PTEROSAURS OF THE ENGLISH MIDDLE JURASSIC

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Abstract : This work is based upon a pterosaur humerus (=the Eyford humerus) of Bathonian age from the North Cotswolds equivalent of the Stonesfield Slate. The horizon from which the pterosaur humerus came was identified in the field, and its exact stratigraphic position and approximate lateral extent determined, near the centre of the Eyford Member (=Cotswold Slates) of the Fuller's Earth Formation. Associated fauna was collected, suggesting a mixture of terrestrial and marine faunas. Collaborative sedimentological evidence suggested that the pterosaur horizon was deposited as a tempestite during or immediately following a strong storm. Erosion of the articular extremities of the humerus suggest some transport before deposition and fossilisation. The humerus was preliminarily identified as the left humerus of *Rhamphocephalus* sp., and was described, compared with other humeri assigned to *Rhamphocephalus*, and to the humeri of other genera. Analysis of this data resulted in the resolution of two, or perhaps three species-groups within the *Rhamphocephalus* humeri studied, including the Eyford humerus. This was backed up by previous work by Seeley (1880). Following detailed analysis of the literature on pterosaurs from the Stonesfield and Cotswold slates, many faults were found in the systematic practices used to erect the genus *Rhamphocephalus* and its three constituent species. As a result, all bones, bar the three original holotypes of the genus and its species, were necessarily reclassified as Pterosauria sp. indet., including the Eyford Humerus. Suggestions were made concerning the reclassification of these bones, and a new genus, *Oolithorhynchus*, was proposed. Suggestions for future studies include a comprehensive review of English Middle Jurassic pterosaurs, beyond the scope of this work; and a study of the functional morphology of the pterosaur humerus, and its relationship to flying style and lifestyle.

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[1] An explanation for their enormous eyes, perhaps!

1.0 INTRODUCTION

Pterosaurs hold an exalted position in the palaeontological firmament, just beneath that of the dinosaurs, in terms of the levels of public fascination that they garner. This is due in part at least to the collateral early history of fossil finds that both groups share. Pterosaurs figure amongst some of the earliest described vertebrate fossils that helped mark the inception of palaeontology as a scientific discipline in the early nineteenth century. As *Megalosaurus* and *Iguanodon* were wowing the Victorian scientific community and public alike, exquisite finds of pterosaurs from southern England and Germany demonstrated an aerial as well as terrestrial distinction between modern and Mesozoic faunas. *Dimorphodon macronyx* from the Lias of Lyme Regis, and *Rhamphorhynchus* and *Pterodactylus* from the Upper Jurassic Solnhofen Limestone of Germany, were amongst the first and most spectacular finds of the time, leading Münster to describe pterosaurs as "most wondrous creatures of the prehistoric world" and Goldfuss (1831) to profess pterosaurs as being more akin to the product of an artist's unbridled imagination than a product of nature.

Following initial description during the early 19th century of the first pterosaurs to be recognised as such, by such notables as Georges Cuvier and William Buckland, the number and diversity of new finds increased considerably. The lithographic limestones centred around Eichstätt and Solnhofen, Germany, proved to be especially prolific, revealing a number of different species, amongst them the first find of a long-tailed, or 'rhamphorhynchoid'[2], pterosaur, *Rhamphorhynchus longicephalus* (MÜNSTER) 1839. In addition, an anatomically diverse short-tailed, or pterodactyloid, pterosaur fauna was discovered to cohabit the Solnhofen lagoons at the same time as *Rhamphorhynchus*. Elsewhere, bones found in the Lower Cretaceous 'Wealden' strata of south east England, originally described by Gideon Mantell as those of a bird (Mantell, 1822, 1827, 1837) were found by Owen (1846) to be those of a pterosaur, and were later assigned by Seeley (1869) to the genus *Ornithocheirus*. In 1870 Othniel Charles Marsh found in Kansas, remains of the Cretaceous aerial giant

[2] Until recently, the accepted wisdom concerning the systematics of pterosaurs separated the Order Pterosauria into two suborders - the Pterodactyloidea and the Rhamphorhynchoidea, and was introduced by Felix Plieninger in 1895 (Wellnhofer, 1991). The rise of cladistics as a systematic tool in the last 25 years has broken down this orthodoxy. While the sub-order Pterodactyloidea is monophyletic and thus still stands, the sub-order Rhamphorhynchoidea is polyphyletic, and long-tailed pterosaurs of the Triassic and Jurassic are now referred to as being of the 'rhamphorhynchoid' grade (note inverted commas), or non-pterodactyloid (Clark *et al* 1998).

Pteranodon - the first pterosaur from North America, and the first giant pterosaur to be found (Wellnhofer, 1991).

<u>**Figure 1:** The Jurassic Period, based upon the GTS 89 definitive time scale (Harland *et al*, 1990).</u>

Period	Epoch	Stage	Age (top)	Duration			
Jurassic	Upper Jurassic	Tithonian	145.6 Ma	6.5 Ma	Malm	11.5 Ma	62.4 Ma
		Kimmeridgian	152.1 Ma	2.6 Ma			
		Oxfordian	154.7 Ma	2.4 Ma			
	Middle Jurassic	Callovian	157.1 Ma	4.2 Ma	Dogger	20.9 Ma	
		Bathonian	161.3 Ma	4.8 Ma			
		Bajocian	166.1 Ma	7.4 Ma			
		Aalenian	173.5 Ma	4.5 Ma			
	Lower Jurassic	Toarcian	178.0 Ma	9.0 Ma	Lias	30.0 Ma	
		Pliensbachian	187.0 Ma	7.5 Ma			
		Sinemurian	194.5 Ma	9.0 Ma			
		Hettangian	203.5 Ma	4.5 Ma			
			208.0 Ma				

Already apparent by the end of the 19th century was the rarity of pterosaur finds of Middle Jurassic age. The reason for this was undoubtedly geological, as most of the Lower and Upper Jurassic pterosaurs had been found in very fine-grained sediments deposited in low energy environments; konservat lagerstätten such as the Solnhofen lithographic limestones and the 'Posidonienschiefer' - bituminous shales of Toarcian age (see Figure 1), centred around Holzmaden, Germany. The formation of such rocks was in accord with the conditions required for the preservation of fragile pterosaur bones, and rocks of comparable preservation potential are a relative rarity in Middle Jurassic strata.

1.1 - Middle Jurassic pterosaurs.

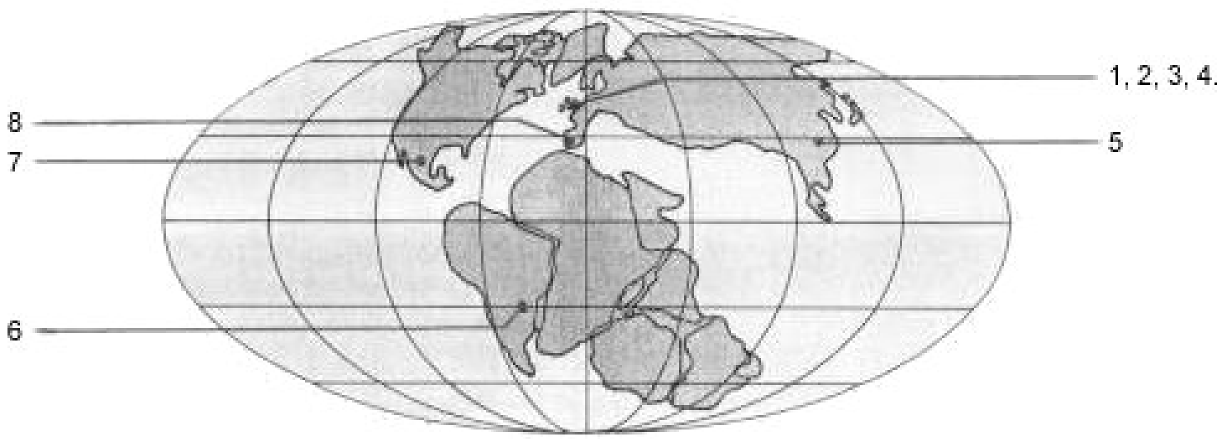
One notable exception which had yielded pterosaur bones of Middle Jurassic age by the early 19th century, was the so-called Stonesfield Slate of Oxfordshire, from which Hermann von Meyer named and briefly described *'Pterodactylus' bucklandi* (Meyer, 1832). Although no articulated bones have been recovered from these deposits as yet, they are preserved, often in their entirety, in three dimensions in a fine-grained matrix, and as such approach the preservation levels found in the aforementioned lagerstätten. Ammonites found in the same strata have enabled assignation of the 'Stonesfield Slate' to the Bathonian stage (see Figure 1).

In the years since Meyer's initial description of the Stonesfield bones, new finds and systematic modifications have resulted in the recognition today of three species of pterosaur from the 'Stonesfield Slate' and equivalent strata. In 1859 T. H. Huxley assigned all 'Stonesfield Slate' bones to the genus *Rhamphorhynchus* MEYER 1846, and described a new species from equivalent strata (Arkell, 1933) at Sarsden, Oxfordshire, which he called *Rhamphorhynchus depressirostris* (Huxley, 1859). H. G. Seeley was the next to deal with pterosaurs of the 'Stonesfield Slate', assigning all bones to the genus *Rhamphocephalus* SEELEY 1880, as well as describing a new species, *Rhamphocephalus prestwichi*, from equivalent strata at Kineton, Gloucestershire (Seeley, 1880).

More recently, a scattering of finds have been made in Middle Jurassic strata worldwide. Xinlu *et al* (1983) described and named a new Middle Jurassic 'rhamphorhynchoid' pterosaur from the enormous dinosaur graveyard of Dashnapu Quarry in Sichuan province, China. The find, named *Angustinaripterus longicephalus*, consists of a well-preserved, almost complete skull (only the back of the cranium is absent) with long alternately biting dentition similar to that of *Dorygnathus* from Holzmaden. With no evidence as yet of the nature of post-cranial elements of *Angustinaripterus*, its affinities to other Middle and Lower Jurassic pterosaurs remain obscure. Eight years earlier, fragmentary skeletal remains from Callovian (see Figure 1) rocks of Neuquén, northern Patagonia, had been described by R. M. Casamiquela (1975) as a coelurid dinosaur, which he named *Herbstosaurus pigmaeus*. However, John Ostrom, who examined the specimen in the course of describing another coelurid dinosaur, *Compsognathus longipes*, came to the conclusion that the pelvis, femur and other remains found were actually those of a 'rhamphorhynchoid' pterosaur (Ostrom, 1978). No further conclusions can be drawn due to the fragmentary nature of the remains.

In 1996, J. M. Clark and colleagues reported the discovery of an uncrushed, exceptionally preserved and articulated partial skeleton of a 'rhamphorhynchoid' pterosaur from Callovian rocks of Tamaulipas, Mexico. Named *Dimorphodon weintraubi*, this skeleton is the most complete Middle Jurassic pterosaur found to date, and has already enabled a reinterpretation of foot posture in primitive pterosaurs (Clark *et al*, 1998). Unfortunately, as yet no detailed description of the whole skeleton has been published. In Portugal, isolated teeth from Upper Callovian rocks have been assigned by R. A. Thulburn (1973) to the genus *Rhamphorhynchus*. Finally, from Hornsleasow, Gloucestershire, as yet unidentified pterosaur bones have been found in a Lower Bathonian palaeokarst (Metcalfe *et al*, 1992). So far, therefore, only eight localities in the world have yielded pterosaur remains of Middle Jurassic age - Stonesfield, Sarsden, Kineton and Hornsleasow (England); Dashnapu, China; Neuquén, Patagonia; Tamaulipas, Mexico; and Portugal (see Figure 2).

Figure 2: Palaeogeographic map of the Jurassic, showing locations of Middle Jurassic pterosaur finds.



1: *Rhamphocephalus bucklandi* - Stonesfield, Oxfordshire, England.
2. *Rhamphocephalus depressirostris* - Sarsden, Oxfordshire, England.
3. *Rhamphocephalus prestwichii* - Kineton, Gloucestershire, England.
4. Pterosauria sp. indet. - Hornsleasow, Gloucestershire, England.
5. *Angustinaripterus longicephalus* - Dashnapu, Sichuan, China.
6. *Herbstosaurus pigmaeus* - Neuquén, Patagonia, Argentina.
7. *Dimorphodon weintraubi* - Tamaulipas, Mexico.
8. *Rhamphorhynchus?* sp. - Portugal.
(Palaeogeographic map based upon Lemon [1993].)

1. 2 - The 'Stonesfield Slate'

This work is primarily concerned with the pterosaur material collected from the Bathonian of southern England, all of which is at present assigned to the genus *Rhamphocephalus*. As mentioned above, most of the material in question was collected either from the 'Stonesfield Slate' of Stonesfield, Oxfordshire or equivalent strata in the north Cotswolds of Gloucestershire, known colloquially as the 'Cotswold Slate', and until recently included in the now defunct (Boneham & Wyatt, 1993) Stonesfield Slate Beds. The rocks from which the fossils were obtained are not slates in the geological sense, but are sandy, fissile limestones, or tilestones, which have been quarried extensively since Roman times (Dreghorn, 1967) for use as roofing tiles. Quarrying of these rocks reached its acme during the 19th and early 20th centuries; correspondingly, most of the *Rhamphocephalus* material was unearthed during this time. The nature of the slating process was amenable to the discovery of small fragile pterosaur fossils - as the slates were split by hand, bones on the bedding planes were invariably noticed and preserved.

Apart from pterosaurs, the tilestones of the Cotswolds and Oxfordshire generally, and the 'Stonesfield Slate' especially, also contain a wide variety of other fossils. The Stonesfield slate draws its fame not so much from the pterosaurs encased within it, as for two other finds. In 1824 William Buckland published the first ever description of a dinosaur, *Megalosaurus bucklandi*, from Stonesfield. Six years earlier, Cuvier (1818) published information concerning the discovery of a lower jaw belonging to a mammal, *Amphitherium prevostii*, in the Stonesfield strata. Although true mammals are now known from the Triassic, for several decades this was the first instance of a pre-Tertiary mammal, and was of great significance to the palaeontologists of the time in demonstrating the antiquity of the mammalian lineage. Other vertebrate material from these strata include the remains of numerous fish and sharks, a tortoise, *Testudo stricklandi*, an ichthyosaur, a plesiosaur and two species of *Teleosaurus*, a marine crocodile. In addition there exists an abundance of plant and invertebrate remains (Phillips, 1871; Richardson, 1929; Sellwood & McKerrow, 1974).

Tilestone production declined precipitously throughout the 20th century, halting altogether in Stonesfield. Consequently, the incidence of new fossil discoveries decreased correspondingly. The 'Cotswold Slate' is still quarried in the region of Eyford and Kineton, about 6 kilometres west of Stow-on-the-Wold, but for road aggregate (for which it is ideal due to its comparatively high sand content) rather than for tilestones. Demand for tilestones is still high, however, especially at present, due to the need for renovation of old buildings and the demand for new houses built using traditional materials. This has resulted in the recent implementation of an MSc. at Cheltenham & Gloucester College of Higher Education investigating the viability of reinitiating tilestone production.

Figure 3: Southern Britain, showing area in the north Cotswolds of Gloucestershire, where fieldwork pertaining to this work was carried out.

1. 3 - Stratigraphic relationships

A new find - a three-dimensionally preserved, almost complete, pterosaur humerus, forms the basis of this work. The fossil in question was found in the 1970's by Michael Bishop and Michael Oates in a small quarry at Eyford, near Kineton, Stow-on-the-Wold, Gloucestershire, (see Figure 3) and was subsequently loaned to David Martill at Portsmouth University. The rocks from whence the fossil came belong to the Eyford Member (=Cotswold slates) of the

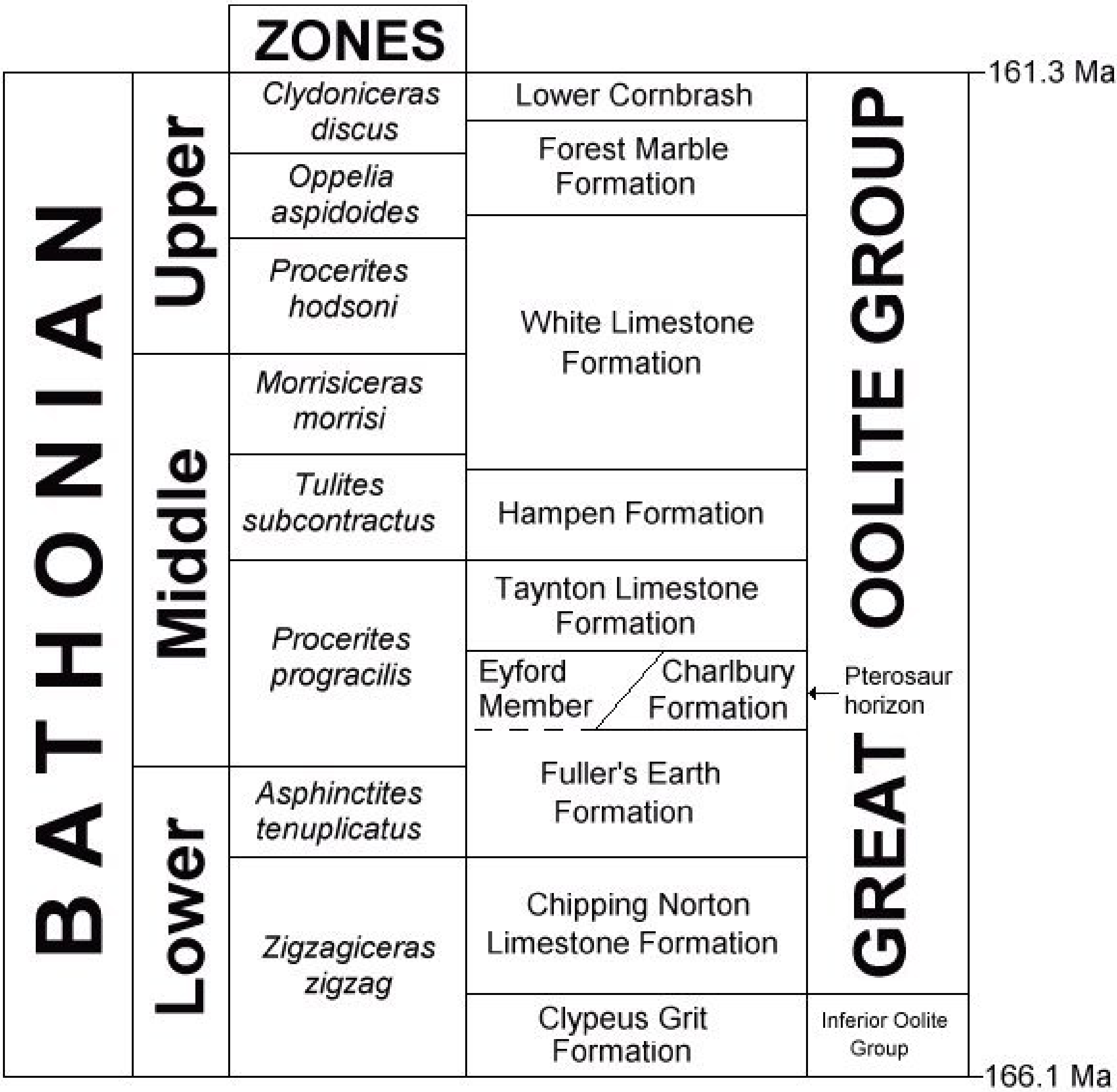
Fuller's Earth Formation (see Figure 4) and as mentioned previously are at approximately the same stratigraphic level as the tilestones of the 'Stonesfield Slate', which occur at several horizons within the Charlbury Formation (see Figure 4) at Stonesfield, Oxfordshire.

Debate presently rages over the stratigraphic relationships of the various fissile arenaceous limestone beds that were in the past assigned to the Stonesfield Slate Beds. This is especially motivated by the fact that the 'Stonesfield Slate' has been regarded as the type horizon of the *Procerites progracilis* Biozone of the Bathonian stage (see Figure 4); consequently, an understanding of its stratigraphic relationships is especially important (Boneham & Wyatt, 1993). Early researchers such as Richardson (1929, 1933) and Arkell (1931, 1933) included all fissile tilestones of Middle Bathonian age, on both sides of the Moreton Hinge[3], as belonging to the Stonesfield Slate Series, and always underlying the Taynton Limestone Formation. Sellwood & McKerrow (1974) then erected the Eyford and Stonesfield Members for the Gloucestershire and Oxfordshire tilestones respectively.

