells and thin burrows, grading up to a paler grey mudstone devoid of obvious fossils and finally to a pale greenish calcareous clay with vertical, carbonaceous, roots. In addition to the typical small root traces, large subvertical roots, seen to penetrate at least 1.5 m and reach 0.1 m in diameter, are present, being initiated from several different palaeosol surfaces. In places, below flooding surfaces fs7 and fs9, small incised depressions are filled with laminated pale mudstone containing (where studied) a non-marine ostracod and charaphyte biota. In some sections, a level above surface fs7 comprises a dark green and brown mudstone with greenish slickensides. This presumably represents a subaqueous rooted horizon, in contrast to the other rooted levels that were subaerial. Above surfaces fs8 and fs9 are black, gritty (bioclast-rich) mudstones with a restricted marine biota of oysters and other bivalves, echinoids (*Himicidaris*) and diverse neoselachian sharks. One interval, Bed 6 of Horton et al. (1995) of this more marine interval forms a dark impure limestone with a similar restricted fauna, but at site S1 also contains large numbers of highly bio-eroded coral colonies. It is likely that older records of a “Monster Bed”, Bed 5 of Palmer (1973), refer to the succession between surfaces fs5 and fs6, which yielded dinosaur remains within a palaeosol in 2002.

4.1.6 White Limestone Formation.

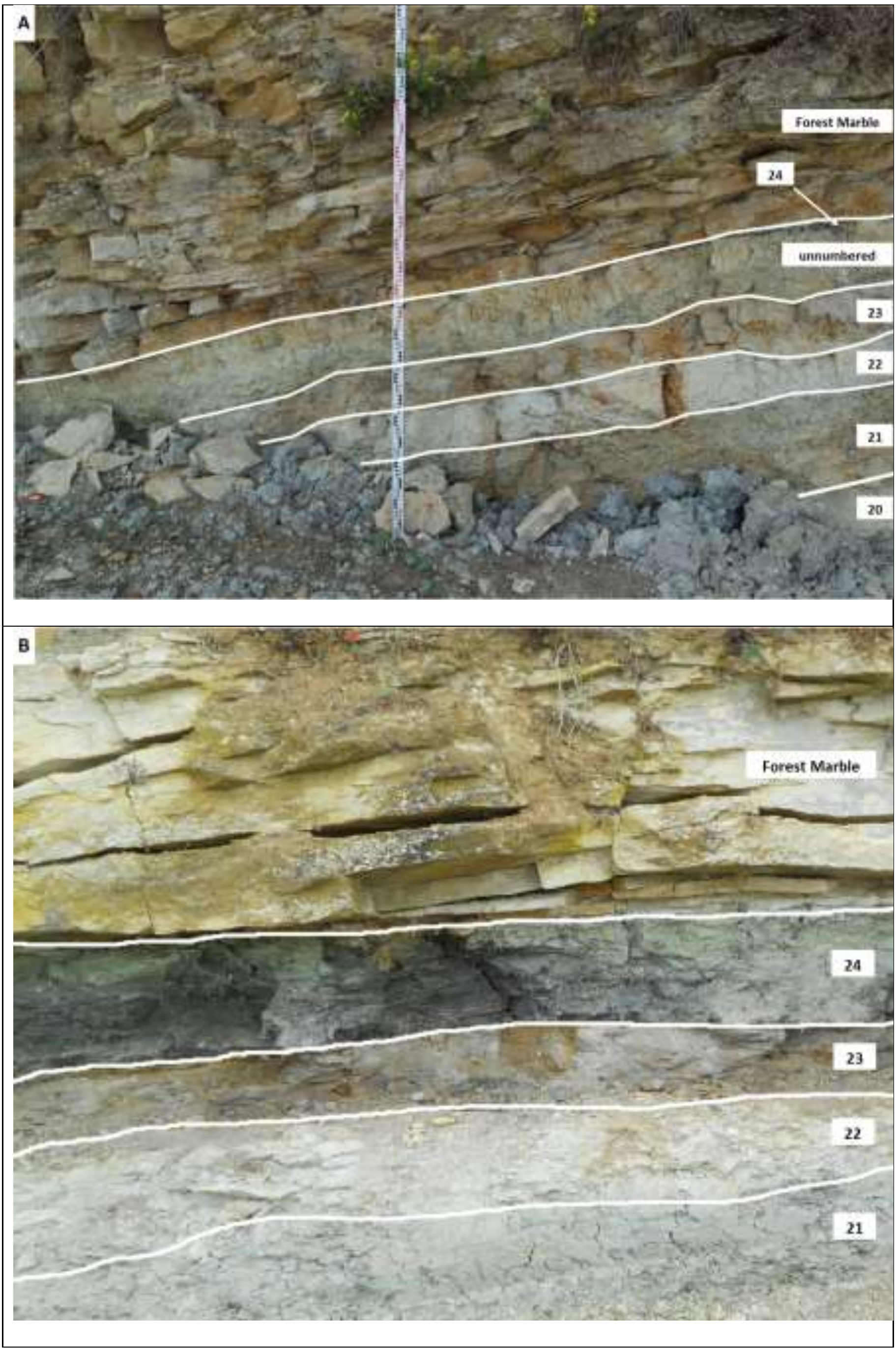
The White Limestone Formation is about 13 m thick, although some of the lowest part was not exposed. It is typically divided into the Shipton, Ardley and Bladon Members, but at Woodeaton Quarry the Shipton Member and lower part of the Ardley Member cannot be readily separated on lithological grounds. The lower part of the formation, up to Bed 16 of Horton et al. (1995), comprises massive pale limestones with several thin seams of marl (Beds 8, 10 and the base of Bed 7). The limestones are typically micrites or oolitic wackestones although a finely biocalstic level (Bed 15) is also present. Sedimentary structures are limited to low angle tabular cross stratification in Beds 12 and 15. Fossils are rare in some beds, but common in others where a low diversity but marine biota is dominated by oysters, modiolids and the brachiopod *Epithyris*. The upper part of the White Limestone Formation is very variable in lithology, with considerable lateral variation.

The first major lithological deviation from the pale limestones of below comes with Bed 17 (Horton et al., 1995). This varies from 1.1 – 2 m in thickness and comprises a dark grey to orange clay, marl or rubbly muddy limestone matrix with matrix to clast supported oyster shells. There are ooids in places in addition to an associated fauna including echinoderms, brachiopods, pectenid bivalves and common neoselachian sharks. Above this are two laterally impersistent units that were not noted in previous studies. The lower of these is a very hard grainstone composed of finely comminuted shell fragments but with no recognizable fossils. There is also a laterally discontinuous black clay with thin partings of ooids but no obvious fossils. Above these units the remainder of the Ardley Member comprises pale soft limestones and marls, variably bioturbated and oolitic. The lithology is laterally rather variable and the beds numbered by Horton et al. (1995) cannot often be recognized with certainty.

The Bladon Member (Fig. 7) is thin, usually less than 1 m thick, and the base is sharply defined in some places but gradational in others. The lower part of this, Bed 23 of Horton et al. (1995), is laterally persistent but overlying beds are not. Bed 23 comprises a pale grey to almost white, massive clay, marl or impure limestone within which the degree of lithification is highly variable. This is the *fimbriatus-waltoni* Bed of previous studies. Small aragonitic bivalves (mostly *Corbula)* as well as naticid, cerithiid and planorbid gastropods are common in the more calcareous parts, but are present as moulds elsewhere. Small dark fragments of both fusinite and lignite are common throughout. In most places this is overlain by a hard pale, often rather oyster rich, marl with numerous small rootlets. The contact between these is in places seen to be highly undulose and there is often a thin heterolithic or lamninated band at the contact. This upper unit was apparently not recognised by Horton et al. (1995). Above these two beds are two additional units that are discontinuously present. These appear to correspond to Beds 24 and 25 of Horton et al. (1995), although their descriptions only loosely match the observed lithologies. One unit comprises a dark grey to black clay. This has an irregular base and appears to be associated with the rootlets seen below it. In places a thin limonitic crust is developed at the base with small irregular quartz fragments present. The other unit is a pale nodular micrite with *Epithyris*. The latter appears to correspond to eroded remnants of the Coral-*Epithyris* Limestone of other Bathonian sites in the region (McKerrow et al., 1969). These uppermost units are not seen in contact (although it is inferred that they do by Horton et al. 1995), but one section showed the black rooted clay overlying a very thin weathered limestone containing small calcrete nodules. It therefore appears that the *Epithyris*-bearing unit (Bed 25) is overlain by the dark clay (Bed 24).