Subsequent re-examination of the 'Stonesfield Slate' proper (McKerrow & Baker, 1988; Boneham & Wyatt, 1993) revealed that the 'Stonesfield Slate', at Stonesfield at least, is a recurrent lithological facies rather than a formal lithostratigraphical unit. Boneham & Wyatt (1993) consequently erected the Charlbury Formation to include all strata, including tilestones, above the underlying Sharp's Hill Formation and below the base of the Taynton Limestone Formation. In this and later studies by Wyatt (1996, 1999), the Eyford Member was subsumed into the Charlbury Formation. Sumbler (1999), however, disagrees with this arrangement, claiming that the coastal nature of the Sharp's Hill Formation in Oxfordshire does not extend past the Moreton Hinge into Gloucestershire, where the fully marine Fuller's Earth beds replaces it. Neither, he feels, does the Charlbury Formation extend beyond the Moreton Hinge, and attributes any tilestones in this area to the Eyford Member of the Fuller's Earth Formation. As this is the version used by the British Geological Survey (BGS) in their memoirs (Barron, 1999) and lexicon of named rock units (BGS website), this is also the lithostratigraphical framework that will be favoured in this study (see Figure 4).

[3] A NNW-SSE trending positive structure between Stonesfield and the north Cotswolds, over which the Eyford Member/Charlbury Formation are thin or absent. Called the Moreton Axis, Swell and Anticline by various researchers.

Figure 4: Lithostratigraphic and Biostratigraphic subdivision of the Bathonian stage.



Absolute dates drawn from GTS 89 definitive time scale (Harland *et al* 1990). Biostratigraphic data drawn from Torrens (1969). Lithostratigraphic data drawn from Sumbler (1999).

1. 4 - Aims

The aims of this work are as follows:

(i) To identify the exact horizon from whence the aforementioned humerus was derived;

(ii) To describe the geological and palaeoenvironmental setting in which the bone was found;

(iii) To deduce taphonomic processes leading to fossilisation;

(iv) To identify the specimen as accurately as possible;

(v) To compare and contrast the specimen to the humeri of other pterosaurs;

(vi) To assess the validity of all names assigned to pterosaurs of the Middle Jurassic, in particular the genus *Rhamphocephalus*.

2.0 METHODOLOGY

2. 1 - Fieldwork

Fieldwork pertaining to this work was carried out from the 2nd to the 19th of September, 1999. Fieldwork was undertaken in the Kineton and Eyford region of the north Cotswolds, around six kilometres to the west of Stow-on-the-Wold (see Figure 5). Using the most recent 1:50,000 geological map of the area - Sheet 217, Moreton-in-Marsh (Richardson, 1929[4]) (Figure 5), the outcrop of the Eyford Member[5] was projected onto a 1:25,000 Ordnance Survey map of the area[6] (see Figure 6). All quarries (disused and active) falling within or nearby the outline of the Eyford Member outcrop were then marked on this map. British Geological Survey Memoirs (Richardson, 1929, 1933; Barron, 1999) and relevant scientific papers (McKerrow & Baden-Powell, 1952; McKerrow *et al*, 1964; Sellwood & McKerrow, 1974; Wyatt, 1996; Sumbler, 1999) and books (Dreghorn, 1967; Ager *et al* 1973) were of particular assistance during fieldwork.

In collaboration with the relevant 1:10,000 Ordnance Survey maps of the area, these localities were subsequently visited, on foot, using as a base the campsite at Cotswold Farm Park (circled on map, grid reference: SP 11232670). Disused quarries were visited first, to identify any *in-situ* exposures still present and attempt to identify the source horizon of the pterosaur humerus[7]; the remainder of the fieldwork was spent studying the strata exposed in active quarries. These quarries are indicated on Figure 6, and their exact locations are as follows: Huntsman's Quarry, grid reference SP 125255; Brockhill Quarry, grid reference SP 134239 and Grange Hill Quarry, grid reference SP 113244. No natural *in-situ* exposures were observed in the area, on account of the nature of the countryside - rolling hills covered in a thick layer of soil and vegetation. Likewise, no road cuttings were observed.

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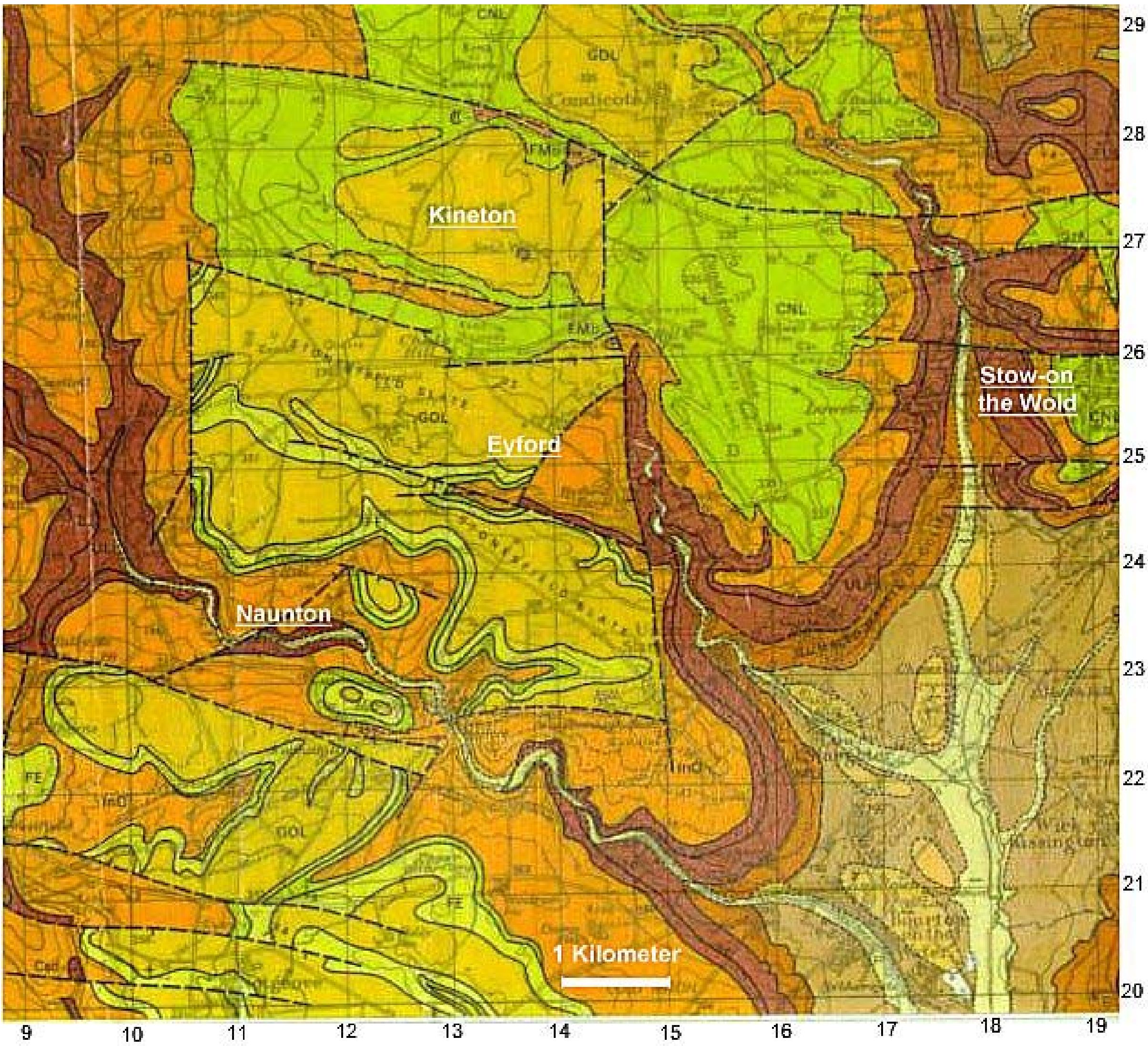
[4] The area under study is the last in Britain to be re-mapped by the British Geological Survey, and no updated 1:50,000 geological map of the area has as yet been published. Subsequently, the map referred to is essentially that of Richardson (1929), with some modification of terms by later authors.
[5] Equal to the 'Stonesfield Slate' of Figure 5 (see section 1.3 for explanation of differing terms).
[6] Ordnance Survey 'Outdoor Leisure' series Nº 45 - The Cotswolds. (Figure 6)
[7] Designated the 'Pterosaur horizon' until further notice.

Figure 5: Extract from 1:50,000 British Geological Survey map - Sheet 217 (Moreton-in-Marsh), showing region where fieldwork was undertaken.



GOL - Great Oolite; InO - Inferior Oolite; FE - Fuller's Earth; CNL - Chipping Norton Limestone; ULi - Upper Lias; FMb - Forest Marble

2. 2 - Problems encountered during fieldwork

Problems encountered which hindered one or more aspects of data collection during the period outlined above are detailed below:

(i) High rainfall, especially during the second week of fieldwork, resulted in some of the lower-level exposures at quarries being submerged underwater. This was especially problematic at Grange Hill Quarry and the northern, disused section of Huntsman's Quarry.

(ii) Complicating matters further was the extreme paucity of genuine *in-situ* outcrops in the study area. Only the three aforementioned quarries and a small, reopened 'disused' quarry[8] afforded such luxuries.

(iii) The very slightly dipping strata coupled with the slope of the floor of the quarry meant that the pterosaur horizon was particularly poorly exposed at the Huntsman's Quarry main working face - unfortunate circumstances considering this was the most extensive exposure in the region under study.

(iv) The owner of Brockhill quarry, Julian Palmer, was less than forthcoming when asked for permission to enter his quarry. As studying the exposed section at this quarry was essential to this work, fieldwork was undertaken there on the only day possible - a Sunday, when quarrying was not taking place. However, the weather conspired to make this a difficult and imperfect survey.

(v) The hardness of the pterosaur horizon meant that even with a 2lb geological hammer and great expenditure of brute force, breaking up the rock to search for fossils and take samples proved difficult.

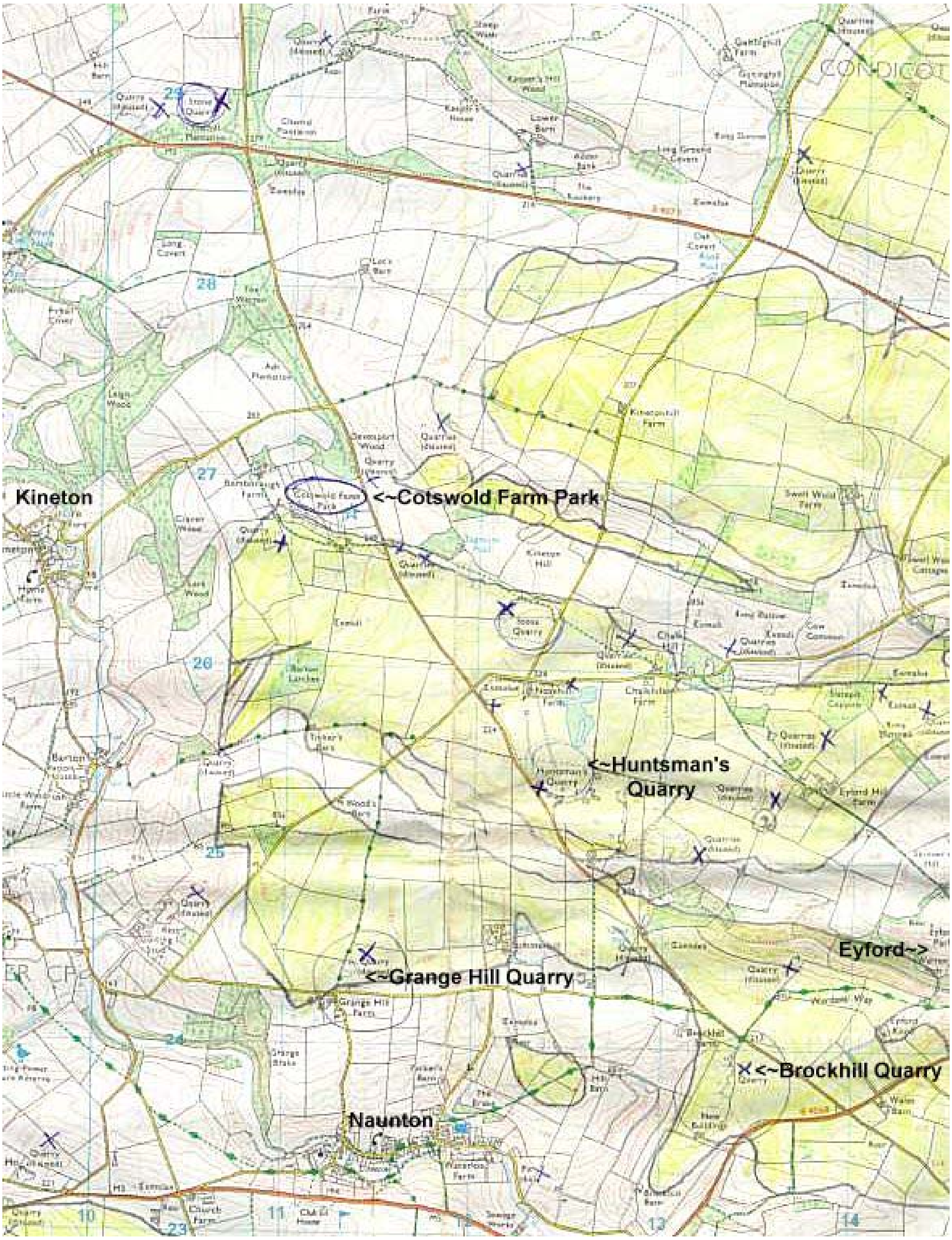
2. 3 - Museum work

Identification of the pterosaur humerus was undertaken by comparing it both to bones previously collected from Middle Jurassic strata in England (i.e. *Rhamphocephalus* specimens from Stonesfield, Sarsden and Kineton), and to the humeri of pterosaurs from other localities. The two museums ideal for this purpose were the Oxford University Museum of Natural History, Parks Road, Oxford, and the Natural History Museum, London. Most, if not all, of the *Rhamphocephalus* material collected to date is held at these museums, and the Natural History Museum, in keeping with its position at the forefront of palaeontological research and curation, also possesses a diverse collection of pterosaur fossils, or fossil casts, from around the world.

The Oxford University Museum of Natural History was visited from the 20th to the 23rd of September, 1999, with the permission of the vertebrate palaeontology chief curator, Dr. Phillip Powell. In the museum's possession were many specimens assigned to *Rhamphocephalus*, a number of which were complete, although all were individual,

[8] Termed 'Eyford Hill Quarry' in this work, this small (30m x 20m), unnamed quarry seemed to have been reopened to supply tilestone for the purpose of re-roofing a nearby building under construction at the time.

Figure 6: Extract from 1:25,000 Ordnance Survey map, Outdoor Leisure N^{o} 45 - The Cotswolds, showing area fieldwork was undertaken and localities visited.



[---------------------]
1 km

disarticulated bones; only one complete humerus was found. The most complete specimens, and any others deemed to be of interest, were drawn, briefly described, and photographed from above, using a centimetre scale. All associated information, such as locality information, previous descriptions and figures, and any other available data, was noted in a notebook.

The Natural History Museum, London, was visited at various times during November and December, 1999, with the permission of the vertebrate palaeontology curator, Sandra Chapman. Several more specimens assigned to *Rhamphocephalus* were in the museum's possession, including specimens from Eyford. Again, all specimens were individual, disarticulated bones; four humeri were present - two complete specimens (although small), one partial specimen and one questionable specimen. In addition, the humeri of a number of other pterosaurs were studied, including, among others, specimens of *Pterodactylus*, *Rhamphorhynchus*, *Dimorphodon macronyx*, *Sordes pilosus*, *Ornithocheirus* and *Pteranodon*. Methods of data collection were as for Oxford.

Work undertaken at the above museums was not without its problems. At Oxford, a number of the more scientifically important specimens, including some holotype specimens for *Rhamphocephalus* species, had been borrowed since 1990 by Dr. David Unwin, and were therefore unavailable for study. In addition, some of the material, although seemingly encased in matrix characteristic of lithologies encountered during fieldwork, was labelled as originating from Stonesfield. If the locality information was indeed erroneous, it may have been due to the actions of a past curator at the museum, whom upon receiving material from a private collection labelled only as having been collected from the Stonesfield Slate, may have assigned it as having been collected at Stonesfield itself.

2. 4 - Preparation of the pterosaur humerus from its encasing rock

In order to better study all aspects of the humerus, and to aid identification, it was decided that it would be advantageous to prepare the bone out of its encasing rock. This was carried out in November of 1999, previous to the second visit to the Natural History Museum, London, so that the bone could be more thoroughly compared with the specimens available there. Preparation revealed the medial view of the bone for study, and enabled more accurate measurements to be taken.

Preparation was undertaken by hand, using a mounted needle, a dental scraper, a small chisel and a toffee hammer, under a bright lamp. Delicate work was undertaken under a binocular microscope at low magnification. The bone is very slightly crushed, resulting in much cracking of the surface layer; consequently great care had to be taken not to disturb any potentially loose flakes. Acetic acid was not used at any point, as this may have dissolved the carbonate matrix within the hollow bone, and seriously impaired the bone's stability. Halfway down the shaft, the distal end of the bone had been broken and subsequently glued back on to the rock, using excessive amounts of glue, by its previous holder. Accordingly, this also had to be removed, in part using a pair of tweezers. Preparation of this bone was surprisingly difficult; after completion of the preparation, the bone was recovered in full from its matrix, with no loss of material. See Plates 1 and 2 for photographs of the humerus pre- and post-preparation from the encasing rock.

2. 5 - Dissolving rock samples for associated vertebrate fauna

Following fieldwork, samples of rock collected from the pterosaur horizon and the beds directly above it were dissolved in 10 % acetic acid in an attempt to find any more vertebrate remains. Insect and plant material, known to derive from these strata, would also be exposed this way.

Plate 1: Pterosaur humerus encased in rock prior to preparation.

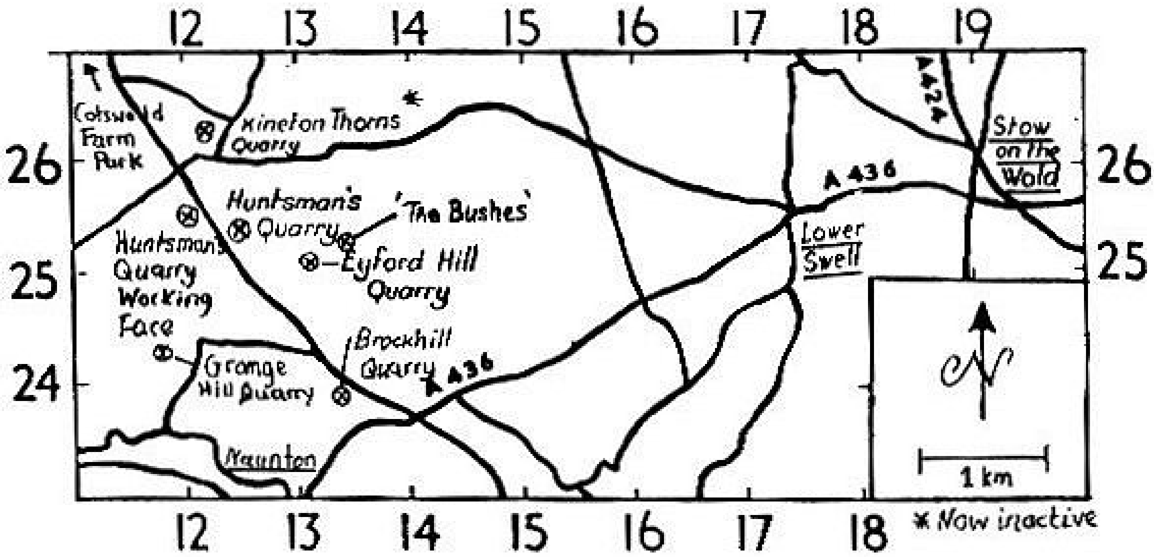
Plate 2: Pterosaur humerus prepared from encasing rock.

3.0 GEOLOGICAL ASPECTS

3. 1 - General account of the geology in the area under study

The area under study falls within the region covered by the SP 12 SW and SP 12 NW 1:10,000 sheets of the Ordnance and British Geological Surveys. All sites visited are marked on Figure 6. Previous surveyors of this area include Richardson (1929), Barron (1999) and (Sumbler, in press) for the British Geological Survey, and McKerrow *et al* (1964) and Ager *et al* (1973) for the Geologists' Association. These publications are of limited use; Barron (1999) deals only with the region covered by the SP 12 SW sheet (Naunton), Sumbler has not yet completed the technical report concerning the northern part of the area under study (SP 12 NW - Chalk Hill), and most if not all exposures studied by Richardson (1929), and to a lesser extent, McKerrow *et al* (1964) and Ager *et al* (1973), have become overgrown or quarried to a lesser or greater extent. Notwithstanding some exceptions, however, the main exposures (i.e. the active or recently restored quarries) studied in this work correspond with those studied by the above authors (see Figure 7).

Figure 7: Map showing main exposures studied in the region of Naunton and Eyford.



The oldest geological formation which outcrops within the area under study is the Lower Jurassic Whitby Mudstone Formation, restricted to some of the valley bottoms. The Inferior Oolite Group overlies the Liassic rocks, composed chiefly of limestone beds, and is separated into three formations - the Birdlip Limestone, Aston Limestone and Salperton Limestone Formations (Barron, 1999). Overlying the Inferior Oolite Group in turn is the Great Oolite

Group, which is fully subdivided into the formations outlined in Figure 4. The youngest solid formation in the area is the Forest Marble Formation. Dip of the beds is very slight to non-existent (0.5 - 1.5° to the south-east), but can vary locally, due to fault movements or cambering. Major and minor faults can be observed in the area - main faults are depicted in Figure 5; some valleys approximately follow the line of faults, although several do not.

The specific lithostratigraphic unit under study is the Eyford Member of the Fuller's Earth Formation. The Eyford member has a variable sandy limestone/calcareous sandstone overall lithology, and is developed to its maximum thickness of circa 7 metres in the region around Huntsman's Quarry (SP 121256) (Sumbler, 1999). This thickness can vary considerably, however, due to rapid facies variation in the Fuller's Earth Formation (Barron, 1999) coupled with an erosive base to the overlying Taynton Limestone Formation. Rather than undergoing a comprehensive survey of the geology of the area, exposures of the Eyford Member specifically were sought out for the purpose of determining the lithostratigraphical position and lateral extent of the pterosaur horizon.

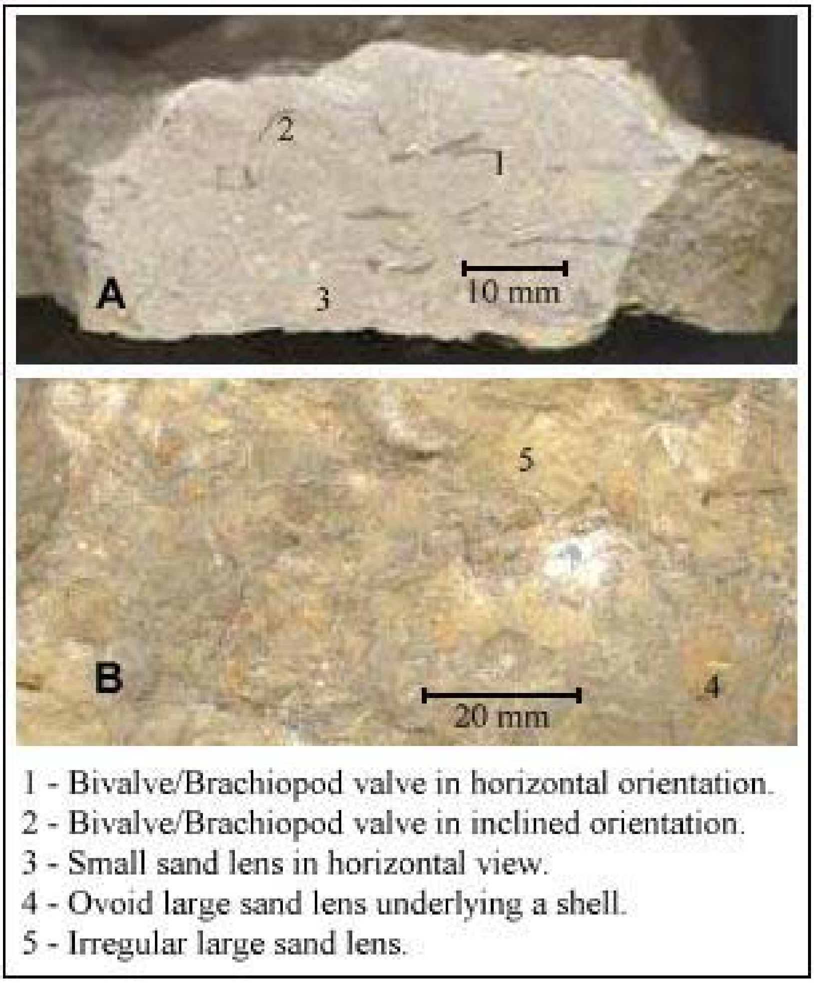
3. 2 - Description of the rock encasing the pterosaur humerus.

In order to aid identification of the pterosaur horizon, the rock in which the pterosaur humerus was encased was studied carefully prior to fieldwork. The rock is a light grey, bioclastic sandy limestone, with grain size variably fine to medium sand. The sand gives the rock a mottled-yellow appearance under a hand lens. The sediment is cemented by small sparite crystals. No laminations are visible; ooids[9] (generally < 1mm diameter) are scattered within the rock in a random manner. Particles, including bioclasts, fine upwards slightly. The rock is very fossiliferous, although not to the point of being bioclast-supported. The majority of the bioclasts are indeterminate (shells are only seen in cross-section) disarticulated valves of brachiopods and bivalves. There is little evidence of any current sorting - although some shells are horizontal, others are positioned randomly in the sediment. The rock is permeated with sand lenses which are friable and range from yellow-brown to orange in colour. The sand lenses can be separated into two classes; large (up to 30mm in diameter) lenses, many of which are ovoid in outline and some of which underlay shell valves; and small (circa 1mm diameter) irregularly shaped lenses. Of the above described features, the characteristics most useful for identifying this rock in the field were the presence of sand lenses, the abundance of

[9] In the Stonesfield Slate and tilestones of the Cotswold Slate, oolitic laminae are present (often no more than one ooid in thickness) which account for the fissility of these rocks.

disarticulated bivalve/brachiopod valves, and the fine-grained and very hard nature of the rock (see Plate 3).

<u>**Plate 3**: ***A*** - Polished vertical section of the rock in which the pterosaur humerus was encased; ***B*** - Underside of the rock in which the pterosaur humerus was encased.</u>



<u>3. 3 - Identification of the pterosaur horizon in the field.</u>

After visiting twenty one disused and three active quarries in the region shown in Figure 6, the pterosaur horizon was found *in-situ* at only three localities - Eyford Hill Quarry, 'The Bushes' and the working face at Huntsman's Quarry (See Figure 7), all of which are geographically adjacent to each other. In addition, *ex-situ* blocks of the pterosaur horizon were discovered at two disused quarries - Eyford Hill Farm Quarry and Cotswold Farm Park Quarry (see Figures 6 and 7). At Brockhill and Grange Hill active quarries, the Eyford Member was exposed but the pterosaur horizon was not. The remaining disused quarries were either overgrown with no exposed *in-situ* rocks, or contained small exposures of lithologies absent in the Eyford Member.

3. 3. 1 - Eyford Hill Quarry

Mick Oates, who along with Mike Bishop found the pterosaur humerus in the 1970's, stated in correspondence that the fossil was found in a rarely used small quarry near Huntsman's Quarry, accessed by a track leading to Eyford Park. Finding the quarry based upon this information was difficult but eventually successful. Eyford Hill Quarry (grid reference SP 13032506) is labelled on the 1:25,000 Ordnance Survey map (see Figure 6) as a disused quarry, but was clearly still active on a small scale, supplying tilestones to a nearby house which was in the process of being reroofed during fieldwork. Blocks of the Eyford Member had been laid out on the quarry floor for frost-splitting into a thickness suitable for roofing tiles (see Plate 4, A).

Figure 8: Eyford Hill Quarry, plan view.

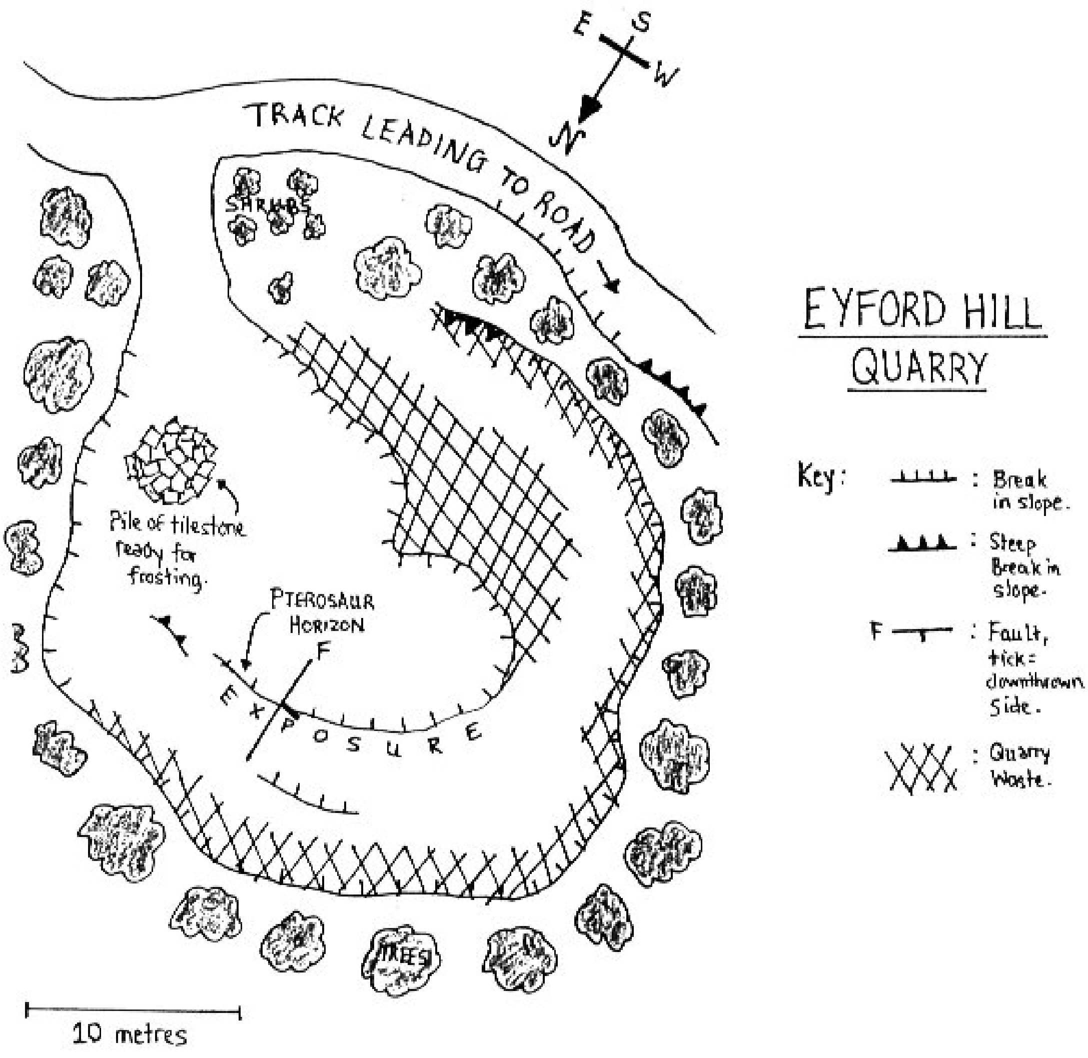
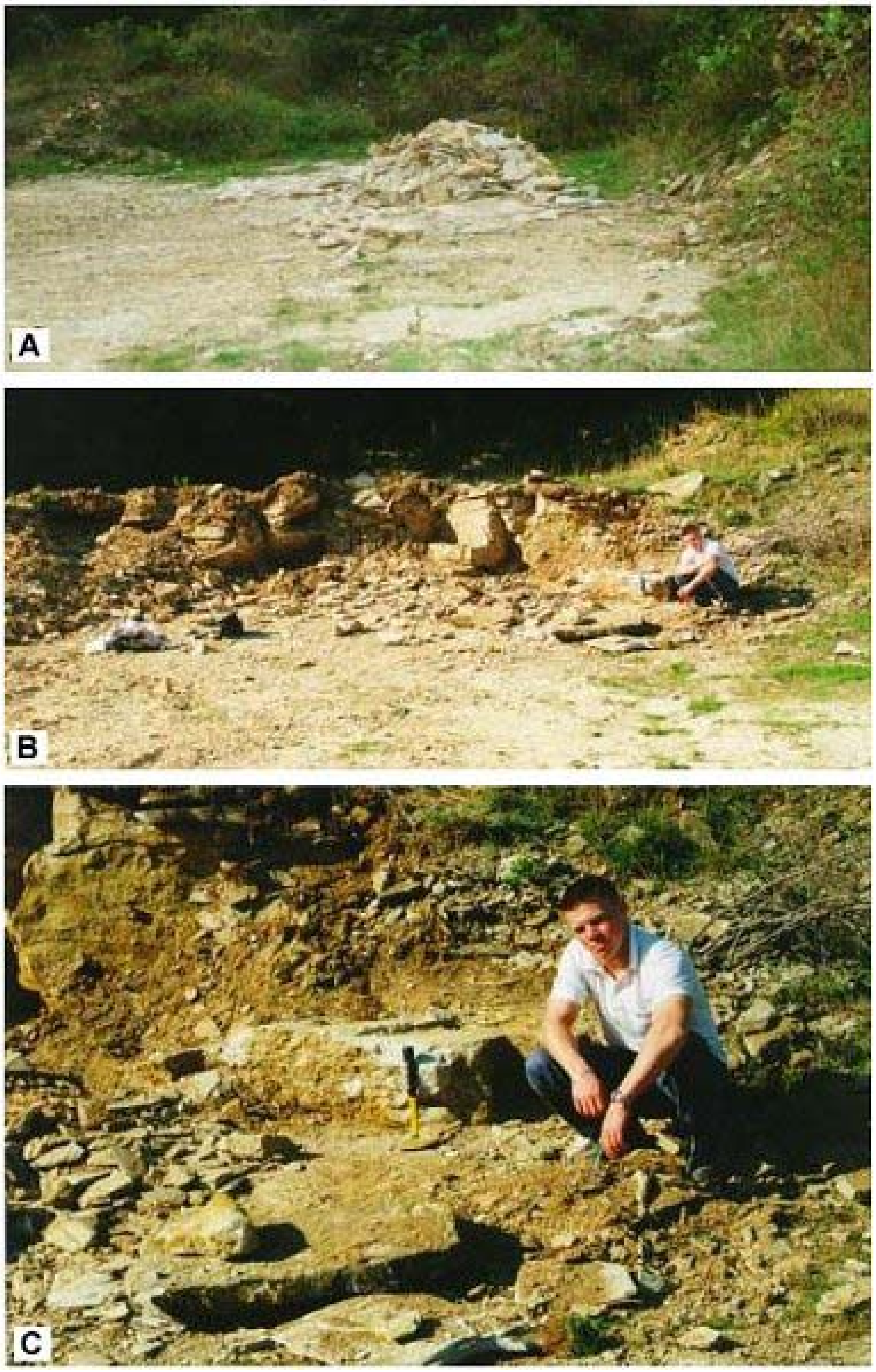


Plate 4: ***A*** - Blocks of the Eyford Member laid out on the floor of Eyford Hill Quarry for frost-splitting into tilestones. ***B*** - Eastern end of exposure at Eyford Hill Quarry. The pterosaur horizon is exposed where the figure (Rhys Whalley) is crouching. ***C*** - Close-up of ***B***, with geological hammer indicating position of pterosaur horizon.



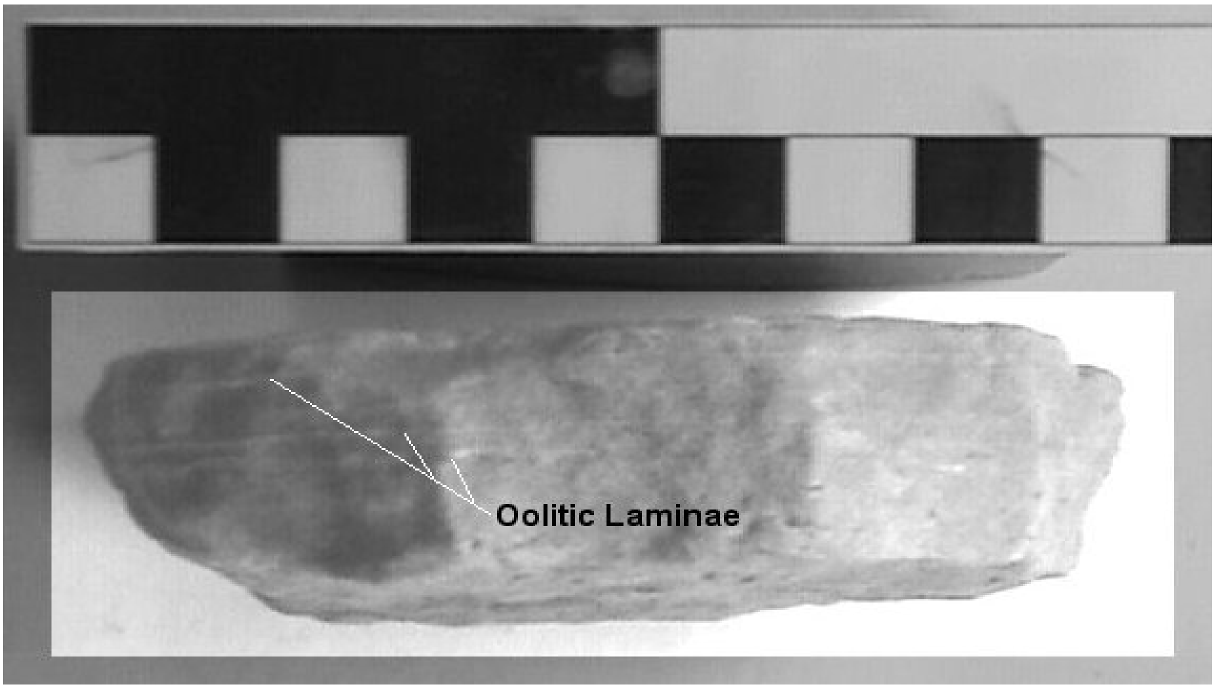
Eyford Hill quarry is accessed by a dirt track leading to the main north-west → south-east trending road which passes Huntsman's Quarry. *In-situ* exposures are located at the northern end of the quarry opposite its entrance; much of the rest of the quarry is covered in waste (see Figure 8). The rocks exposed alternate between sandy limestones and calcareous sandstones; the latter are weathered to an orange sand in places. No calcareous mudstones characteristic of the Fuller's Earth Formation or cross-bedded oolites characteristic of the Taynton Limestone Formation were exposed in this quarry; thus all rocks exposed could be attributed to the Eyford Member.

The exposure at this quarry (see Plate 4, ***B***) is crescent-shaped, trending east-west. Its maximum thickness is only 1.5 metres, and it is not laterally extensive, measuring approximately 15 metres in length. A small dip-slip fault intersects the exposure 3 metres in from the eastern extremity, with the downthrown block to the west. The throw of the fault is minimal - 0.8 metres, and can be observed by the matching of beds on either side. It is within the upthrown block, near the base of the exposure, that the pterosaur horizon can be observed. It is not exposed to the west of the fault. The pterosaur horizon is identifiable by the high concentration of disarticulated brachiopod and bivalve valves seen in section, and by the concentration of yellow/orange sand lenses, which reduce in size upwards.

For a detailed description of the succession at Eyford Hill Quarry, see Appendix 1. What follows is a synopsis of this description and its accompanying graphic log. The base of the section consists of 50 mm of a fissile laminated calcareous sandstone (Unit 1), often decalcified to a friable rottenstone. Above this is a laminated sandy limestone (Unit 2), which is largely unfossiliferous, contains small sand lenses in the upper 30 mm and is gradational into the next unit. Unit 3 is the pterosaur horizon, and is 0.26 m thick at this locality. Sand lenses and fossils fine upwards, and there is some evidence of *Skolithos* burrows at the top of the unit. The top of the unit is rippled. Overlying the pterosaur horizon, Unit 4 is 0.11 m thick and is of identical lithology to Unit 1, albeit more fossiliferous. The laminae surfaces are covered by a layer of ooids one ooid thick, which explains the rock's fissile nature[10] (see Plate 5). Unit 5 is at least 1 m thick (its top appears to have been quarried away), and consists of a series of beds of largely uniform lithology, with localised low angle cross-bedding towards the top of the unit and thin death assemblages often comprising the bed boundaries. It is otherwise sparsely fossiliferous. (See Appendix 1, Log 1.)