4.1.7 Forest Marble Formation.

The Forest Marble Formation overlies the White Limestone Formation with a clearly undulose and erosive base. The exposed part of the Forest Marble Formation is almost entirely with limestone facies, although mudstone-dominated facies have been mapped very close to Woodeaton Quarry (Fig. 3). The limestones are strongly cross stratified and bed thicknesses and geometries are extremely variable. The limestone lithology varied from packstone to grainstone and the grains vary from largely ooids with rare bioclasts to almost entirely comminuted shell fragments. Mudstone intraclasts ate present in places. Some bedding surfaces have diverse assemblages of bivalves and echinoderms but generally the diversity appears low. Thin drapes of yellow to grey clay are present between some of the limestone units but remain volumetrically insignificant. Acid digestion of limestones yielded a rather diverse vertebrate assemblage including neoselachian and hybodont sharks, osteichthyan fish teeth and rare tetrapod fragments.


A
Forest Marble
24
unnumbered
23
22
21
20
B
Forest Marble
24
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22
21

Fig. 7. Sections through the Bladon member (White Limestone Formation) to the Forest Marble Formation. Bed numbers correspond to those shown on Fig. 5. A. Section W2 showing the almost complete removal of bed 24 by the erosion surface at the base of the Forest Marble Formation, and the addition of a small channel deposit between beds 23 and 24 penetrated by roots from the overlying bed 24. B, section W1 beds 21 to 24 of the Bladon Member overlain by flaggy cross stratified limestone of the Forest Marble Formation.

4.2 Systematic palaeontology

Vertebrate remains are present in a number of horizons at Woodeaton Quarry. Large dinosaur bones have previously been recovered from both the Rutland Formation and White Limestone Formation (Fig. 5). Palmer (1973) referred two large dorsal vertebrae from Bed 5 of the Rutland Formation (the “Monster Bed”, Fig. 5) to the sauropod *Cetiosaurus*. These could not be located in the OXUMNH collections and are best referred to Sauropoda indet. Previous work by the NHM recovered the partial remains of a sauropod (currently awaiting formal description) from a pond deposit at a similar level in the Rutland Formation. Fragmentary large bones of indeterminate dinosaurs are also present in Bed 23 of the White Limestone Formation (Fig. 5) along with possible ornithischian remains collected by illegal diggers from roughly the same horizon. A partial incisor from Bed 5 (the “Monster Bed”, Fig. 5) of the Rutland Formation was tentatively identified as a mammal (personal communication by Eric Freeman in Clemens et al. (1979), Evans and Milner (1994) and to H. Ketchum (2017)); however, this cannot be confirmed. Sampling of beds above and below Bed 5 by researchers at University College London in 1983 and CJU in 2002, produced no evidence of mammals (personal communication by Frances Mussett in Evans and Milner, 1994). The most abundant macroscopic fish remains from Woodeaton Quarry are the teeth and scales of ginglymodian fish and the teeth of pycnodonts. These remain the most abundant fossil in bulk samples of the non-marine parts of the Rutland Formation. In contrast, the most abundant microvertebrate remains in the more marine parts of the Rutland and White Limestone Formations are the abundant teeth of various neoselachian sharks and rays, along with rare teeth of hybodont sharks (Rees and Underwood, 2008; Underwood and Ward, 2004). Identifiable tetrapod fossils were not recorded in bulk samples from the marine parts of the Rutland and White Limestone Formations (Underwood and Ward, 2004).

Extensive sampling of Bed 23 of the Bladon Member, White Limestone Formation (Fig. 5) as part of the present study has yielded a diverse microvertebrate assemblage including mammals (teeth and edentulous jaws), tritylodontids (teeth and possible vertebrae), dinosaurs (teeth), pterosaurs (teeth), crocodiles (teeth), turtles (carapace fragments), lizards (jaw fragments), albanerpetontids (jaw fragments), salamanders (jaw fragments), frogs (limb elements) and fish (teeth). In addition, numerous small fragmentary pieces of reptilian eggshell (including dinosaur) have been recovered from this bed. The systematic palaeontology of the dinosaur, mammal and fish microvertebrate fauna for this bed is given below.