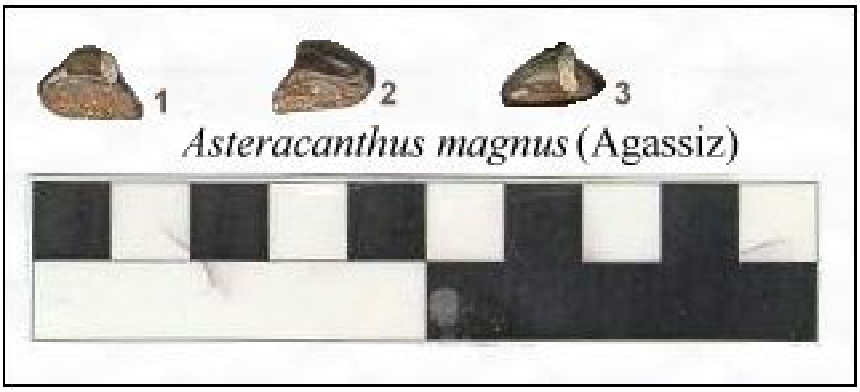
[10] This phenomenon can also be seen in rocks of the Stonesfield Slate.

Plate 5: Sample of unit 4, Eyford Hill Quarry, showing oolitic laminae.



Fossils were moderately abundant at this locality but were often fragmentary. The most fossiliferous rocks were units 3 and 4 - the pterosaur horizon and overlying calcareous sandstone. Apart from the marine invertebrate fauna described above, unidentifiable in section, the pterosaur horizon also contained various small fragmentary pieces of bone, plant matter and insect carapaces (e.g. *Buprestidium egertoni*), of terrestrial origin. From the overlying fissile calcareous sandstone, more fragmentary bone, plant and insect material was found, both on the bedding planes of the laminae and within the laminae. In addition, the tooth of a shark, *Asteracanthus magnus*, was recovered from this unit (see Plate 6), revealing the amalgamation of fossils of both marine and terrestrial origin into these sediments.

Plate 6: Grinding tooth of the shark *Asteracanthus magnus*, recovered from unit 4 at Eyford Hill Quarry (1 - lingual view, 2 - labial view; 3 - occlusal view).



3. 3. 2 - 'The Bushes'

'The Bushes' is the name given by quarry workers at Huntsman's Quarry to an old, disused part of the quarry which has been recently restored to arable land, but where a sizeable north-south trending face is still exposed. It is located at the eastern extremity of the quarry (Grid reference SP 13002540) in what is now a field belonging to Chalk Hill Farm, and is about 350 m directly north of Eyford Hill Quarry. The exposed face is approximately 300 m in length, and reaches a maximum height of 5 m. Both the Eyford Member and the Taynton Limestone Formation are exposed at this locality; the latter is seen to considerably overstep the former to the north. As a result, the most complete section of the Eyford Member at this locality can be seen at the southern end of the face, which although lower in height exposes more of this lithology than to the north.

The pterosaur horizon is exposed for approximately 10.5 m at this exposure (Grid reference SP 12962544), following which it dies out laterally to the north, and does not reappear further along the face (see Plate 7, Figure 9). Again it can be identified by its relative hardness, the numerous disarticulated bivalve and brachiopod valves seen in section on a fresh surface, and the abundant sand lenses present within the rock. Rocks of the Eyford Member at this locality are more decalcified than at Eyford Hill Quarry, probably as a result of longer exposure of this old rock face to weathering. A beneficial side-effect of this process is that some of the more resilient shells in the pterosaur horizon have partially weathered out, enabling their identification as the bivalves *Trigonia impressa* (see Plate 8), *Lima cardiiformis* and *Plagiostoma subcardiiforme*. A fragment of a rhynchonellid brachiopod was also observed.

For a detailed description of the succession at 'The Bushes', see Appendix 1. What follows is a synopsis of this description and its accompanying graphic log. The base of the section consists of 0.3 m of a heavily bioturbated sandy limestone (Unit 1), easily identified and therefore useful as a marker bed. Above this is 20 mm of grey-green clay (Unit 2), followed by a fissile, laminated calcareous sandstone 0.13 m in thickness (Unit 3). Above this unit is the pterosaur horizon (Unit 4) which is 0.2 m thick at this locality. Again, sand lenses and fossils fine upwards, and there is evidence of *Skolithos* burrows at the top of the unit. Unit 5 is a gradational continuance of unit 4, albeit less fossiliferous. Units 6, 7 and 9 and are all calcareous sandstones of similar lithology to unit 3, exhibiting varying degrees of lamination and fossil content. This variation may be an artefact due to varying amounts of weathering.

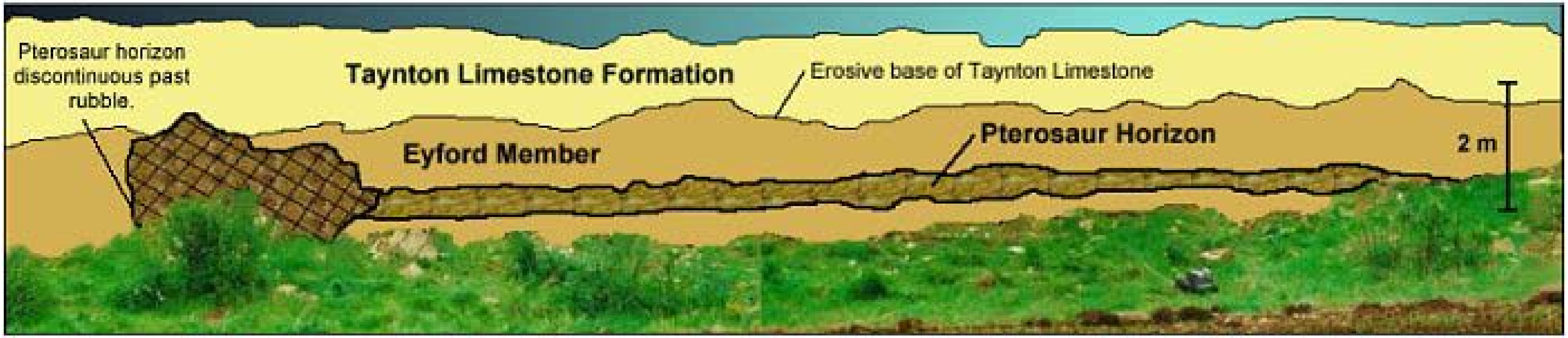


Plate 7 (top)**:** Composite photograph of the old quarry face at 'The Bushes', (SD 129254) where the Eyford Member, pterosaur horizon and Taynton Limestone Formation are all well exposed.

Figure 9 (bottom): Vertical map of the exposure depicted in Plate 7, showing limited lateral extent of pterosaur horizon, and the erosive, non-sequential disconformity at the base of the Taynton Limestone Formation.

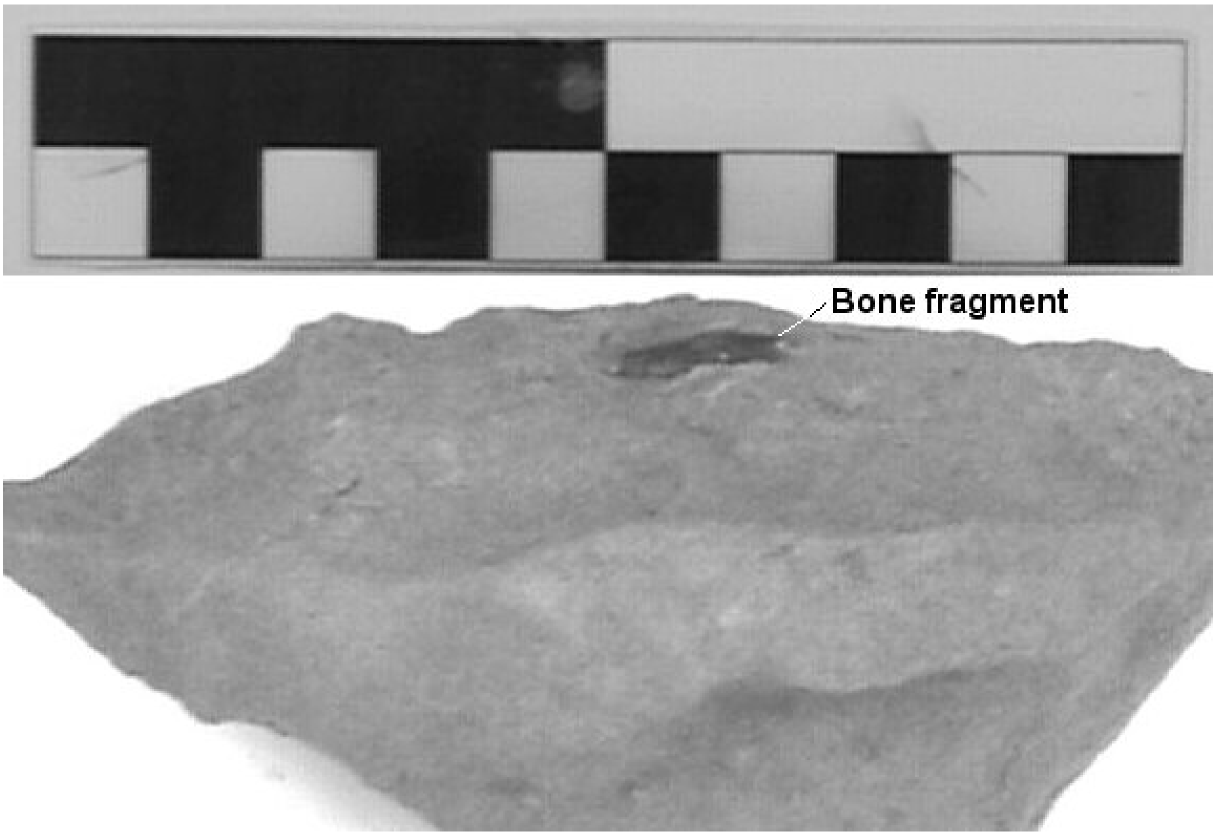
Unit 8 is a thin 20 mm layer of sandy clay. Units 6 to 9 measure 0.35 m in thickness collectively. Unit 10 is of similar lithology to the underlying units, but exhibits low angle cross-bedding. Fossils are rarer in this unit than below. Unit 11 is 50 mm thick, and is a much decalcified, calcareous sandstone with some clay. Unit 12, a laminated, low angle cross-bedded sandy limestone, is the uppermost unit of the Eyford Member exposed at this locality, and is 0.32 m thick, exhibiting cross-stratification in places and being almost completely devoid of fossils. Unit 13 is the base of the Taynton Limestone Formation, and exhibits a scoured base representing a non-sequential disconformity between that formation and the Eyford Member. The unit is a jointed and flaggy oolitic and shell-fragmentary limestone, and is heavily cross-bedded. (See Appendix 1, Log 2.)

Fossils were generally more difficult to find at this locality than at Eyford Hill Quarry, due to the highly weathered nature of many of the calcareous sandstones. The most fossiliferous rocks were units 3, 4, 7 and 9 - the pterosaur horizon and the less weathered of the surrounding units of calcareous sandstone. In contrast to Eyford Hill Quarry, some of the marine invertebrates in the pterosaur horizon could be identified as they weathered out of the rock, as mentioned above. *Trigonia impressa* (see Plate 8) in particular, was very numerous and distinctive[11]. The pterosaur horizon also contained various small fragmentary pieces of bone, plant and possible insect material of terrestrial origin. From the surrounding fissile calcareous sandstones, more fragmentary bone (see Plate 9), plant and insect material was found.

Plate 8: Fragments of *Trigonia impressa*, recovered from the pterosaur horizon at 'The Bushes'.

[11] *Trigonia impressa* is a bivalve unique to the Stonesfield Slate and Eyford Member (Boneham & Wyatt, 1993), and can therefore be used as a marker fossil.

Plate 9: Indeterminate bone fragment typical of that found in Eyford Member, recovered from Unit 7 (see Appendix 1, Log 2) at 'The Bushes'.

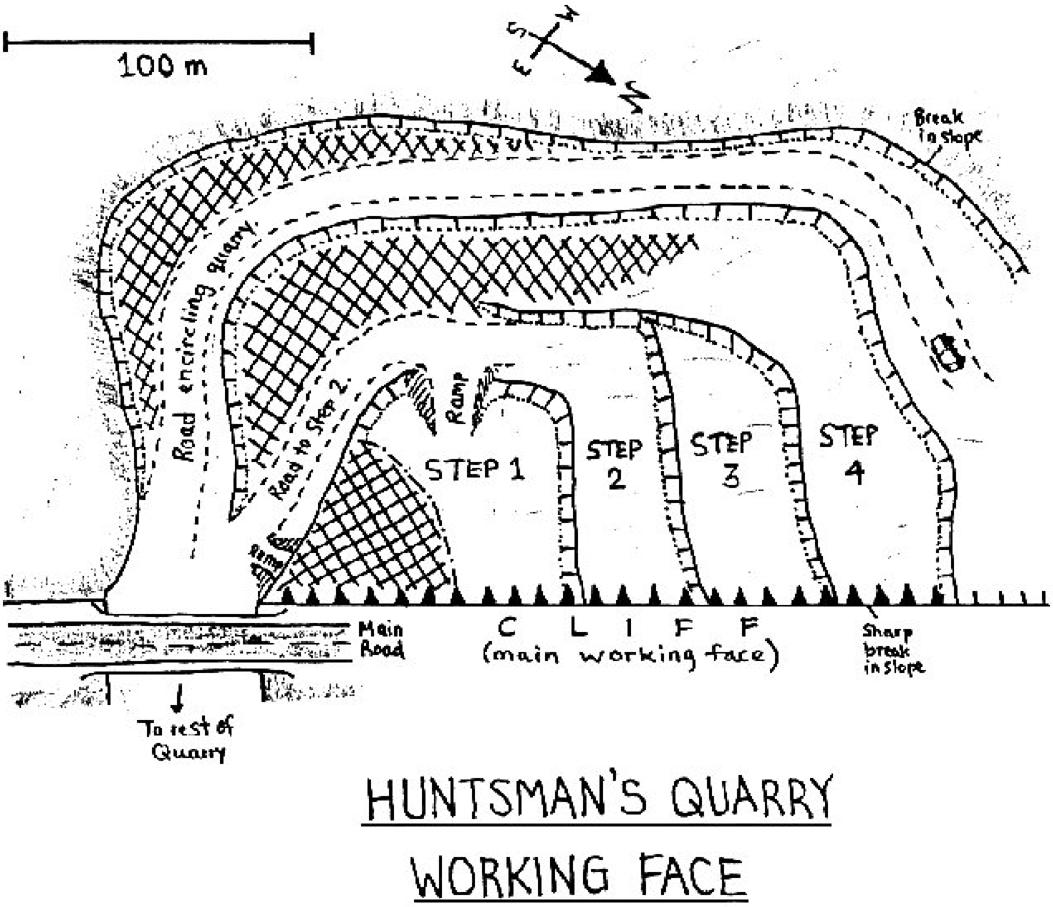


3. 3. 3 - Huntsman's Quarry working face.

This face (Grid reference SP 12102563) is the one currently worked by Huntsman's Quarries Ltd. for rocks of the Eyford Member and Taynton Limestone Formation for use as road metal. It lies 1 km west-north-west of Eyford Hill Quarry, and 750 m directly west of 'The Bushes'. The main face is 12 metres high in the deepest part of the quarry. The floor of the quarry has been shaped into a series of steps, each quarried a little at a time; consequently, a series of smaller (c. 2.5 m high) faces are available for study. The main face is approximately 200 m in length, and the lateral expansion of the steps is about 100 m. The working face is accessed by entering the quarry and passing westwards under the road (see Figure 10).

Three lithostratigraphic units are exposed in this quarry - silty mudrocks of the Fuller's Earth Formation, which consist the floor of the lowest part of the quarry; the Eyford Member, of which over 5 m was exposed at the time of fieldwork[12], and of which this quarry is the type section, and the Taynton Limestone Formation, which makes up the rest of the exposure. The pterosaur horizon, as mentioned in section 2. 2, was especially difficult to find at this exposure, as the dip of the beds, although shallow, resulted in the horizon outcropping in the main on the quarry floor, which was covered in mud and rainwater at the time of fieldwork. In addition, due to the fresh nature of this exposure, no characteristic *Trigonia impressa* had weathered out of the rock. When found, exposing a fresh surface with a hammer revealed the telltale characteristics of this rock - a bioclastic hard sandy limestone full of disarticulated shells and sand lenses. Unfortunately, no sample could be taken for thin section as work recommenced on the face as soon as the horizon had been found. However, the similarities between the succession at the working face and those at 'The Bushes' and Eyford Hill Quarry, with the characteristic pterosaur horizon surrounded above and below by an often fissile calcareous sandstone, coupled with the geographical proximity of all three localities, results in a high level of confidence that the pterosaur horizon is one and the same at all three localities.

Figure 10: Huntsman's Quarry working face - plan view.



[12] Sumbler (1999) measured a thickness of over 7m for the Eyford Member at this locality. The difference between that account and this work can easily be accounted for by the high relief of the disconformity between the Taynton Limestone Formation and the Eyford Member.

Plate 10: View of Huntsman's Quarry from southern extremity, showing main face on right and smaller steps extending perpendicularly.

Plate 11: Cross-bedding in the Taynton Limestone Formation.

Plate 12: Fuller's Earth Formation and Eyford Member laterally interdigitating at the base of Huntsman's Quarry working face.

For a detailed description of the succession at Huntsman's Quarry working face, see Appendix 1. What follows is a synopsis of this description and its accompanying graphic log. The basal unit at this locality (Unit 1) has only 0.3 m exposed. It is composed of laterally interdigitating fissile calcareous sandstone and laminated siltstone units (see Plate 12) and may represent either initial deposition of the Eyford Member (sandstone) on top of the irregular surface of the Fuller's Earth Member (siltstone), or coevally deposited sediment followed by minor erosion (ripple marks) representing a transition at the top of the Fuller's Earth Formation into the sandier Eyford Member. Unit 3 is the pterosaur horizon, 0.3 m thick at this locality, with the characteristic sand lenses and fossils fining upwards, and evidence of *Skolithos* burrows at the top of the unit. Surrounding this unit, as at the previously described localities, are units of predominantly laminated, fissile calcareous sandstone (Unit 2 - 2.2 m thick; Unit 4 - 0.8 m thick). Near the top of unit 2 is a heavily bioturbated sandy limestone bed, 0.15 m in thickness but otherwise identical to unit 1 at 'The Bushes'. Units 5 and 7 are sandy limestones (0.65 and 1 m thick respectively) separated by a thin (0.2 m) bed of calcareous sandstone (Unit 6), and are very similar to equivalent pterosaur horizon-overlying rocks at the previously described localities. The top of unit 7 is scoured and irregular, and overlain by 5.65 m of the oolitic and shell-fragmentary, quartz-free, cross-bedded (see Plate 11) Taynton Limestone Formation (Units 8 and 10), providing further evidence for a non-sequential disconformity between the Eyford Member and Taynton Limestone Formation. Unit 9 is an enigmatic clay layer, 0.6 m in thickness, which may or may not be a palaeokarst. Few fossils were collected from this locality due to the vertical nature of the faces and the inaccessibility of the pterosaur horizon.

3. 4 - Lateral persistence of the pterosaur horizon.

As mentioned previously, two other active quarries were visited in order to determine the lateral persistence of the pterosaur horizon - Brockhill Quarry (SP 13522393) and Grange Hill Quarry (SP 11352440). The succession at the former is logged and described in appendix 1; this was not possible at the latter due to weather conditions during fieldwork, but about 1 m of rocks of upper Eyford Member lithology were observed, overlain disconformably by rocks of the Taynton Limestone Formation. Exposure of the pterosaur horizon at Grange Hill Quarry is therefore unlikely based upon the evidence from the successions described in section 3. 3, but the high relief of the aforementioned disconformity means that this possibility cannot be ruled out. The pterosaur horizon was not observed within the 0.4 m of Eyford Member exposed at Brockhill Quarry (the beds of which are comparable with the upper beds of the Eyford Member at the exposures described in section 3. 3), although it is feasible that it does persist laterally to this point, but is simply not exposed.

Plate 13: Eyford Hill Farm disused quarry, where *ex-situ* slabs of the pterosaur horizon were found.

Although not *in-situ*, blocks of the pterosaur horizon were discovered at two disused quarries which lacked any exposures, suggesting that this rock had once been quarried at those localities. One of those localities, Eyford Hill Farm Quarry (Grid reference SP 13512532), formerly the site of the workings of the Cotswold Slate Company, is only 500 m east north-east of Eyford Hill Quarry, and 550 m directly east of 'The Bushes'. However, the other locality is a small disused quarry behind Cotswold Farm Park. The rock is identical to that found *in-situ* at other localities, and is large enough (roughly 1 m by 1 m by 0.25 m) that it is unlikely to have originated elsewhere. This locality is 1.6 km north-west of Huntsman's Quarry working face - the most westerly of the three localities in which the pterosaur horizon outcrops, and 1 km north of 'The Bushes', where the pterosaur horizon dies out to the north. This suggests that the pterosaur horizon is an ubiquitous unit of the Eyford Member, and that non-deposition in certain areas (such as the northerly part of 'The Bushes') may be due to palaeotopography of the seafloor as much as anything else. Alternatively, it may be absent due to erosion prior to deposition of the Taynton Limestone Formation (no examples of which were observed).

3. 5 - Thin section analysis of the pterosaur horizon.

In order to ensure the homogeneity of the pterosaur horizon at 'The Bushes' and Eyford Hill Quarry with the rock encasing the pterosaur humerus, thin section of each were made. These are reproduced on plates 14 and 15. The thin sections collaborate the stratigraphical and sedimentological evidence concerning the homogeneity of the aforementioned rocks. The thin sections can be seen to possess the same types of allochems, sedimentary particles and crystals, at very similar proportions. Quartz grains, which can be recognised by its lack of features under plane-polarised light, and its variable extinction under cross-polarised light, is abundant in all thin sections, comprising about 25 % of the rock. The cement of the rock consists of sparry calcite crystals in all examples, which display very high birefringence, and exhibit very light pastel-coloured under cross-polars; these comprise about 40 % of the rock. Allochems, such as bioclasts, ooids, peloids and (rare) rock fragments, are abundant in the three thin sections, comprising about 35 % of the rock in each. Other minerals, such as feldspar, are very rare but present. No pore spaces are visible in this rock The ooids, present in all three thin sections, are actually pseudo-ooids, where the calcitic coating is thinner than the diameter of the nucleus. They exhibit a radial structure, suggesting possible recrystallisation. Peloids are comparatively rare but present, and are quite large, measuring about 1/3 of the diameter of the nearby ooid in plates 14/15, photograph 2. A section of bivalve shell can be seen in photograph 1 (Plates 14/15) where the original, probably aragonite, microstructure has been destroyed and replaced by sparry calcite crystals. A fragment of a probable echinoid can be seen in photograph 2 (Plates 14/15), and in addition there are a number of smaller unidentifiable fragmentary bioclasts present in the rock.

<u>Plate 14</u><u>: Photographs of thin sections in plane-polarised light (Magnification - × 16.13).</u>

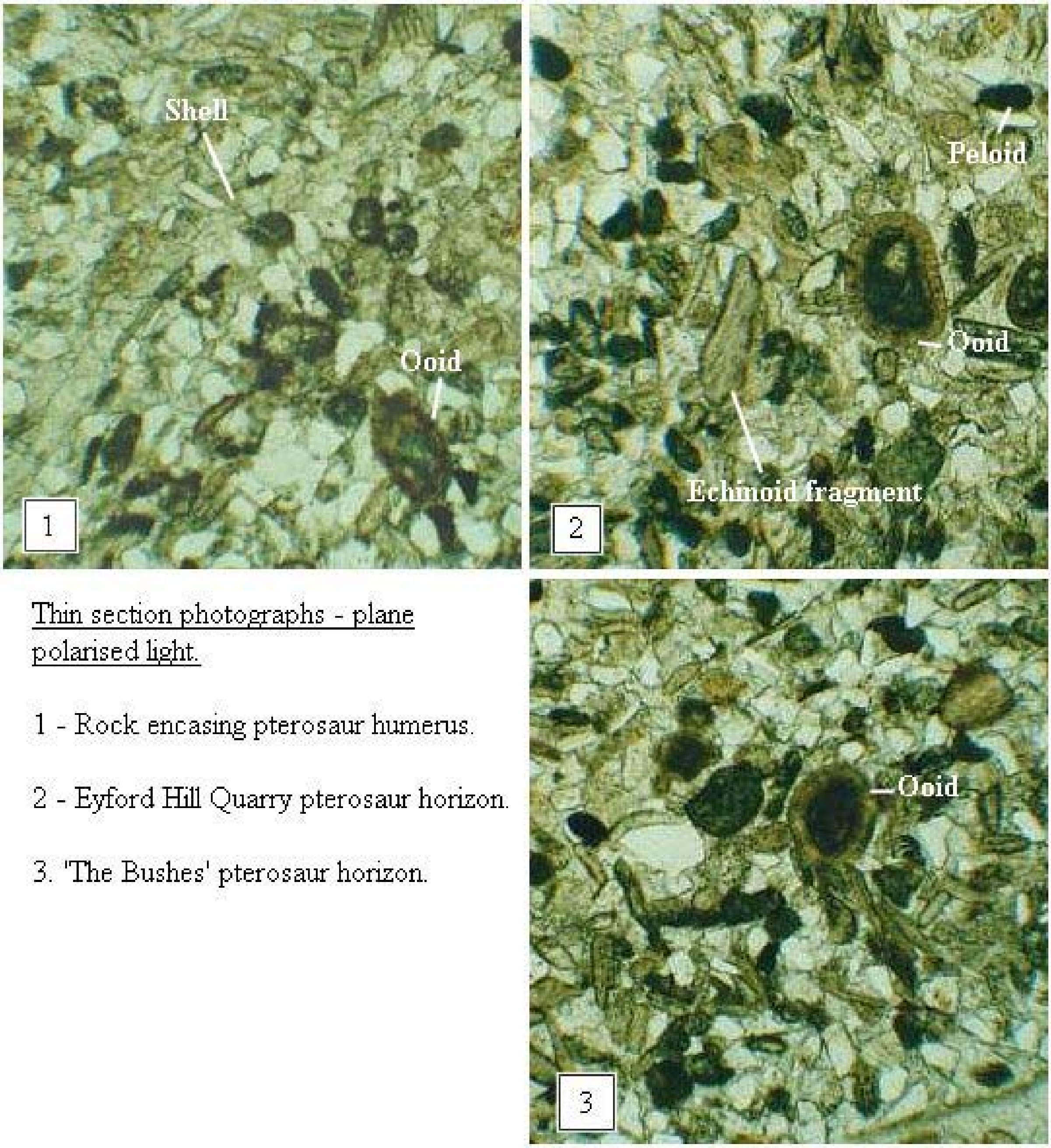
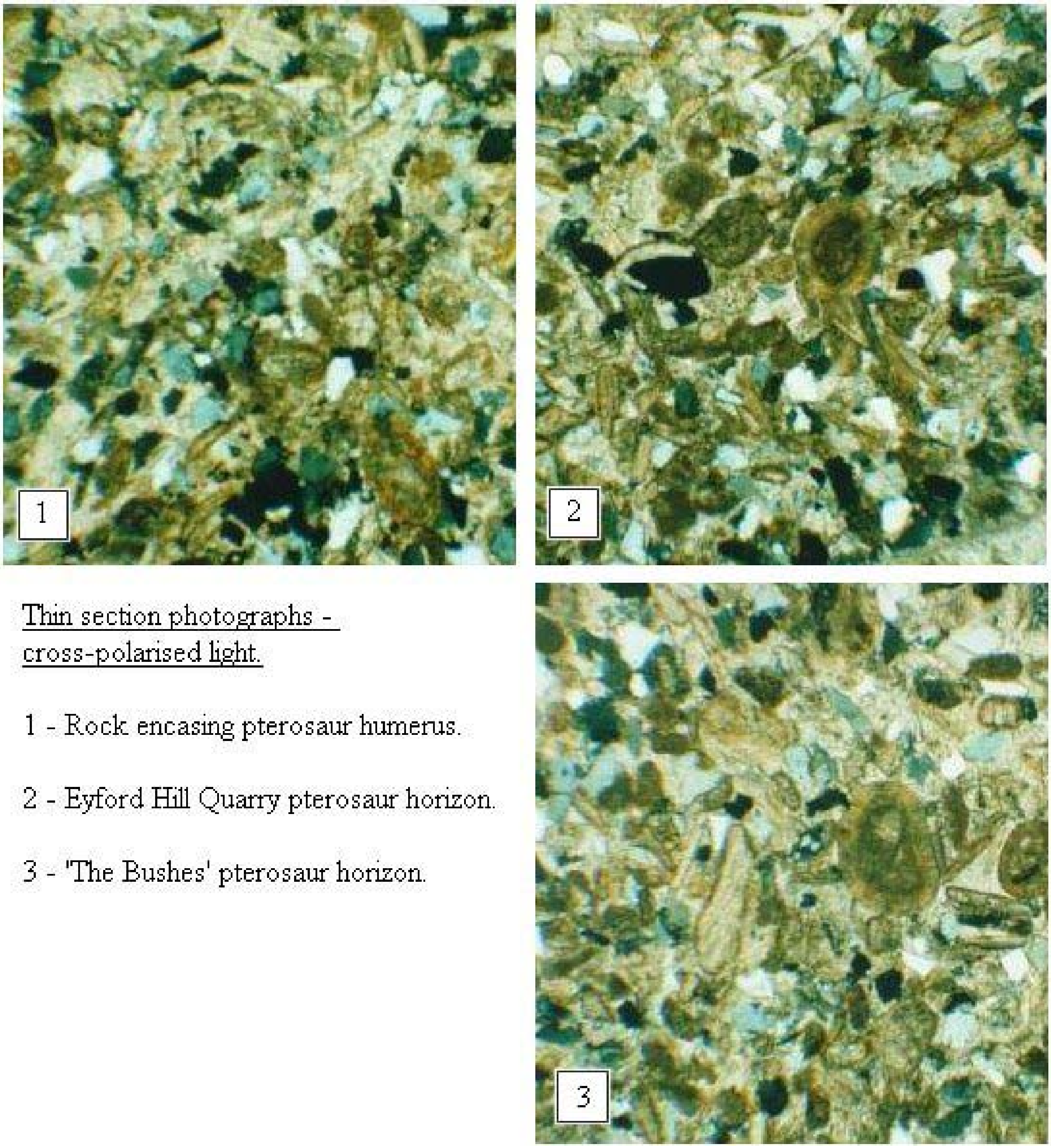


Plate 15: Photographs of thin sections in cross-polarised light (Magnification × 16.13).



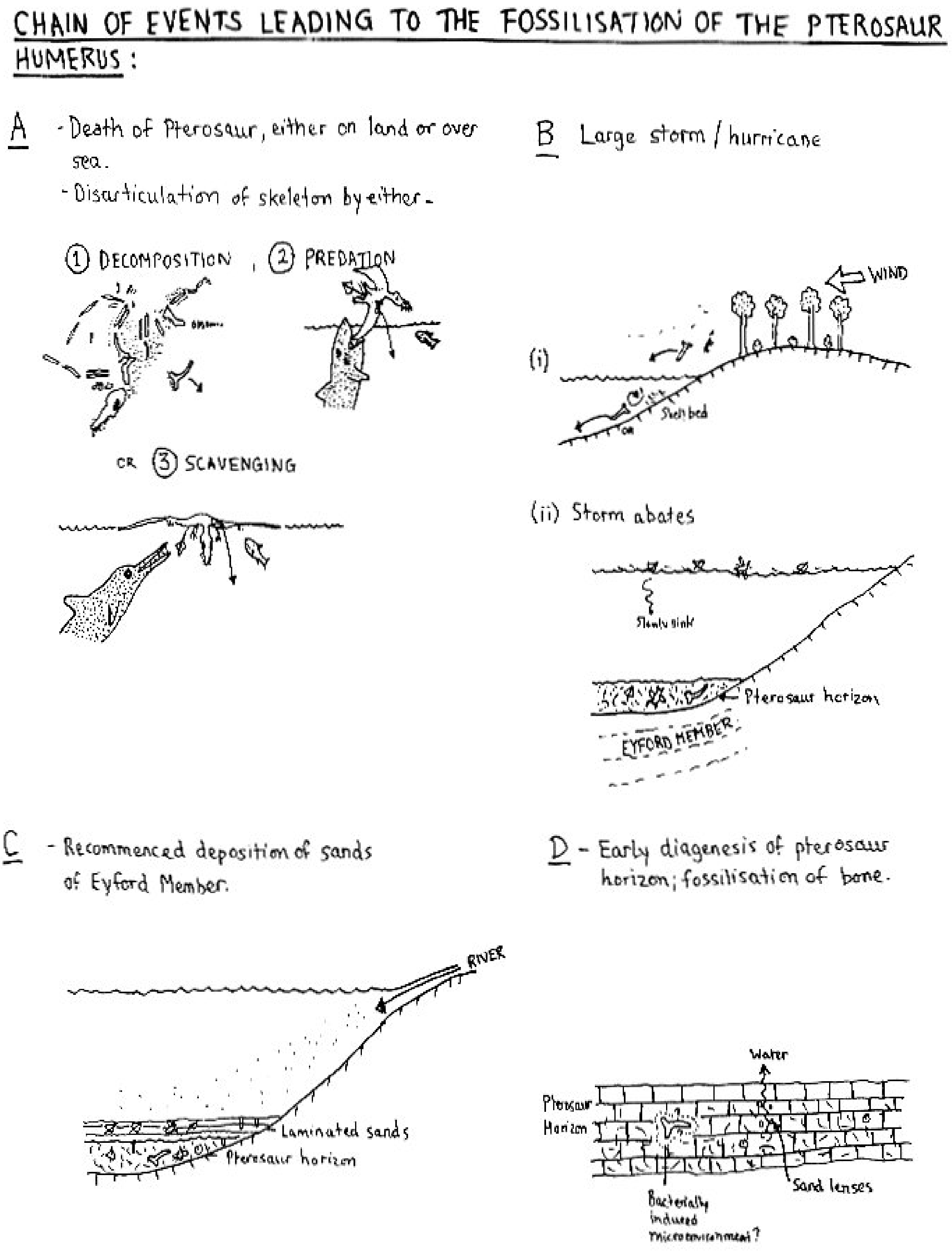
3. 6 - Taphonomy of the pterosaur humerus and deposition of the pterosaur horizon.

The pterosaur horizon exhibits a number of features which suggest it was deposited as a single catastrophic event under shallow water at or near the storm wave base. The largely random orientation of the shells within the sediment, along with the admixture of fossils of both fully marine (shark tooth, echinoderms, brachiopods) and terrestrial origin, suggest that the whole bed was lain down at once, incorporating sediment from a wide area, with little or no current sorting. The various features of this rock can be explained by a single large storm, such as a hurricane (Britain was certainly at a suitable latitude during the Bathonian). The first winds of the storm may have caused the seafloor to be eroded in some areas (c.f. the undulatory base to the pterosaur horizon at 'The Bushes') while depositing sediment in other, possibly lower relief, areas (c.f. the transitionary base of the pterosaur horizon at Eyford Hill Quarry). As the energy of the storm increased, waves may have flooded nearby low-lying land areas (such as the Moreton Axis or the coast of the London massif), washing off terrestrial material into the sea. Of equal likelihood is that high winds may have resulted in the blowing out to sea and drowning of terrestrial organisms such as insects, plant matter and pterosaurs. The latter possibility is insufficient to explain the presence of the pterosaur humerus, however; a solitary disarticulated bone rather than a whole skeleton suggests instead that death and subsequent predation or decomposition took place previous to the storm, removing the humerus from the rest of the skeleton, following which it was deposited with the pterosaur horizon. Certainly, the extremities of the bone are broken off, indicating at least some transport before deposition.

The marine invertebrates, most of which are disarticulated, but some of which are not, suggest that a local shell bed (comprising some living organisms but mostly dead shells) was uprooted en masse, along with a large amount of sandy and calcareous sediment, and redeposited as the energy of the storm abated. Deposition was quick, resulting in a semi-chaotic mixture of fossils, sand and water; the smaller sand lenses may represent sand infilling of water escape structures. As the energy of the storm decreased further, any remaining suspended sediment settled and the surface of the new bed was rippled.

Before infaunal scavengers could recover from the effects of the storm, normal sand (which also underlays the horizon) deposition had resumed. Some opportunistic burrowers may have entered the area at this time, creating small *Skolithos* burrows at the top of the pterosaur horizon. Decomposition in the pterosaur horizon of high amounts of organic matter by bacteria may have raised the redox boundary, rendering the pterosaur horizon impenetrable to many infauna. Remant terrestrial matter floating on the water's surface following the storm (such as leaves and insect material) would have eventually sank to become entombed in the laminated sands above the pterosaur horizon. Early diagenesis of the rock then took place within the pore spaces, with any aragonite fossils converted to calcite, and small sparite crystals formed as a cement throughout the rock. Any ooids may have been recrystallised at this time. The fossilisation of the bone may also have occurred at this point, details of which are discussed below.

Figure 11: Hypothesised taphonomy of the pterosaur humerus.



Following preparation of the humerus from its encasing rock, the sediment in the hollows at the proximal end of the medial side of the bone, hidden underneath the bone prior to preparation, was available for observation. This sediment was less sandy and more crystalline than the rest of the rock; it was easily removed by hand both from the bone and the rock below. It seemed to be distinct from the rest of the rock, being removed as a smooth-surfaced undulous flake, following the contours of the bone on one side, yet following a different, yet equally smooth contour on its other side. The surface of the flake previously abutting the bone was stained brown; more surprising was the fact that the undersurface of the flake, previously abutting the rest of the rock, was also stained the same shade of brown, although the internal sediment was grey.

There are a few possible explanations to this anomaly, centring around the decomposition and early diagenesis of the bone. It is possible that at the time of deposition, some soft tissue remained around the proximal end of the bone - a region of the pterosaur body doubtless laden with muscle, tendons and cartilage. Deposition may have been quick enough for this tissue to avoid consumption by nektic or epibenthic macro-scavengers; deposition under very high energy may have frustrated the efforts of infaunal scavengers. As a result, decompostion of this soft-tissue would have been undertaken by bacteria. The side effects of the metabolism of these bacteria may have resulted in the formation of a micro-environment within the region formerly occupied by the soft tissue, altering pore-water chemistry and enabling a separate regime of calcite crystallisation from the rest of the rock in the space left vacant by soft-tissue. This may explain the larger, slowly forming sparite crystals in the rock flake when compared to the fast-forming small sparite crystals prevalent in the rest of the rock. Alternatively, decomposition of blood vessels and pneumatic tissue within the bone may have sufficed in creating a bacterially induced micro-environment. Another alternative may be that a trapped air bubble, or gas from tissue decomposition, may have remained in place under the proximal end of the bone for long enough to make the impression in the underlying sediment. When this eventually escaped, pore water would have leeched into the space, and in the absence of large nucleating particles available in the rest of the sediment, finer calcium carbonate crystals may have been precipitated.

The brown surface of this sediment flake may be a carbonaceous film; a remnant of the soft-tissue and resultant bacterial action. Equally, it may be iron staining resulting from the conditions peculiar to the micro-environment formed by the bacteria, although this does not fully explain why only the surfaces of the flake are stained brown. A more mundane explanation may be that seepage of minerals from the fossilising bone may have stained the surfaces of the flake, although this does not explain the nature of the flake.

4. 0 PALAEONTOLOGICAL ASPECTS

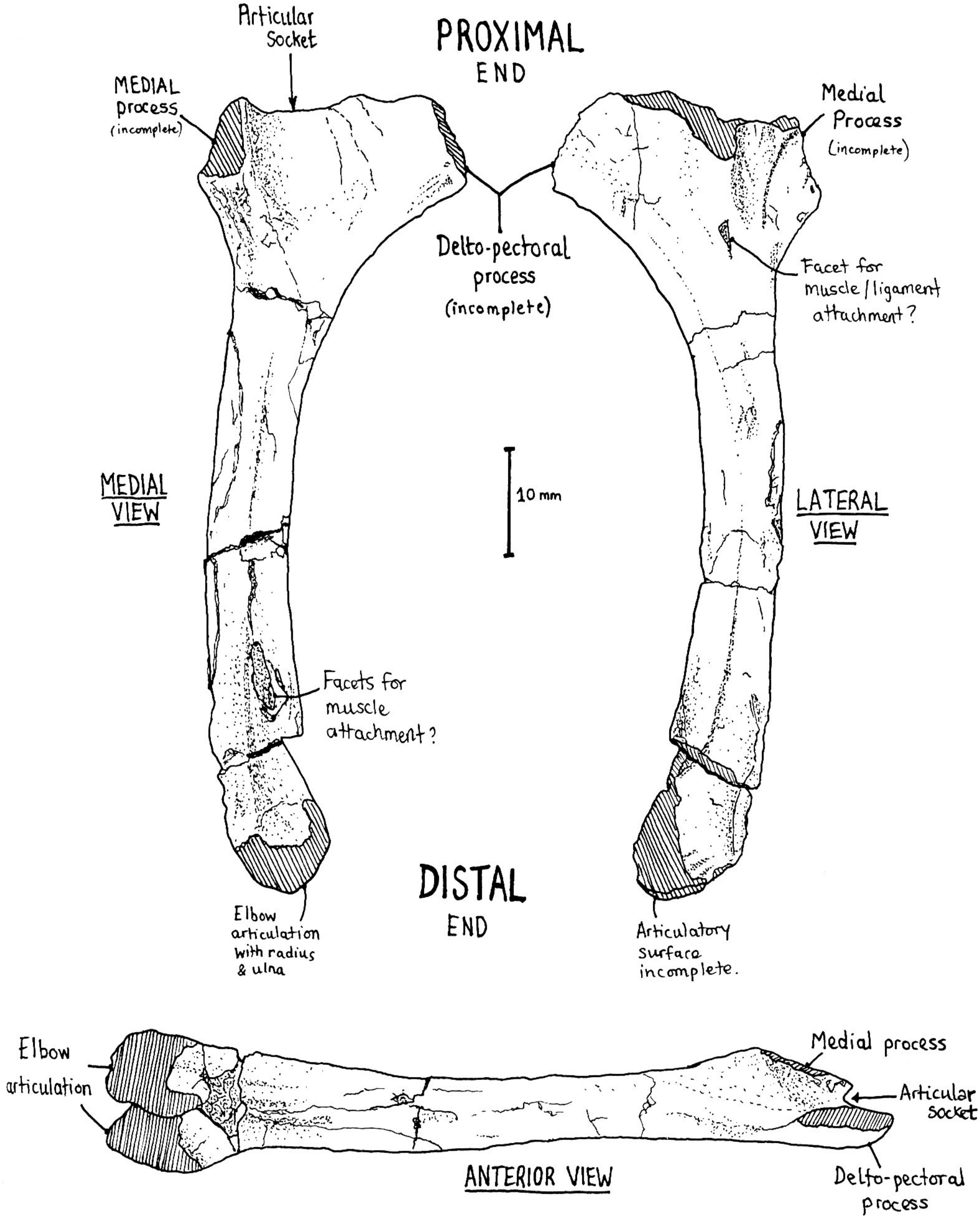
The bone that forms the basis of this work is the left humerus of a rhamphorhynchoid pterosaur, provisionally *Rhamphocephalus* sp. This has been ascertained by the following characteristics: There is a saddle shaped articular head at the proximal end; the shaft is bent forwards; the bone is hollow (see Plate 15); the bone is very similar to the humeri of *Rhamphocephalus* and other 'rhamphorhynchoids'; and the proximal end of the bone is very similar to that of *Rhamphocephalus*, especially the curvature of the shaft towards the delto-pectoral process.

Plate 16: Section through the shaft of the humerus, showing the hollow nature of the bone.

4. 1 - Humerus description.

(Terminology from Wellnhofer, 1991, 1999; Bennett, 1989; Martill *et al*, 1996)
The articular heads of the humerus have been eroded prior to deposition, affecting the authenticity of any measurements involving these areas of the bone. Extrapolation of the original dimensions of the bone would be ideal; unfortunately none of the *Rhamphocephalus* humeri studied are sufficiently large, similar or complete for this method to have any real accuracy. The maximum length of the humerus is 83 mm, measured from the distal extremity of the delto-pectoral process, at the proximal end of the bone (see Figure 12), to the distal end

Figure 12: Left humerus of *Rhamphocephalus* sp., as described in this work.



of the bone. Its maximum width at the proximal end is 30 mm, and the width at the median point of the shaft is 8.5 mm, equal also to the thickness of the bone at this point. The wall of the bone at the centre of the shaft is less than 1 mm thick, but thickens until solid towards the articular ends. Its surface is slightly cracked, suggesting compression, and results in difficulties when determining what is a true feature of the bone and what is an artefact due to compression.

The shaft of the humerus is almost cylindrical in the upper half of its extent, towards the proximal end, becoming more prismatic towards the distal end. When observed medially or laterally, there exists a strong degree of curvature between the upper part of the shaft and the delto-pectoral process, bearing almost 45° away from the long axis of the bone. A lesser degree of curvature exists between the upper part of the shaft and the medial process, bearing about 20° away from the long axis of the shaft. The degree to which the distal processes angle away from the lower end of the shaft is not discernible due to erosion of this area. While the proximal end of the bone is medio-laterally flattened, the distal end of the bone tends towards compression along the posterior-anterior axis. As viewed laterally, the surface of the proximal end nearest the medial process is undulose, while that nearest the delto-pectoral process is smooth. As viewed medially, a raised convex ridge runs from the top of the shaft towards the centre of the medial process, to the right of which is a concave depression running down to the delto-pectoral process. Raised ridges run down the lower half of the shaft on opposite sides of the bone, although it cannot easily be determined whether or not these are artefacts of compression.

4. 2 - Comparison with other humeri assigned to *Rhamphocephalus*.

As mentioned previously, only three other complete humeri assigned to the genus *Rhamphocephalus* were discovered during investigations at the natural history museums at Oxford (1) and London (2, both of which were tiny). In addition, a well-preserved (i.e. non-compacted) proximal end of a humerus was studied. Strangely, the incomplete humerus and one of the small humeri, from the Natural History Museum, London, both have the same specimen number, NHM 40126; as a result the small humerus will be referred to by this specimen number and the partial humerus will be referred to as NHM 40126a from this point forth. The second London specimen, also small, has the specimen number NHM 28610c. The Oxford specimen, J 23043a, is a larger specimen, and is complete but poorly preserved, with the exact outline of the bone difficult to determine against the stained matrix.

Plate 17: Photographs and figure of other humeri assigned to *Rhamphocephalus*.

Explanation of Plate

1 - J 23043 (OUNHM)
2 - J 23043 (from figure in Huxley, 1859)
3 - 28610c (NHM)
4 - 40126 (NHM)
5 - 40126a (NHM)

All the aforementioned humeri derive from Stonesfield and have thus been assigned the specific name *Rhamphocephalus bucklandi*, a 'dustbin' name for all pterosaur specimens from this locality. What is immediately obvious from the humeri shown in Plate 17, along with the humerus forming the basis of this work (henceforth referred to as the Eyford humerus) is that they can be separated into two, or possibly even three, distinct species-groups. J 23043a from Oxford and the partial humerus NHM 40126a from London, both right humeri, are similar enough so as to belong to the same species. They are characterised by the particularly smooth surface of the lateral proximal end, and a convex approach to the delto-pectoral process (as opposed to a planar approach on the Eyford specimen). Unfortunately, the extremities of the processes are eroded and partially hidden below matrix in both specimens, as are the medial sides of the bones, hindering further comparisons.

The small (15.5 mm in length) right humerus NHM 40126 from London, and the Eyford humerus, can also be compared favourably, with the diverging angles of the proximal processes from the shaft and the contours of the medial proximal end appearing very similar. The medial process is broken off on NHM 40126, and the lateral side of the bone is encased in matrix, again hindering further comparisons, but the distal end and delto-pectoral process of the bone are complete, which would enable partial reconstruction of the relevant missing parts of the Eyford humerus, if the two specimens were indeed found to belong to the same species. Raised features on NHM 40126 are less distinct than on the Eyford humerus; when considering the small size of the former compared to the latter, ontogenetic factors are as good an explanation as any for this disparity (see Bennett [1995] for studies on ontogenetic changes in pterosaurs).

The final humerus assigned to *Rhamphocephalus bucklandi*, NHM 28610c, while of similar length (14 mm) to NHM 40126, is particularly different to this or any other of the humeri. The proximal end of the bone, a left humerus, appears entirely convex and featureless, and a groove runs almost the entirety of the shaft - a feature not observed in any of the previously discussed specimens. The bone may be a very young individual of one of the aforementioned species-groups, orientated strangely in the sediment, going some way towards explaining the disparity between this bone and those discussed previously. It may equally be the bone of a third species of pterosaur from Stonesfield - a possibility first mentioned by Seeley (1880). Three distinctly different humeri all assigned to the same species, *Rhamphocephalus bucklandi*, suggests that the Stonesfield and Eyford pterosaur material is in need of review.

4. 3 - Comparison of *Rhamphocephalus* humeri to those of other genera.

In order to ensure that the Eyford humerus, and humeri assigned to the *Rhamphocephalus* genus in general, do not actually belong to a long living Lower or Upper Jurassic pterosaur genus, the *Rhamphocephalus* humeri were compared to the humeri of *Dimorphodon macronyx, Rhamphorhynchus gemmingi, Scaphognathus crassirostris* and *Pterodactylus* *kochi*. Upon comparison, it was immediately clear that none of the bones described above belong to any of these genera, and are far more similar to each other than the humeri shown in

Plate 18: Humeri of one pterodactyloid and three 'rhamphorhynchoid' Jurassic pterosaurs.

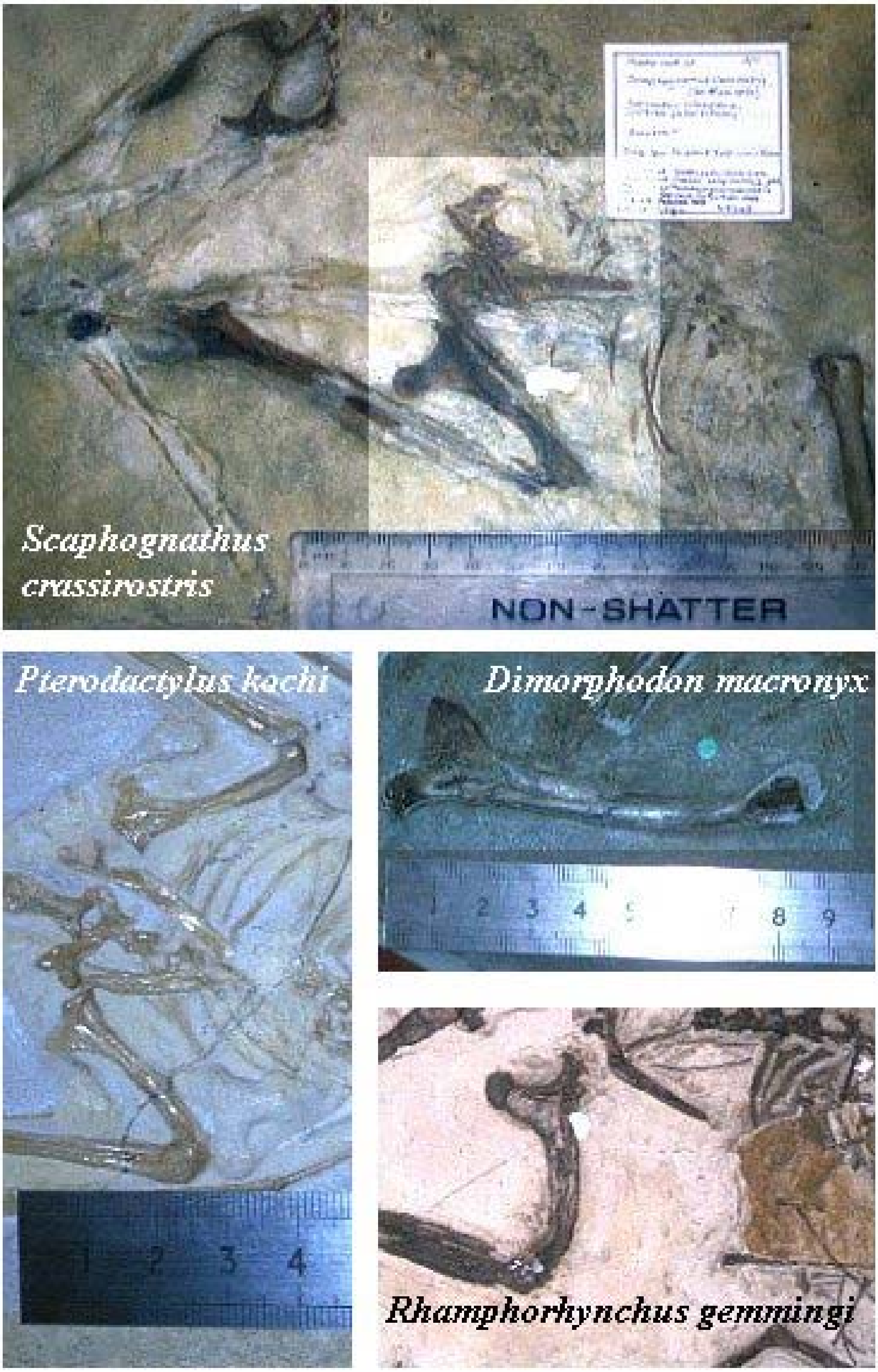


Plate 18. Certain features of the humeri of these genera immediately distinguish them from the Middle Jurassic humeri described above. For example, the delto-pectoral process of

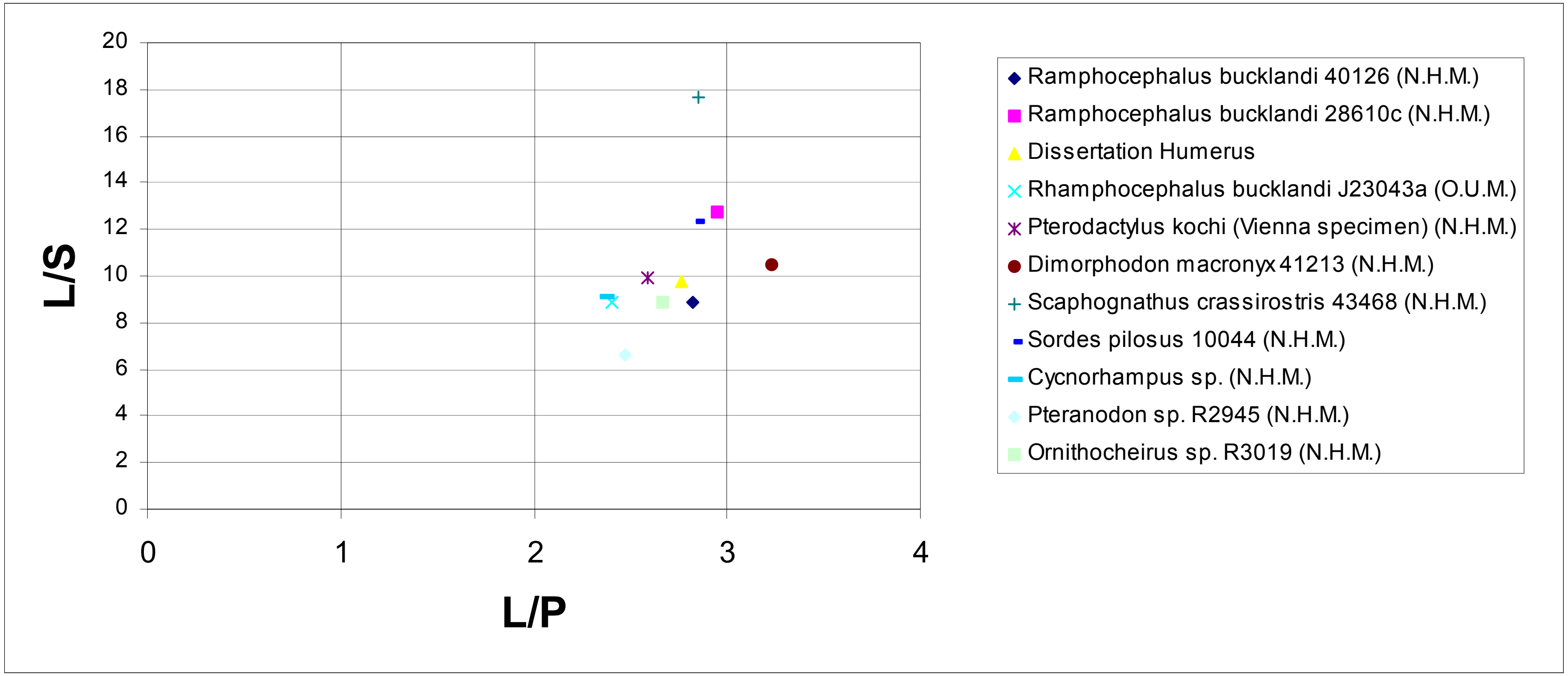
Scaphognathus is broadly circular rather than broadly rectangular as in *Rhamphocephalus*, and the shaft is shorter; *Dimorphodon macronyx* possesses a triangular delto-pectoral process and a more slender shaft; *Rhamphorhynchus* possesses a distinctly crescent-shaped proximal end, and has a thicker, more curved shaft; and *Pterodactylus kochi* possesses a straighter, ridged shaft and a rhomb-shaped proximal end. NHM 28610c, although possessing a more curved shaft, otherwise superficially resembles the humerus of *Pterodactylus kochi*. While a Middle Jurassic pterodactyloid pterosaur may be of great importance, it is unrealistic as yet to assert any pterodactyloid affinities to any of the Stonesfield and Eyford bones based upon the evidence of a single enigmatic and probably juvenile humerus.

Upon observing the considerable variation in the shapes and sizes of the delto-pectoral and medial crests, each the site of muscle attachment, in different pterosaurs, it became clear that the variations may indicate adaptation for considerably different modes of flight, such as gliding, quick flapping and/or better manoeuvrability. As far as can be determined, a comprehensive study of this aspect of pterosaur humeri has not yet been carried out, and may represent a new avenue of pterosaurian research.

A biometric analysis of the complete *Rhamphocephalus* humeri studied, combined with measurements of the humeri of other species of pterosaurs, was carried out to further determine the stability of the *Rhamphocephalus* genus. The following measurements were taken - maximum length, width of the proximal end and width of the shaft at the median point of the bone. The latter two sets of measurements were each divided into the maximum length to give ratios that could be plotted against each other, resulting in a two dimensional point in space for each specimen. Ideally, specimens belonging to the same species should then group together, while specimens belonging to different species should be separated. See Figure 13 for the results of this analysis.

The results are not altogether conclusive, with species that possess very different shaped humeri closely associated, such as *Ornithocheirus* and *Pterodactylus kochi*. However, the results do support the division of the *Rhamphocephalus* humeri into three distinct species groups, with the Eyford humerus and NHM 40126 grouped closely together and J 23043a and NHM 28610c separated from both these humeri and each other. Unfortunately, measurements of the only complete *Rhamphorhynchus* humerus observed (see Plate 18) were unavailable, as

Figure 13: Results of the biometric analysis of *Rhamphocephalus* and other pterosaurian humeri.



L = Maximum Length
P = Maximum Width - Proximal End
S = Width of shaft at median point of bone.

the specimen (at the Natural History Museum, London) had been mislaid and was only discovered and quickly photographed at the end of the visit.

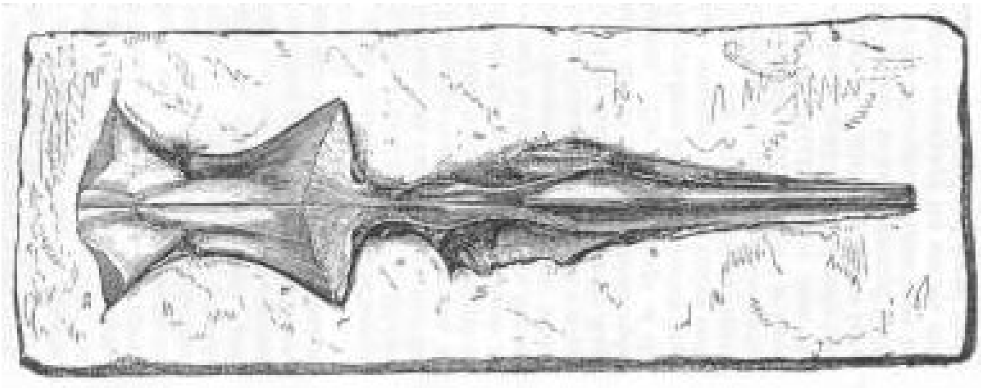
4. 4 - Systematics of the genus *Rhamphocephalus*.

The taxonomical and phylogenetic importance of the genus *Rhamphocephalus* is paramount, as it is the only Middle Jurassic pterosaurian taxon for which any substantial amount of material has been assigned to. With the origin of the short tailed pterodactyloidea probably falling in the Middle Jurassic, any pterosaur fossils of this age are of great significance. However, the validity of the genus may need to be called into question, both on anatomical and systematic grounds. Studies detailed above have indicated that there may be at least two or three distinct species groups, which may or may not be closely related; this possibility was first indicated by Seeley (1880), and indeed, there are three named species within the genus. The source of the problem is that no *Rhamphocephalus* bones have been found articulated to one another, or even sufficiently closely associated to warrant consideration as part of the same animal. As a result, holotypes have been erected based on isolated bones. There are two main problems with this approach. Firstly, there can no certainty that the holotypes for the mandible and flight metacarpal of *Rhamphocephalus bucklandi*, for example, with which all other mandibles and flight metacarpals found must be compared, are derived from the same species. The only route to certainty would involve the discovery of an articulated skeleton with both elements present. Secondly, unless a new find is the same element as a holotype, it cannot be assigned to a species until an articulated specimen is found with both that element and the holotype present.

Despite this conundrum, all pterosaur bones from the Stonesfield Slate and Cotswold Slate have been assigned to the genus *Rhamphocephalus*, and mostly to the species *Rhamphocephalus bucklandi*. This is erroneous systematic procedure, and as such needs to be overturned. What follows is a test of the validity of the genus *Rhamphocephalus*, based upon all previous descriptions of the pterosaur bones found in the Stonesfield and Cotswold slates.

H. G. Seeley erected the genus Rhamphocephalus in 1880. The holotype specimen for the genus, and the species *Rhamphocephalus prestwichi*, was a cast of the upper surface of a cranium (See Figure 14). No other bones are described or included as type specimens, and there are no articulated or associated elements. In addition, the holotype specimen is currently listed as lost. As a result of this, in theory, the taxon *Rhamphocephalus prestwichi* stands, but no other bones can be assigned to the species or genus, unless isolated crania, or crania articulated with post-cranial elements, can be compared and assigned. Until the holotype is rediscovered, however, *Rhamphocephalus* is *nomen dubium* - redundant as a taxon.

Figure 14: - Holotype specimen for the genus *Rhamphocephalus* and the species *Rhamphocephalus prestwichi*, a cast of the upper surface of a cranium, now listed as lost (taken from Seeley, 1880).



All other pterosaur bones from the Stonesfield and Cotswold slates were assigned to the genus *Rhamphocephalus* by Seeley, with the following statement:
"I shall be quite prepared to find that all the [pterosaurs] from Stonesfield belong to this (*Rhamphocephalus*) or an allied genus, which had *Rhamphorhynchus* as its nearest ally."
For the reasons described above, this is not valid taxonomic practice; as a result, only the holotype shown in Figure 14 may remain as *Rhamphocephalus*, as no other crania and upper mandibles have as yet been found from the Stonesfield or Cotswold slates. All other species previously assigned to *Rhamphocephalus* must therefore revert back to their previous name, although Seeley was correct in stating that the English Middle Jurassic bones are sufficiently different from the German Upper Jurassic bones to warrant the erection of a separate genus.

The first worker to name and describe the Stonesfield bones, according to Huxley (1859), was Meyer (1832) who named and described *Pterodactylus bucklandi*, which, again according to Huxley (1859), was based upon an isolated, toothless lower jaw (although there is no record of such a description in Meyer's text). This is the only valid holotype of '*Pterodactylus*' *bucklandi*; therefore, as above, no other bones can be assigned to the species until a matching lower jaw is found articulated or closely associated with other elements. Huxley (1859) described a number of other bones, including the humerus J 20343, and assigned them to *Rhamphorhynchus bucklandi*, itself based on Meyer's non-existent description of

'*Pterodactylus*' *bucklandi*. Assignation of any of these bones to *R. bucklandi* was erroneous, as they were isolated elements of potentially different species. Similarly, *Rhamphorhynchus depressirostris*, erected and described by Huxley (1859), although sufficiently different from the *R. bucklandi* type specimen to warrant a new species, is still based on only one element - an isolated lower jaw.

As a result, only three pterosaur bones from the Stonesfield and Cotswold slates have been named in the correct manner, each the holotype specimen. All other bones, including the Eyford humerus, unless comparable to these three valid holotypes, must be classified as Pterosauria sp. indet. until further notice. As the genus name *Rhamphocephalus* is already in use, albeit by a single missing specimen, and the pterosaur material previously assigned to this genus is sufficiently distinct to warrant its inclusion in a separate genus, a new genus must be erected. A detailed study of all cognate elements, incorporating biometric analysis, must first be carried out in order to determine whether they are similar enough to be grouped within the same genus. Typical specimens should then be designated as holotypes. If distinct species groups can then be discerned within the new genus, characteristic features may be described and new species may be erected, which although not systematically inviolate, would be more solidly based on sound scientific ground than the previous taxonomy. A preliminary name, *Oolithorhynchus*, (beak of the oolite) is proposed for the new genus. However the problem of having isolated disarticulated specimens still remains, and will do so until articulated elements are found. This may still be possible, due to renewed interest in the large scale quarrying of tilestones for building materials in the Cotswolds (see section 1. 2).

5. 0 - CONCLUSION

The aims of this work were met in full. The horizon from which the pterosaur humerus came was identified in the field, and its exact stratigraphic position and approximate lateral extent determined, near the centre of the Eyford Member of the Fuller's Earth Formation. Associated fauna was collected, suggesting a mixture of terrestrial and marine faunas. Collaborative sedimentological evidence suggested that the pterosaur horizon was deposited as a tempestite during or immediately following a strong storm. Erosion of the articular extremities of the humerus suggest some transport before deposition and fossilisation.

The humerus was preliminarily identified as the left humerus of *Rhamphocephalus* sp., and was described, compared with other humeri assigned to *Rhamphocephalus*, and to the humeri of other genera. Analysis of this data resulted in the resolution of two, or perhaps three species-groups within the *Rhamphocephalus* humeri studied, including the Eyford humerus. This was backed up by previous work by Seeley (1880). Following detailed analysis of the literature on pterosaurs from the Stonesfield and Cotswold slates, many faults were found in the systematic practices used to erect the genus *Rhamphocephalus* and its three constituent species. As a result, all bones, apart from the three original holotypes used to name '*Pterodactylus*' *bucklandi* MEYER 1832, '*Rhamphorhynchus*' *depressirostris* HUXLEY 1859 and *Rhamphocephalus prestwichi* SEELEY 1880, were necessarily reclassified as Pterosauria sp. indet., including the Eyford Humerus. Suggestions were made concerning the reclassification of these bones, and a new genus, *Oolithorhynchus*, was proposed.

Suggestions for future studies include a comprehensive review of English Middle Jurassic pterosaurs, beyond the scope of this work; and a study of the functional morphology of the pterosaur humerus, and its relationship to flying style and lifestyle.

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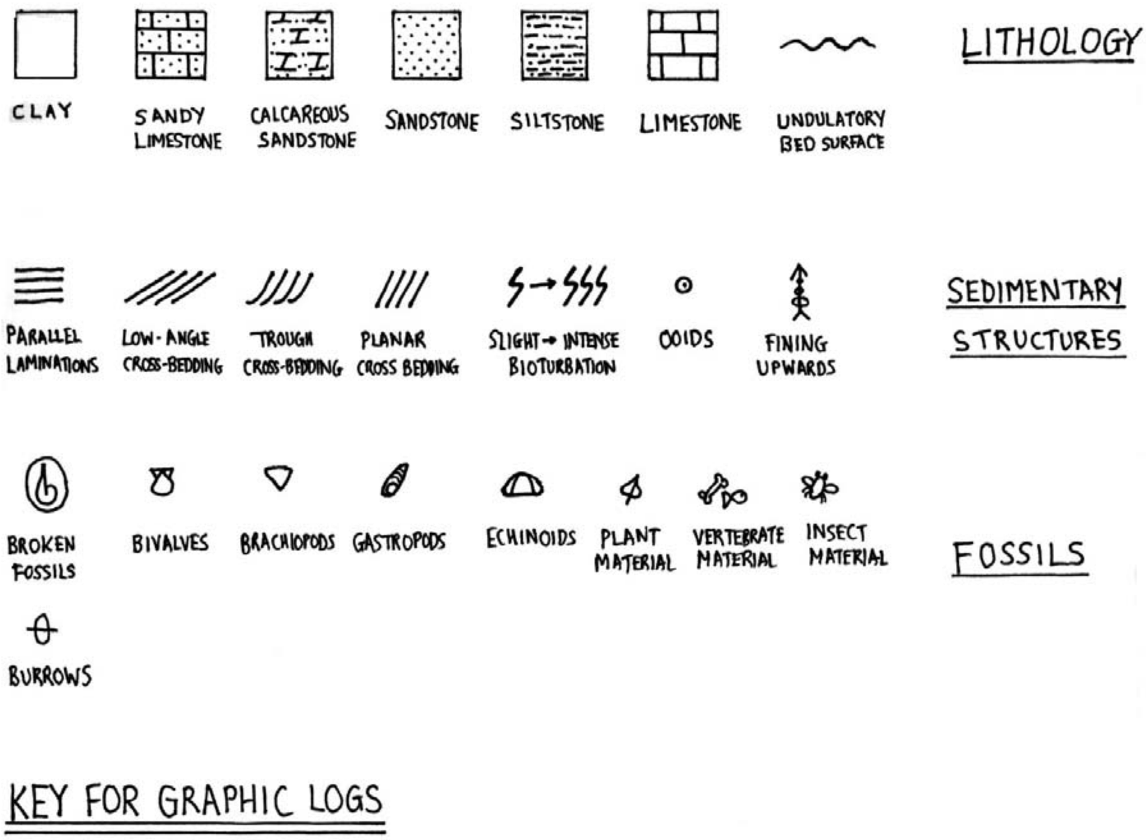
WEBSITES

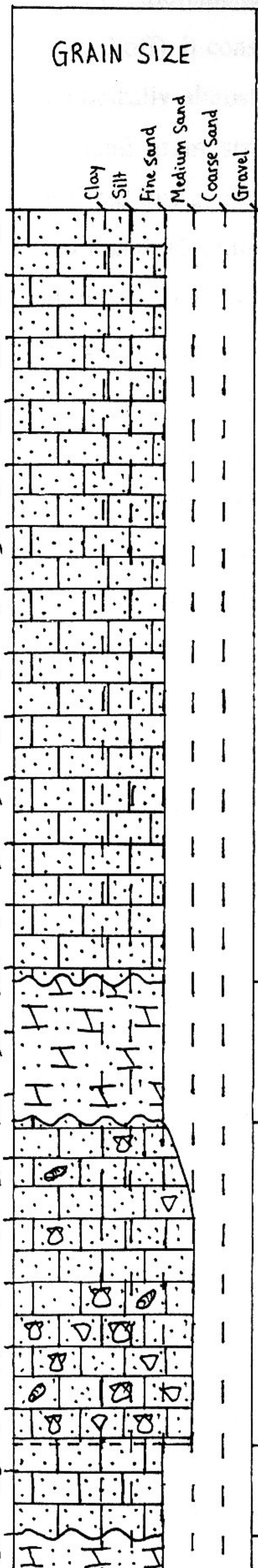
http://home.stlnet.com/~azero/	"The Pterosaur Homepage"
http://www.bgs.ac.uk/scripts/lexicon/	The British Geological Survey Lexicon of named rock units in the British Isles.

APPENDIX

GRAPHIC LOGS AND EXPOSURE DESCRIPTIONS


CLAY
SANDY LIMESTONE
CALCAREOUS SANDSTONE
SANDSTONE
SILTSTONE
LIMESTONE
UNDULATORY BED SURFACE
LITHOLOGY
PARALLEL LAMINATIONS
LOW-ANGLE CROSS-BEDDING
TROUGH CROSS-BEDDING
PLANAR CROSS BEDDING
SLIGHT → INTENSE BIOTURBATION
OOIDS
FINING UPWARDS
SEDIMENTARY STRUCTURES
BROKEN FOSSILS
BIVALVES
BRACHIOPODS
GASTROPODS
ECHINOIDS
PLANT MATERIAL
VERTEBRATE MATERIAL
INSECT MATERIAL
FOSSILS
BURROWS
KEY FOR GRAPHIC LOGS

Log 1: Graphic log of the exposure at Eyford Hill Quarry, Grid reference SP 13032506



Depth	Sedimentary structures	Colour	Fossils	Additional notes	Unit No.
0.50 m – 1.10 m	(In parts); (Low angle) (Not extensive)	Grey/ Light grey	(within some beds); Death assemblages at bases of some beds.; (v. rare)	Consists of numerous beds of near-identical lithology. Rare *Thalassinoides*-like burrows.	5
0.40 m – 0.50 m		Grey with orange staining, weathers to Orange.	Less than 5%; ? ? (Possible insect material)	Lithology identical to Unit 1. More fossiliferous than Unit 1.	4
0.12 m – 0.40 m	(Rare)	Yellowy-Grey.	10-15% of rock	Very hard. Small & Large sand lenses. - Small lenses prevalent throughout (2-5 mm diameter). - Large lenses in lower half only (20-100 mm diameter). - Base gradational. - PTEROSAUR HORIZON	3
50 mm – 0.12 m	(Rare)	Grey, weathers to orange	? ? <5%	Ooids often dissolved out. Non-fissile. Small 2 mm diameter Sand lenses in top 30 mm of unit.	2
0 – 50 mm		Grey, orange staining; weathers to orange	? ? (All - < 5%)	Often sandy rottenstone: decalcified. Friable Fissile. Iron stained. Upper 2-5 mm often completely decalcified to sand.	1

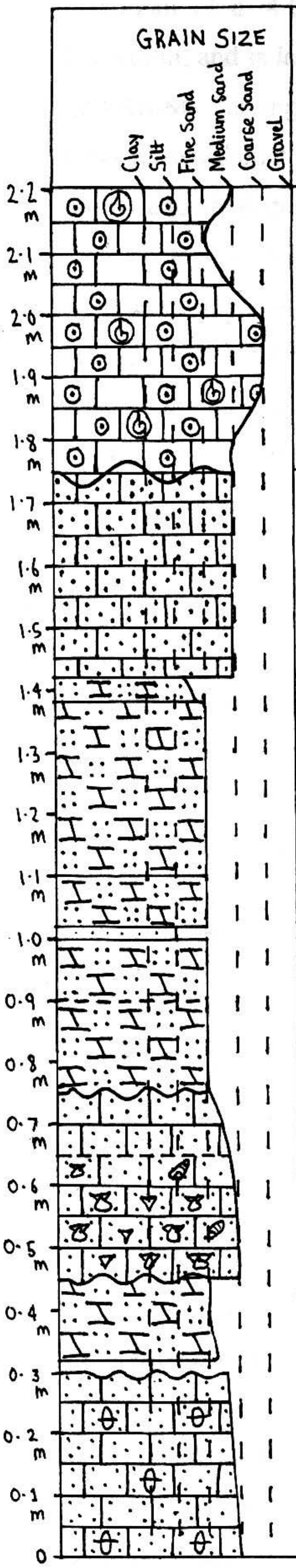
A description of the section at Eyford Hill Quarry follows, taken from the upthrown block to the east of the fault:

- Unit 5 (of aforementioned log): Unit is at least 1 m thick (top of unit appears to have been quarried off). It consists of a number of beds of varying thickness (0.1 - 0.3 m) which are lithologically almost identical. The rock is a SANDY LIMESTONE, light grey in colour, of fine sand grain size, and is intermittently laminated (2-4 mm thick when present). Localised low angle cross-bedding can be observed in the upper beds, with sets between 50 mm and 0.2 m in height. Ooids are present but rare. Beds are bioturbated by *Skolithos* and, rarely, *Thalassinoides*-like burrows. Fossils are rare or absent from the main body of the beds, but are often concentrated into thin death assemblages of bivalves, brachiopods and, rarely, gastropods at the bases of beds.
- Unit 4: Unit is 0.11 m thick. The rock is a fissile CALCAREOUS SANDSTONE, identical lithologically to unit 1, albeit with a more varied fossil content. In less decalcified areas of the unit, thin layers of ooids can be seen to be the source of the laminae (see Plate 5). More fragmentary plant, insect and vertebrate remains were found in this unit, including a shark's tooth (*Asteracanthus magnus* - see Plate 6) and indeterminate bone.
- Unit 3: PTEROSAUR HORIZON. Unit is 0.26 m thick. The rock is a BIOCLASTIC SANDY LIMESTONE, of fine to medium sand grain size, is light grey in colour, with abundant sand lenses (2 mm - 0.1 m in diameter) giving it a mottled yellow appearance. Sand lenses decrease in size upwards; grain size also fines upwards. No laminations are present. Bioturbation in the form of *Skolithos* burrows is concentrated at the top of the unit. Fossil content is high, consisting between 10 and 15 % of the rock, and comprises mostly disarticulated brachiopod and bivalve valves of various sizes and thickness, in jumbled orientation. These are seen in section and are thus unidentifiable. Gastropods are present but rare, also seen in section. In addition, the fragmentary remains of plants, insects and possible vertebrates are present. Ooids are present but rare, approach 1mm in diameter, and are scattered throughout the rock. The top of the unit is sharp and irregular.
- Unit 2: Bed is 70 mm thick. The rock is a SANDY LIMESTONE, of fine sand grain size, is grey in colour, weathering to orange, and is laminated. Laminae are faint, uniform in colour and 2-3 mm thick. Bioturbation is absent and fossils are rare, restricted to the occasional small (4 mm diameter) brachiopod. Ooids are present but rare, often dissolved out of the rock. Small 2 mm diameter sand lenses occur in the upper 30 mm of this unit, the top of which is gradational into unit 3.
- Unit 1: Bed is of indeterminate thickness; 50 mm are exposed. The rock is a fissile CALCAREOUS SANDSTONE, of fine to medium sand grain size, is grey in colour with iron-

stained bands, and is laminated[13]. Much of the rock is decalcified to a friable rottenstone and weathered to an orange colour, especially the upper 5 mm of the bed. Fossils consist less than 5% of the rock; disarticulated bivalves, articulated brachiopods, gastropods, and plant and insect fragments are present but rare. Bioturbation is present but slight, consisting of small (1mm diameter, 5mm depth) *Skolithos* burrows. The top of the bed is rippled.

[13] Laminae are of different colours and vary in thickness accordingly - reddish, iron-stained laminae are c. 7mm thick, while grey laminae are c. 1-2mm thick.

Log 2: Graphic log of the exposure at 'The Bushes', Grid Reference SP 12962544



SEDIMENTARY STRUCTURES	COLOUR	FOSSILS	ADDITIONAL NOTES	UNIT Nº.
	White, Pale grey, Brown.		Taynton Limestone Formation. Very jointed, flaggy. Maximum thickness at this locality - 2·5 metres. Scoured base. Coarser grain size - broken fossils.	13
(Low angle)	Grey.	(V. rare)	Beds 10 cm thick. Sandy Limestone. Recrystallised. Cross-stratified in places. Eyford Member (1-12)	12
	Grey.		Higher clay content.	11
(Low angle)	Grey, weathers to orange.	Rare	Sandstone, calcareous. Decalcified in places - then friable, iron-stained. Non-laminated.	10
	Grey, weathers to Orange	<5% ? ? ?	Fissile, finely laminated. Often decalcified to friable sand.	9
	Brown		Sandy Clay	8
	Grey, weathers to Orange	<5% ? ? ?	Fissile, finely laminated. Often decalcified to friable sand.	7
	Grey, weathers to orange	Rare	Decalcified, not laminated. Friable. Iron-staining.	6
(Rare)	Yellowy-Grey	(Small, rare) ? ?	Less fossiliferous than Bed 4. Small sand lenses.	5
(Slight) (Rare)	Yellowy-Grey	c. 10-15% of rock ? ?	Bed dies out to North. Large & small sand lenses. PTEROSAUR HORIZON	4
(On bedding planes only)	Grey, Weathers to Orange	<5% ? ? (Possible vertebrate material)	Calcite veins perpendicular to bedding. Fissile, finely laminated. Often decalcified to sand	3
	Green-Grey		Clay	2
	Grey, Orange tint when weathered	(Very rare)	Intensely burrowed. Rubbly surface appearance. Burrows infilled with coarser material. Eyford Member (1-12)	1

A description of the section at 'The Bushes' follows, taken from the southern end of the face as seen in Plate 7 (see Log 2):

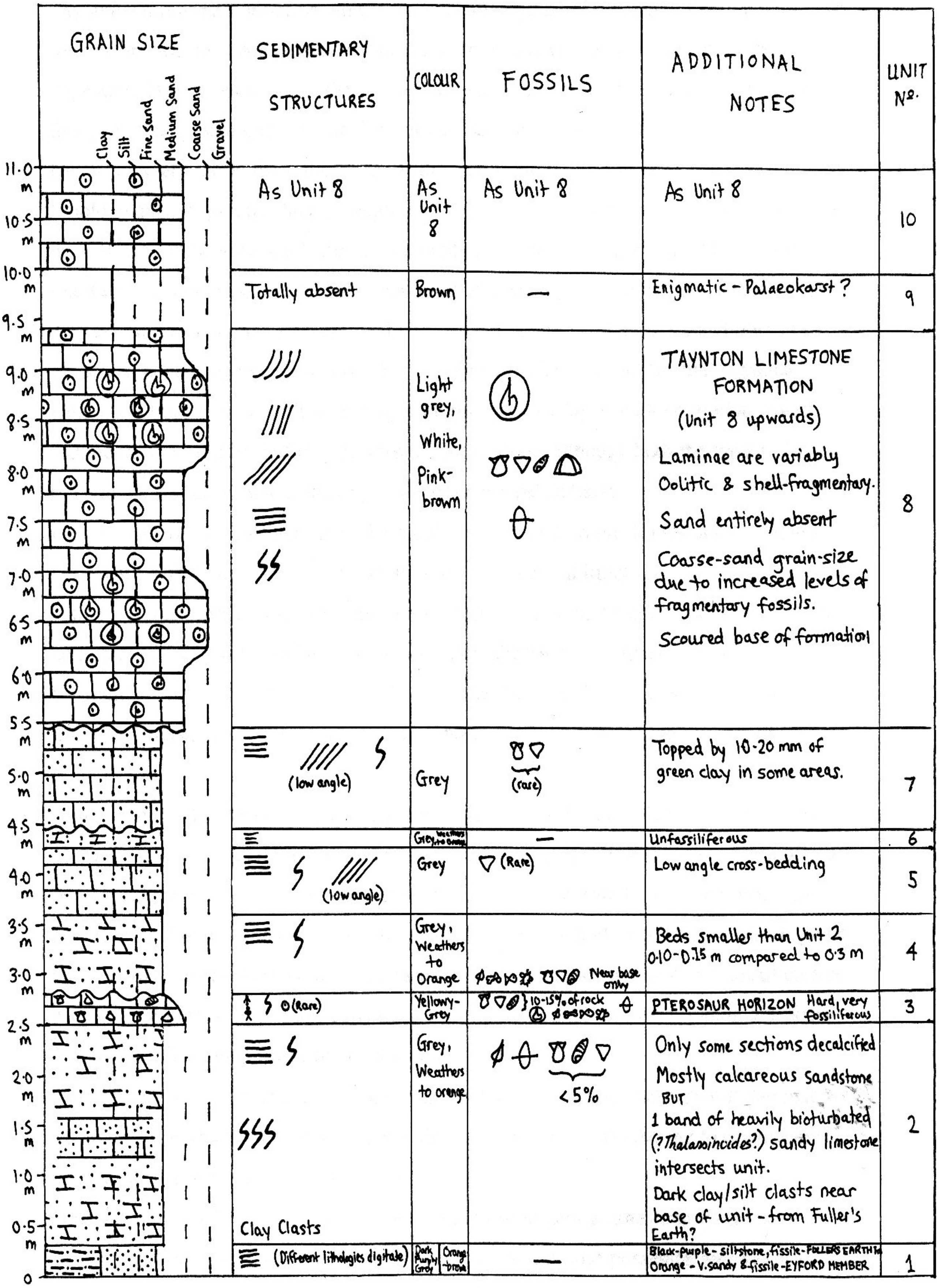
- Unit 13 (of aforementioned log): Unit is 1.5 m thick at area logged, but increases to a maximum of c. 4.5 m to the north. It is the basal unit of the Taynton Limestone Formation, and is largely lithologically homogenous throughout. The rock is an OOLITIC LIMESTONE, varying in colour between white, pale grey and brown, depending largely upon its weathered state. Its most obvious features are its very jointed, flaggy nature, oolitic and shell-fragmentary lithology and ubiquitous planar and trough cross-bedding (sets up to 0.5 m in height). In addition, the unit is completely devoid of quartz, in complete contrast to the underlying Eyford Member. Fragments of bivalves, brachiopods, echinoids (including spines) and gastropods can be seen; these are concentrated into beds in some places, although are fragmented so much as to be sedimentary particles of coarse sand grain size. Bioturbation is moderate, consisting exclusively of *Skolithos* burrows. The base of this unit is scoured and irregular, and seems to represent a non-sequential disconformity with the underlying beds of the Eyford Member.
- Unit 12: Unit is 0.32 m thick. The rock is a laminated SANDY LIMESTONE, of medium sand grain size, grey in colour, and consists of three beds each approximately 0.1 m in thickness. Low angle cross-bedding (sets about 50 mm in height) and some cross-stratification can be seen in places. Fossils are very rare, consisting of bivalves and brachiopods. Bioturbation is moderate, consisting of small *Skolithos* and possible *Thalassinoides* burrows. Laminae are approximately 2-3 mm thick. Ooids are absent. This unit is the uppermost unit of the Eyford Member exposed at this locality, determined as such by its high quartz content and disconformable boundary with the overlying Taynton Limestone Formation.
- Unit 11: Unit is 50 mm thick. The rock is a finely laminated (1 mm or less) CALCAREOUS SANDSTONE, of fine sand grain size, and is grey in colour, weathering to orange. Particles fine upwards, with a greater clay concentration towards the top of the unit. Fossils are absent.
- Unit 10: Unit is 0.28 m thick. The rock is a CALCAREOUS SANDSTONE, of fine sand grain size, and is grey in colour, weathering to orange. Localised low angle cross-bedding can be observed, sets not exceeding 0.15 m in height. Bioturbation is rare, in the form of *Skolithos* burrows. The rock is decalcified in places to a friable orange sand. Fossils are rare, comprising brachiopods, bivalves and gastropods.
- Unit 9: Unit is 80 mm thick. The rock is a fissile, laminated CALCAREOUS SANDSTONE, of identical lithology and fossil content to Unit 7.

- Unit 8: Unit is 20 mm thick. The rock is a brown sandy CLAY, of clay/fine sand grain size. Fossils are absent.
- Unit 7: Unit is 0.1 m thick. The rock is a fissile, laminated CALCAREOUS SANDSTONE, of fine sand grain size and grey in colour with iron staining in places. The rock is decalcified in places to a friable orange sand. Fossil content is less than 5% of the rock; disarticulated bivalves, articulated brachiopods, gastropods and plant and insect fragments are present but rare. Bioturbation is present but slight, consisting of small (1mm diameter, 5mm depth) *Skolithos* burrows. The base of the unit is gradational into Unit 6.
- Unit 6: Unit is 0.15 m thick. The rock is a CALCAREOUS SANDSTONE, of fine sand grain size and grey in colour. Laminations are absent. Much of the unit is decalcified to a friable orange rottenstone. Some evidence of bioturbation can be seen in the form of possible T*halassinoides* and *Skolithos* burrows. Fossils are present but rare, comprising disarticulated bivalves and brachiopods, and gastropods. The base of the unit is irregular and undulose.
- Unit 5: Unit is 0.1 m thick. The rock is a SANDY LIMESTONE, of fine sand grain size, fining upwards, and is yellowy-grey in colour due to the presence of small (c. 2mm diameter) sand lenses. Ooids are present but rare, often weathered out. Small brachiopods are present but rare, as are possible bone, and plant and insect, fragments. Some bioturbation is present in the form of *Skolithos* burrows. The base of the unit is gradational into Unit 4.
- Unit 4: PTEROSAUR HORIZON. Unit is 0.2 m thick. The rock is a BIOCLASTIC SANDY LIMESTONE, of fine to medium sand grain size, fining upwards slightly, and is yellowy grey in colour, weathering to a reddish brown. Sand lenses are abundant, reducing in size from 30 mm in diameter at the base of the unit to 2 mm in diameter at the top of the unit. Ooids are present but rare, approaching 1 mm in diameter. No laminations are present. Bioturbation in the form of *Skolithos* burrows is restricted to the top of the unit. Fossil content is high, consisting between 10 and 15 % of the rock, and comprising mostly disarticulated brachiopod and bivalve valves of various sizes and thickness, in jumbled orientation. These are seen in section and are thus unidentifiable. Gastropods are present but rare, also seen in section. In addition, the fragmentary remains of plants, insects and possible vertebrates are present. The base of the unit is irregular and undulose.
- Unit 3: Unit is 0.13 m thick. The rock is a fissile, laminated CALCAREOUS SANDSTONE, of fine sand grain size, fining upwards, and is light grey in colour with bands of iron staining. Laminae decrease in thickness upwards from 3mm at the base of the unit to 1mm at the top. Ooids are present and restricted to the bedding planes (see Plate 5). In some places small (5 mm diameter) calcite veins can be seen to run perpendicular to the

bedding. In many places, the rock is decalcified to a friable orange sand. Some bioturbation is present in the form of *Skolithos* burrows. Fossil content is less than 5% of the rock; disarticulated bivalves and brachiopods, gastropods, and possible bone, plant and insect fragments are present but rare.

- Unit 2: Unit is 20 mm thick. The rock is a CLAY, of clay grain size, and is green-grey in colour. Fossils and sedimentary structures are absent. The base of the unit is irregular and undulose.
- Unit 1: Unit is 0.3 m thick. The rock is a SANDY LIMESTONE, of medium sand grain size, fining upwards slightly, and is grey in colour, weathering to orange. This unit is intensely bioturbated by *Thalassinoides* burrows, giving the unit a rubbly surface appearance. The burrows are often filled in by a coarser material, often consisting of fragmented shells. It is sparsely fossiliferous, containing brachiopods.

Log 3: Graphic log of the exposure at Huntsman's Quarry working face, Grid reference SP 12102563



A description of the section at Huntsman's Quarry main face follows (see Log 3):

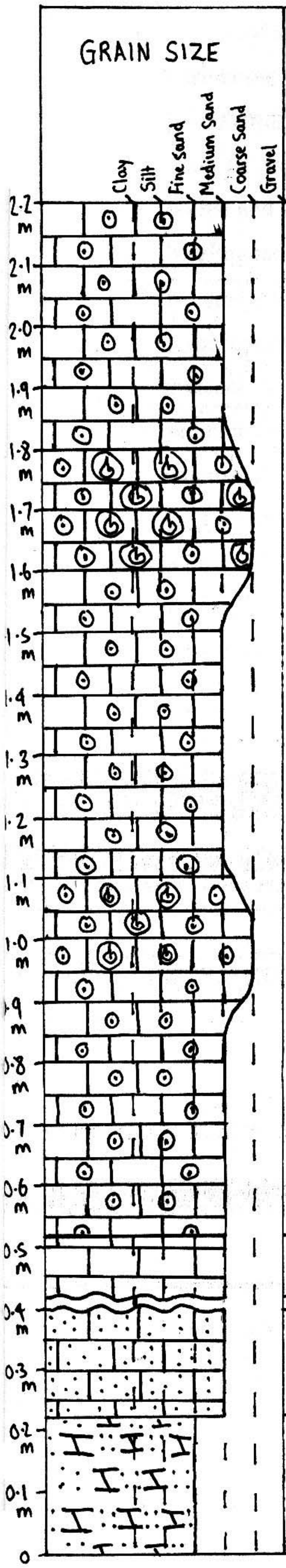
- Unit 10 (of aforementioned log): Unit is 1 m thick, overlain by soil. It is part of the Taynton Limestone Formation, and is largely lithologically homogenous throughout. The rock is an OOLITIC LIMESTONE, varying in colour between white, pale grey and brown, depending largely upon its weathered state. Its most obvious features are its jointed and in this case, flaggy nature (being the first rock to be removed in the quarrying of this face, it has weathered more than the rest of the succession), oolitic and shell-fragmentary lithology and ubiquitous planar, trough (most common) and low angle cross-bedding (sets up to 0.75 m in height) (see Plate 10). In addition, the unit is completely devoid of quartz. Fragments of bivalves, brachiopods, echinoids and gastropods can be seen; in places these are very fragmentary and concentrated into beds of coarse sand grain size. Bioturbation is moderate, consisting exclusively of *Skolithos* burrows. The base of the unit is planar.
- Unit 9: Unit is 0.6 m thick. It is an enigmatic brown CLAY layer, with no obvious fossils or sedimentary structures, and may represent a palaeokarst, although both the top and base of the unit are planar, which is unlikely in the case of a palaeokarst.
- Unit 8: Unit is 4.05 m thick. It is the basal unit of the Taynton Limestone Formation at this locality. The rock is an OOLITIC LIMESTONE, of identical lithology and fossil content to Unit 10. Being more accessible than the aforementioned unit, the cross beds can be seen to be laminated (c. 2 mm thickness), and are often alternately composed of ooids and shell fragments. Some beds have a pinkish hue. The base of this unit is scoured and very irregular, suggesting a non-sequential disconformity with beds of the underlying Eyford Member.
- Unit 7: Unit is 1 m thick. It is the uppermost unit of the Eyford Member at this locality. The rock is a laminated SANDY LIMESTONE, of fine sand grain size, grey in colour, and possesses localised low angle cross-bedding, sets no larger than 0.15 m. Laminae measure no less than 2 mm in thickness. It is topped by a very thin and intermittent layer of green clay in some areas. Fossils are very rare, consisting of brachiopods and disarticulated bivalves. Bioturbation is rare, consisting of small *Skolithos* burrows. Ooids are absent. The base of this unit is irregular and undulous.
- Unit 6: Unit is 0.2 m thick. The rock is a laminated CALCAREOUS SANDSTONE (laminae no less than 2 mm thick), of fine sand grain size, grey in colour, weathering to orange, and is unfossiliferous as far as can be seen. It has a planar base.
- Unit 5: Unit is 0.65 m thick. The rock is a laminated sandy limestone (laminae no less than 2 mm thick), of fine sand grain size, grey in colour, and possesses low angle cross-bedding, sets no larger than 0.2 m. Cross stratification can also be seen in places. Ooids

are absent. Fossils are very rare, only small brachiopods were found. Bioturbation is rare, consisting of *Skolithos* burrows. The base of the bed is planar.

- Unit 4: Unit is 0.8 m thick. The rock is a laminated, fissile CALCAREOUS SANDSTONE, grey in colour with bands of orange iron stains, weathering to orange, and is of fine sand grain size. Unit comprises a number of beds, thicknesses in the region of 0.1 - 0.15 m. Terrestrial fossils characteristic of this lithology at other localities are restricted to the lower 0.3 m of this unit; the usual marine fossils - disarticulated bivalves, brachiopods and gastropods, are ubiquitous throughout the unit although more numerous towards the base, but never make up more than 5 % of the rock. Bioturbation is low, consisting of rare *Skolithos* burrows. The rock is rarely decalcified (as a result of its recent exposure to the elements) to a friable orange sand. The base of the unit is irregular and undulose.
- Unit 3: PTEROSAUR HORIZON. Unit is 0.3 m thick. The rock is a BIOCLASTIC SANDY LIMESTONE, of fine to medium sand grain size, fining upwards slightly, and is yellowy grey in colour, weathering to a reddish brown. Sand lenses are abundant, reducing in size from 30 mm in diameter at the base of the unit to 2 mm in diameter at the top of the unit. Ooids are present but rare, approaching 1 mm in diameter. No laminations are present. Bioturbation in the form of *Skolithos* burrows is restricted to the top of the unit. Fossil content is high, consisting between 10 and 15 % of the rock, and comprising mostly disarticulated brachiopod and bivalve valves of various sizes and thickness, in jumbled orientation. These are seen in section and are thus unidentifiable. Gastropods are present but rare, also seen in section. In addition, the fragmentary remains of plants, insects and possible vertebrates are postulated, although were not observed due to the problems described in section 3. 3. 3. The base of the unit is irregular and undulose.
- Unit 2: Unit is 2.2 m thick. The rock is predominantly a fissile, laminated CALCAREOUS SANDSTONE, grey in colour, with orange bands of iron staining, weathers to orange, and is of fine sand grain size. Most beds within this unit are lithologically homogenous; there is one exception - a heavily bioturbated (*Thalassinoides* burrows) sandy limestone bed 0.15 m thick, near the top of the unit. This is very similar/identical to the basal unit at 'The Bushes'. Very small micro-ooids (< 0.5 mm diameter) were observed in some beds. Fossil content is similar to the upper beds of Unit 4. The basal bed of this unit contains angular very dark grey clasts, which may be clay/siltstone clasts from the underlying Fuller's Earth Formation. This unit is the basal unit of the Eyford Member.
- Unit 1: 0.3 m of unit is exposed here, before dissappearing into the ground. It consists of a orange-grey fissile, laminated calcareous sandstone, interdigitating laterally with a laminated slightly fissile dark purple-grey siltstone, and may represent initial deposition of

the Eyford Member onto the irregular surface of the Fuller's Earth Formation (see Plate 12). The surface exposed on the quarry floor is rippled across both lithologies, suggesting either a slight erosive sequence before deposition of unit 2, or showing that the sandy lithology is actually part of the Fuller's Earth Formation, instead possibly representing a transition to the more sandy Eyford Member.

Log 4: Graphic log of the exposure at Brockhill Quarry, Grid reference SP 13522393



SEDIMENTARY STRUCTURES	COLOUR	FOSSILS	ADDITIONAL NOTES	UNIT Nº.
⊙ ; //// ; S→SS→SSS	White, Light grey, Pink-brown	▽	TAYNTON LIMESTONE FORMATION (Units 4 & 5) Sand entirely absent Coarse sand grain size due to increased levels of fragmentary fossils. Scoured base to formation Much evidence of cross-bedding, indicative of High-energy conditions. Biotubation levels vary and are mainly *Skolithos*.	5
⊙ (Decalcified)	Light grey	▽ (1 specimen)	Friable if not decalcified, T.L.Fm. Contains some clay, no sand.	4
	Grey-Green		Clay	3
≡ //// (Low angle) SS	Grey	▽	Beds c. 80mm-0.1m thick Sandy Limestone Some X-stratification?	2
S	Grey, weathers to orange	▽ < 5%	Decalcified, unlaminated. Friable, Iron stained (1&2-Eyford Member)	1

A description of the exposure at Brockhill Quarry follows (see Log 4):

- Unit 5 (of aforementioned log): Unit is over 2 m thick. It is part of the Taynton Limestone Formation, and is largely lithologically homogenous throughout. The rock is an OOLITIC LIMESTONE, varying in colour between white, pale grey and brown, depending largely upon its weathered state. Its most obvious features are its very jointed, flaggy nature, oolitic and shell-fragmentary lithology and ubiquitous planar, trough and low angle cross-bedding (sets up to 0.5 m in height). In addition, the unit is completely devoid of quartz, in complete contrast to the underlying Eyford Member. Fragments of bivalves, brachiopods, echinoids (including spines) and gastropods can be seen; these are concentrated into beds in some places, although are fragmented so much as to be sedimentary particles of coarse sand grain size. Bioturbation is moderate, consisting exclusively of *Skolithos* burrows. The base of this unit is planar.
- Unit 4: Unit is 0.1 m thick. It is the basal unit of the Taynton Limestone Formation, and seems to be a partly decalcified variant of the overlying unit. It is partly friable, containing some clay but no sand. Its base is scoured and irregular, and seems to represent a non-sequential disconformity with the underlying beds of the Eyford Member.
- Unit 3: Unit is 20 mm thick. It is a green-grey CLAY, with no noticeable fossils or sedimentary structures. Both the base and top of this unit are irregular and undulose.
- Unit 2: Unit is 0.18 m thick. It is the uppermost bed of the Eyford Member exposed at this locality. The rock is a SANDY LIMESTONE, of medium sand grain size, and is grey in colour. Localised low angle cross-bedding can be observed, sets not exceeding 0.15 m in height. Some cross stratification can also be observed. Bioturbation is moderate, in the form of *Skolithos* and possible *Thalassinoides* burrows. The rock is decalcified in places to a friable orange sand. Fossils are rare, comprising brachiopods and bivalves. The beds are 0.1 m and 80 mm thick respectively. The base of the unit is planar.
- Unit 1: Unit is 0.22 m thick. The rock is a calcareous sandstone, of fine sand grain size, and is grey in colour, weathering to orange. Some bioturbation is present in the form of *Skolithos* burrows. Fossil content is less than 5 % of the rock, and comprises disarticulated bivalves, brachiopods and gastropods. The rock is non-laminated, and decalcifies to a friable orange sand.