Chondrichthyes Huxley, 1880

Chimaeriformes Obruchev, 1953

Callorhynchidae Garman, 1901

?*Ischyodus* Egerton, 1843

Hybodontiformes Maisey, 1975

Hybodontidae Owen, 1846b

Hybodus obtusus Agassiz, 1843

Egertonodus duffini Rees and Underwood, 2008

Parvodus pattersoni Duffin, 1985

Acrodontidae Casier, 1959

Asteracanthus ornatissimus Agassiz, 1837

Heterodontiformes Berg, 1940

- Heterodontidae Gray, 1851
  - *Proheterodontus sylvestris* Underwood and Ward, 2004
- Lamniformes Berg, 1937
  - Incertae familiae
    - *Palaeocarcharias* Beaumont, 1960

Osteoichthyes Huxley, 1880

- Pycnodontiformes Berg, 1937
  - Pycnodontidae Agassiz, 1835
    - *Coelodus* Haeckel, 1854
- “Semionotid”
- Aspidorhynchiformes Bleeker, 1859
  - Aspidorhynchidae Bleeker, 1859
- Lonoscopiformes Grande and Bemis, 1998

Dinosauria Owen, 1842

- Theropoda Marsh, 1881
  - Coelurosauria Huene, 1914
  - Coelurosauria indet. (cf. *Paronchyodon*)
  - Dromaeosauridae Matthew and Brown, 1922
- Ornithischia Seeley, 1887
  - Thyreophora Nopcsa, 1915

Therapsida (Broom, 1905)

  - Tritylodontidae (Cope, 1884)

Mammaliaformes Rowe, 1988

- Amphitheriida (Prothero, 1981)
  - Amphitheriidae (Owen, 1846a)
- Docodonta Kretzoi (Kretzoi, 1946)
  - Docodontidae Simpson (Simpson, 1929)
- “Eutriconodonta” (Kermack et al., 1973)
  - “Amphilestidae” (Osborn, 1887)
  - Gobiconodontidae Chow and Rich (Chow and Rich, 1984)
- “Haramyida” (Hahn G et al., 1989)
  - Eleutherodontidae (Kermack et al., 1998)
- Multituberculata Cope 1884 (Cope, 1884)
  - Kermackodontidae (Butler and Hooker, 2005)
  - Hahnotheriidae (Butler and Hooker, 2005)

5. Discussion and conclusions

The sections described herein demonstrate the extreme lateral and vertical variability of the Rutland and White Limestone Formations. Historically, placing the boundaries between the Rutland, White Limestone and Forest Marble formations has been a matter of considerable debate. Horton et al. (1995) placed the boundary between the Rutland and White Limestone formations at an erosive surface between a mudstone unit (Fig. 5, Bed 8 of the Rutland Formation) and an overlying thin shelly detrital marl, presumably reflecting the gradual change towards the more marine conditions of the White Limestone Formation. It is often difficult to distinguish between these two units in the field due to lateral variation across the section and the similarity in lithology between the two units. Consequently we concur with Palmer (1973) and include the lowermost Shipton Member unit of Horton et al. (1995) in the Rutland Formation rather than the White Limestone Formation (Fig. 5).

The boundary placement between the White Limestone and Forest Marble Formations has had a similarly tortuous history. This is in part due to the variability of the formations both vertically and laterally across the area. Horton et al. (1995) place the boundary above the "Upper Epithyris Bed" (Fig. 5, Bed 25) agreeing with many earlier authors (e.g., Hull, 1859; Odling, 1913; Palmer, 1973; Woodward, 1894) whereas McKerrow et al. (1969) and Benton et al. (2005) include most of the Bladon Member (White Limestone Formation) in the Forest Marble Formation. We note that Beds 24 and 25 (Fig. 5) of Horton et al. (1995) appear to be inverted in the section measured at Woodeaton with Bed 24 overlying Bed 25 (the "Upper Epithyris Bed"). This appears to correspond to the section measured at Kirtlington Quarry by Arkell (1931) who notes a grey clay of varying thickness overlying the "Upper Epithyris Bed". Consequently we concur with Arkell (1931) in placing the White Limestone and Forest Marble Formation boundary at the sharply erosive and undulose contact at the base of the strongly cross stratified, oolitic and bioclastic limestones (Fig. 5), with the Forest Marble Formation limited on lithostratigraphical grounds to this facies above the contact.

The microvertebrate fauna recovered from Bed 23 (Bladon Member, White Limestone Formation, Fig. 5) is comparable to that known from the approximately coeval section at Kirtlington Quarry, Oxfordshire (Evans and Milner, 1994). McKerrow et al. (1969) place the microvertebrate horizon at Kirtlington (the "mammal bed", Bed 3p of McKerrow et al., 1969) in the upper part of the "Upper Epithyris Bed" (the equivalent to Bed 25 at Woodeaton Quarry, Fig. 5) whereas Freeman (1979) and Cripps (1986) suggests it forms a distinct deposit lying above this unit, directly below the overlying Forest Marble Formation. This implies that the Bed 23 microvertebrate horizon at Woodeaton is slightly older than Kirtlington.

British Middle Jurassic microvertebrate deposits represent shallow brackish freshwater ponds or lakes, or marginal marine environments, formed on emergent carbonate platforms or restricted shallow lagoons and are geographically quite restricted with a limited aerial extent (Evans and Milner, 1994; Metcalf et al., 1992). The main microvertebrate bearing unit at Woodeaton appears to be the exception; with the *fimbriatus-waltoni* Bed (Bed 23) being widely present locally (e.g. Horton et al., 1995). The facies of this unit suggests that it represents a larger scale brackish water lagoon hemmed in by some form of barrier. Invertebrate and vertebrate biotas suggest a fluctuating salinity so it is likely that periodic influxes of seawater during tides flooded into the area that otherwise had constant supply of freshwater re-supply from the land. Poorly developed calcrete nodules elsewhere in the succession and abundant evidence of biomass burning may suggest at least seasonal aridity. A detailed taphonomic analysis is required to confirm these findings and to underpin any further analyses (other than taxonomic) on the fossils recovered from this bed.

In contrast to the rich chondrichthian faunas recorded from the Great Oolite Group at Woodeaton Quarry and elsewhere (Rees and Underwood, 2008; Underwood and Ward, 2004), Bed 23 is very poor in chondrichthyan remains. The teeth of *Proheterodontus sylvestris*, *Palaeocarcharias* and the small hybodonts are well preserved, but the occurrence of the neoselachians is at odds with the taxa of neoselachians recorded in low salinity deposits elsewhere in the Bathonian (Underwood, 2004), so all or most of these may also be reworked.

The actinopterygian remains are dominated by the teeth and scales of Ginglymodi (a “semionotid”). It is unclear whether there are one or multiple species, but all of the specimens suggest small sized individuals (maybe <0.15 m) with a crushing dentition. There is only a single minute pycnodont specimen (a partial lower jaw with several teeth preserved) recovered to date, despite the fact that pycnodonts are usually very common in rocks of this age and pycnodont teeth are often common in Bathonian limestones (CJU, DJW personal observation). Small jaw fragments assignable to the Aspidorhynchidae are present as well as teeth of Ionoscopiformes. No *Caturus* specimens have yet been identified; teeth of this genus are normally ubiquitous in marine and brackish facies Jurassic microvertebrate samples (CJU, DJW personal observation). These initial finding suggest that the actinopterygian record, at least, is unusual for this time period and seem to comprise a restricted ginglymodid-aspidorhynchid assemblage capable of surviving in shallow waters with fluctuating salinity.

The dinosaur record in the British Middle Jurassic is dominated by larger bodied taxa. Theropods include the tetanurans: *Magnosaurus nethercombensis* (Benson, 2010b; Huene, 1923, 1926a, b) and *Duriavenator hesperis* (Benson, 2008; Owen, 1883; Waldman, 1974) from the Bajocian Inferior Oolite of Dorset; the historically important taxon *Megalosaurus bucklandii* (e.g. Benson, 2010a; Buckland, 1824; Mantell, 1827; Owen, 1842, 1857, 1883; Phillips, 1871) from the Bathonian Taynton Limestone Formation (Stonesfield Slate facies) of Oxfordshire; *Cruxicheiros newmanorum* (Benson and Radley, 2010) from the Lower Bathonian Chipping Norton Limestone of Warwickshire; and *Eustreptospondylus oxoniensis* (Nopcsa, 1905, 1906; Phillips, 1871; Sadleir et al., 2008; Walker, 1964) from the Callovian Oxford Clay of Oxfordshire. With the exception of *Proceratosaurus bradleyi* (Rauhut et al., 2010) from the Late Bathonian of Minchinhampton, Oxfordshire, and other fragmentary remains, smaller-bodied theropod taxa are less well known. The ornithischian record is sparser but again is dominated by larger bodied taxa such as the stegosaur *Loricatosaurus priscus* (Maidment et al., 2008; Nopcsa, 1911); the ankylosaur *Sarcolestes leedsi* (Galton, 1980a; Lydekker, 1893; Vickaryous et al., 2004); the iguanodontid *Callovosaurus leedsi* (Galton, 1980b; Lydekker, 1889; Ruiz-Omeñaca et al., 2007) plus other indeterminate ornithischian remains. . In contrast to the theropods, all named ornithischians from the British Middle Jurassic are from the Callovian Oxford Clay, with only indeterminate material from the Great Oolite Group. Microvertebrate sites such as Woodeaton indicate that dinosaur diversity is higher than previously recognised and demonstrate that small bodied dinosaur taxa were a common and important part of Middle Jurassic terrestrial ecosystems. The presence of dromaeosaurids confirm earlier suggestions that the clade was present in the Middle Jurassic (Evans and Milner, 1994) and support phylogenetic hypotheses that these clades originated during this period (REFERENCE REQUIRED).

The majority of the UK Jurassic mammal-bearing sites are microvertebrate sites and at least 99% of all UK Jurassic mammalian material was recovered through bulk processing of microvertebrate horizons. Unfortunately, taxa are mostly represented by individual (often broken) teeth. As more complete specimens are rare or absent, identification of tooth positions (particularly the anterior dentition), intra-specific variation and deciduous versus permanent dentition are all subject to debate. The synonymisation of *Palaeoxonodon freeman* and *Kennetheridium leesi* with *Palaeoxonodon ooliticus* (Close et al., 2016) is an example of more complete specimens (in this case from the Isle of Skye) being used to re-identify individual teeth known only from microvertebrate sites. As such, estimates of diversity from these sites should be treated with caution. However, the discovery of more complete specimens of related taxa from other sites such as the Isle of Skye and Shandong Province in China (Luo et al., 2017) is helping to address some of these issues and a reassessment of the taxa in these Jurassic microvertebrate sites is now warranted. Regardless of these issues, due to the rarity and small size of Jurassic mammals (Kielen-Jaworowska et al., 2004), microvertebrate sites are fundamental to our understanding of mammalian evolution. An initial assessment of the mammals from Bed 23 at Woodeaton Quarry suggests that the taxonomic composition is broadly comparable to the “mammal bed” from Kirtlington Quarry and a detailed comparison of the mammalian fauna from the two beds is the next stage in the analysis.

Microvertebrate sites are an important source of faunal information, they preferentially preserve small bodied taxa that do not always fossilise well. Microvertebrates are often overlooked or simply not present in the known fossil record as a result of both preservational and sampling biases towards larger taxa. As a result, information from sites such as Woodeaton plays a crucial role in our understanding of ancient ecosystems without which our models are incomplete and skewed.

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. Due to the volume of material to sort, a team of eight volunteers were selected to assist with the sorting and initial identifications. After careful recruiting of volunteers, one day per week was set aside for those involved with the project to work with the volunteers in the Specimen Preparation Area (SPA), within the Natural History Museum, London so we could interact with the public and explain to them what we were doing. A microscope was linked up to a tv screen and members of the public could ask questions via a microphone. Volunteers were trained in the careful handling and manipulation of the specimens. Initially volunteers separated out specimens from the different size fractions into broad taxonomic groups (fish, mammals, amphibians, reptiles and invertebrates). These were then shown to specialists within or associated with the Museum for further clarification and high resolution images were then taken of each specimen, which will be incorporated into the main Museums collection. A senior volunteer started to produce a *Woodeaton Microvertebrate Identification Guide* to assist others, which has been updated throughout the project. By involving volunteers in our project they gained skills in identification of numerous taxonomic groups, public engagement and basic curatorial skills. Staff were able to gain skills in people and project management, practical geological fieldwork and laboratory skills and the importance of communicating to the public what goes on behind the scenes.

List of figures: