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Beginning of Mesozoic marine overstep of the Mendips: The Rhaetian and its fauna at Hapsford Bridge, Vallis Vale, Somerset, UK

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ABSTRACT

One of the most dramatic environmental changes in the Mesozoic history of Europe was the switch from terrestrial to marine deposition marked by the Rhaetian Transgression, 205 Ma. Beginning with this event, the Mendip Hills, composed primarily of uplifted and folded Lower Carboniferous limestones, were flooded in a stepwise manner from the Late Triassic to mid Cretaceous. The basal Rhaetian beds at the eastern end of the Mendips (Hapsford Bridge, Vallis Vale) lie directly on Carboniferous limestone, which was bored, indicating it functioned as a hardground. Bored pebbles were then eroded, transported, encrusted with bivalves, and deposited in marine muds in the lower parts of the Westbury Formation. At certain levels also, suspended mini-conglomerates within finer-grained sediments suggest continuing storm activity. The Hapsford Bridge Rhaetian bone bed includes microvertebrate remains of four species of sharks and two species of bony fishes, all of them typical of Rhaetian-aged bone beds. The invertebrate fauna is especially rich, including bivalves and echinoids, as well as trace fossils. Unusual elements are barnacles and a possible belemnite.

1. Introduction

The Late Triassic was a time of major environmental change. The Rhaetian transgression marks the switch from primarily terrestrial to marine conditions about 205.5 Ma, and it has been noted across much of Europe. The event is marked in the UK by the switch from the Mercia Mudstone Group to the Penarth Group (Fig. 1), starting with the famous Westbury Formation basal bone bed, which is made up of a rich accumulation of disarticulated vertebrate fossils (Storrs, 1994). The change is evident at many localities, especially those such as Aust Cliff (Cross et al., 2018) where the Mercia Mudstone Group largely comprises red beds and is conformably overlain by the black-coloured shales of the Westbury Formation.

The Rhaetian transgression was probably triggered by the break-up of Pangaea, marked by emplacement of the Central Atlantic Magmatic Province and major rifting on the Afro-European and North American sides (Wall and Jenkyns, 2004). In South Wales and south-west England, from south Gloucestershire to Somerset and Dorset, the Rhaetian and other Mesozoic sedimentary units accumulated on top of an exposed landscape formed from uplifted, folded and subaerially weathered Palaeozoic rocks, primarily Lower Carboniferous limestones, but also Devonian sandstones and Upper Carboniferous coal-bearing sediments. These limestones have been quarried for a long time across the Mendip Hills, south of Bristol, and the quarrying activity often cut down through overlying Mesozoic sediments.

Much of this geological story can be seen in Vallis Vale (Fig. 2A), a narrow valley in the south-eastern Mendips, located between the villages of Great Elm and Hapsford, just north of Frome. By 1890, the Vale was an industrial site, with lime kilns, iron workings, and woollen mills, all powered by the fast-flowing waters of the tiny Mells River. But, when Buckland and Conybeare (1824, p. 225) visited the steep-sided valleys of Mells and Vallis, they were quiet and secluded, and they noted that '[b]eautiful sections may be seen in the precipitous sides of these valleys, exhibiting the oolitic strata in an absolutely horizontal position, reposing on the truncated edges of highly inclined strata of mountain limestone [sic].' Much

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[1] In honour of Charles Copp (1949–2009) who carried out extensive work on the Hapsford Bridge site in the 1980s and from whose unpublished PhD Thesis work we have drawn upon throughout the paper.

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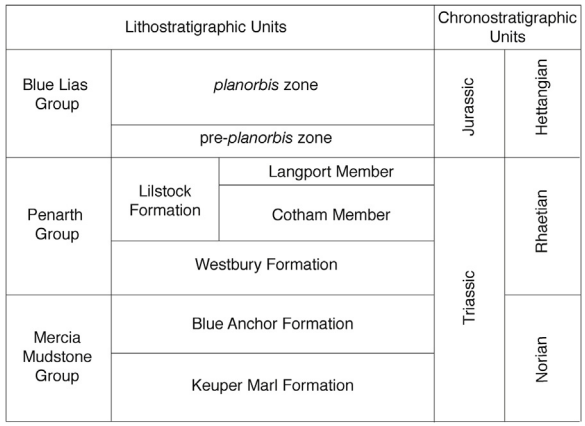

Fig. 1. Summary of Late Triassic and Early Jurassic stratigraphy in England (after Swift, 1999; Trueman and Benton, 1997).

the same observations were repeated by De la Beche (1846, p. 287), when he wrote that Buckland and Conybeare had observed how Vallis Vale and Murdercombe 'show the inferior oolite [sic] in nearly horizontal beds upon the upturned edges of the carboniferous limestone [sic], with occasionally an interposed portion of a conglomerate referable to the lias [sic], and containing organic remains'. De la Beche (1846, p. 288) illustrated the Carboniferous-Middle Jurassic unconformity (now commonly referred to as the De la Beche Unconformity) in the old quarry opposite the confluence of the Egford Brook and Mells River (ST 7557 4918).

Charles Moore collected in the area during the early 1860s and passed some invertebrate fossils to T. Rupert Jones, who named *Estheria minuta* var. *brodieana* (now *Euestheria*), based partly on this material, and gave a brief sketch of the geological succession at Vallis Vale (Jones 1862). It was Moore (1867, pp. 488–491), however, who provided the first detailed information on the Vallis Vale sections, describing the succession in several quarries, including that with the De la Beche unconformity, and noting especially that the rocks either side of the Carboniferous-Jurassic contact could be hard to distinguish in hand specimen, so close was the lithological similarity of the two units. He described quarries along the eastern branch of the Vale, towards Hapsford, where he observed Liassic-age fissures in the Carboniferous limestone, and made the first mention of bedded Rhaetian-age sediments. He noted (Moore, 1867, p. 489) that 'A thin bed of a waterworn pebbly conglomerate, which will be found continuous and of greater thickness in succeeding sections, makes its appearance, resting for a short distance immediately on the Carboniferous Limestone.'

Moore (1875) provided further description of the geology of Vallis Vale, and later (Moore, 1881, pp. 67–68) commented, 'At the entrance to the Vallis at Hapsford the first sections show irregularly bedded Rhaetic conglomerates resting in depressions on the edges of the inclined Carboniferous limestone. They are separated by thin blue clays with *Avicula contorta* and also *Discina Babiana* [sic]. I have no doubt they would yield important vertebrate remains, as I found a very perfect Dinosaurian vertebra; but, unfortunately, these beds have not been worked for some years.' Finally, McMurtrie (1885, pp. 103–106) repeated some of Moore's comments, but especially highlighted how the Carboniferous limestone along the banks of the Mells River was overlaid successively by Rhaetian, Lias and Middle Jurassic rocks, corresponding to an inferred steeply rising palaeotopography of the eroded top of the Carboniferous limestone (Fig. 1B). Woodward (1890) gave a generalised overview of Mendip geology, and provided (p. 489, Fig. 2) a rather poorly redrawn version of the unconformity illustrated by De la Beche (1846, p. 288).

The Rhaetian sections of the Hapsford Bridge end of Vallis Vale were mentioned by Reynolds and Richardson (1909); Richardson (1907,1909, 1911), Richardson and Young (1909); Reynolds (1912); Cox (1941); Savage (1977), and Duff et al. (1985, pp. 135–139). Detailed studies were carried out in his unpublished thesis by Copp (1980), who made extensive collections at Vallis Vale and his sedimentary log was published (Copp in Duffin, 1982), but none of his other work. Orbell (1973) and then Warrington (1984) reported palynological investigations from the section at Hapsford Bridge, comprising miospores and organic-walled microplankton that indicate Rhaetian age, and equivalence to horizons from Chilcompton. Furthermore, Hapsford Bridge became the type locality for the penaeid shrimp, *Aeger gracilis* (Förster and Crane, 1984; Boomer et al., 1999, pp. 141–144). The Hapsford Bridge sections were cleared in 1979–1980 by Charles Copp and colleagues, with funding from the Nature Conservancy Council.

The aim of this paper is to present a report of the Rhaetian at Hapsford Bridge in Vallis Vale. We present evidence that the Rhaetian Transgression was accompanied by hardground formation and the beginning of overstep of the Mendip islands, as well as evidence for several storm events associated with deposition of various levels of the Westbury Formation. We also document the Rhaetian bone bed faunas and compare them with examples from around Bristol and in South Wales.

Repository abbreviations: **BATGM**, Bath Royal Literary and Scientific Institution, geology collection; **BRSMG**, Bristol City Museum and Art Gallery, geology collection; **BRSUG**, University of Bristol, School of Earth Sciences, geology collection.

2. Geological setting

2.1. Quarrying in the Vallis Vale

Hapsford Bridge is part of the Vallis Vale Site of Special Scientific Interest (SSSI), scheduled for conservation especially because of the De la Beche unconformity, where yellow-coloured Middle Jurassic limestones sit horizontally on top of a planed-smooth palaeotopography of uplifted and steeply dipping Carboniferous limestones (De la Beche, 1846, pp. 287–288). Vallis Vale is lined with quarry faces which have been abandoned over time and these have become overgrown. It is a popular site for walkers, with a stream, car park and footpath (Prudden, 2006).

Stone quarrying was a long-established industry in the Mendip Hills, providing a diversity of building stones (Stokes, 1999). Quarrying in Vallis Vale began in 1893 with the formation of the Somerset Quarry Company (Foundations of the Mendips, 2017) to

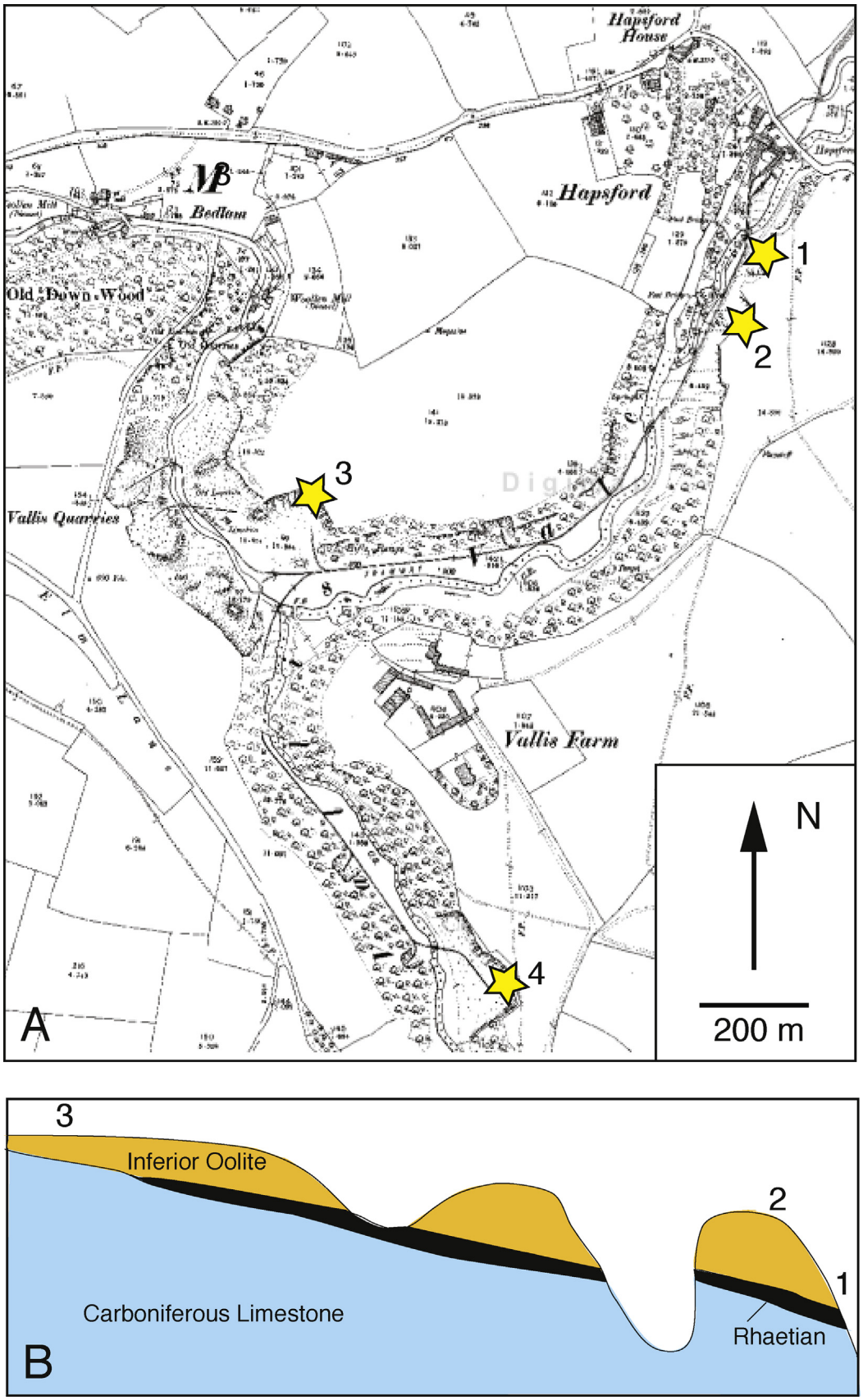

Fig. 2. The context of Vallis Vale, showing the Vale in 1906, when the quarries and mineral railways were active. (A) The four locations discussed in the paper are numbered (1, Hapsford Bridge Rhaetian site; 2, neighbouring quarry also showing Carboniferous-Rhaetian unconformity; 3, the site of the De la Beche unconformity between Carboniferous and Inferior Oolite (Middle Jurassic); 4, Egford quarry, comprising a great thickness of Carboniferous limestone). (B) The Rhaetian overlies the Carboniferous limestone along much of the banks of the Mells River, from localities 1 to 3, but disappears between 2 and 3. For A, © Crown Copyright and Database Right 2018. Ordnance Survey (Digimap Licence).

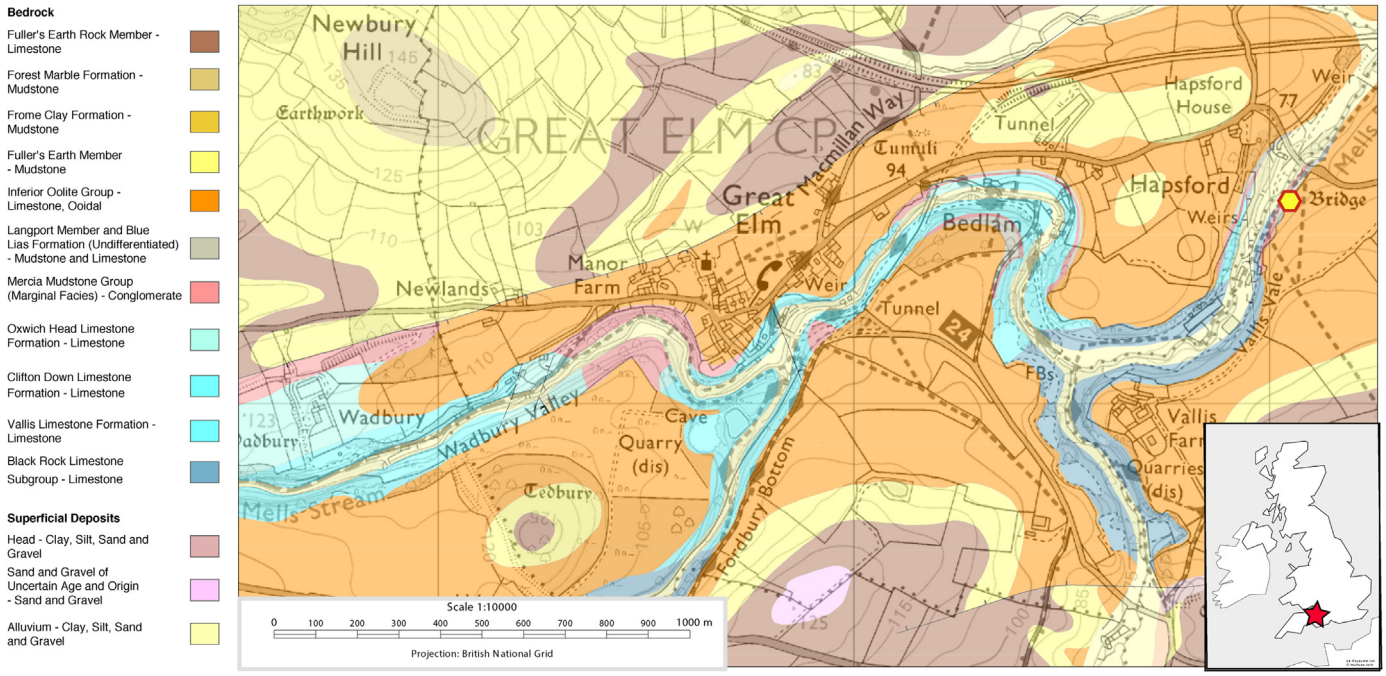

Fig. 3. Geological map of Vallis Vale and neighbouring areas, with map of Great Britain to show general location (marked with star). The Hapsford Bridge site is marked with a hexagon. © Crown Copyright and Database Right 2018. Ordnance Survey (Digimap Licence), and British Geological Survey.

work quarries in the valley of the Mells River beside Hapsford Mill, on the Vallis Road (A362). The company worked four quarry faces along the south bank of Vallis Vale (Fig. 2A, localities 1–3), and the 41-man team produced over 100 tons of rock a day of which 10 % was burnt for lime in two quarry kilns and the rest was crushed for road building (Thornes, 2015, p. 75). The limestone was transported in wagons called 'tubs' and drawn by horses along narrow-gauge rail lines to Hapsford Mill. There, the full tubs of stone were lifted to a higher level by a wire system, and dumped into the hoppers of the stone-crushing machinery, which was powered by the water flow of the Mells River or, when the flow was insufficient, by a steam engine (Anonymous, 1898).

Soon, these horse-drawn wagons were replaced by steam engines on the narrow-gauge rail lines. As the business grew, and became a registered company in 1907, the operation expanded to quarrying six faces along the banks of the Mells River and Egford Brook, and eventually 12, which more or less connected continuously (Fig. 2A, between sites 2–4). The stone was shipped out along the narrow-gauge railway lines, which connected up Vallis Vale past Hapsford Mill eastwards to join the standard-gauge Radstock–Frome line of the Great Western Railway which runs past the Vale (Atthill, 1984). The 1906 and 1936 Ordnance Survey maps show the narrow-gauge railway running on the south bank of the Mells River at Hapsford, right beside the Rhaetian section, and crossing to the north bank of the river to branch eastwards beside Hapsford Mill (Fig. 2A). The lines extended for some $2^1/_2$ miles and were worked by two small four-wheeled Ruston Hornsby diesel locomotives.

The Somerset Quarry Company became Roads Reconstruction (1934) Ltd., and then Hanson PLC in 1989. The narrow-gauge line was replaced in 1943 with a standard gauge system (Thornes, 2015). Quarrying in Vallis Vale reduced after the war and ceased in the 1960s. Meanwhile, New Frome Quarry, later renamed Whatley Quarry (UK National Grid Reference, ST 731479), opened in the 1940s to the west of Vallis Vale, generated over 2.5 million tonnes yearly from the 1980s onwards, and remains one of the two largest quarries still in operation in Somerset (Quarry Faces, 2019). The Somerset limestones also have a history of being used for lime-burning and other by-products including poultry grit, and concrete (Loupekine, 1956). Evidence of the quarrying still remains today, with broad gravel tracks beside the streams where the mineral railways used to run. Remains of eight lime kilns can also be found in the Vallis area.

2.2. The quarry sites

There are some questions regarding the nomenclature of the sites. Moore (1867, pp. 488-490) describes his route round Vallis Vale, from 'Eggford' (Egford), now the visitor car park, heading north beside Egford Brook to the De la Beche unconformity quarry, and then northwards beside the Mells River through wooded slopes. He then turns east along the other branch of the Mells River 'towards Hapsford' and describes a series of quarries on the south side showing considerable thicknesses of Carboniferous limestones, and terminating at Hapsford Bridge (Fig. 2A, south bank of Vallis Vale, including localities 2 and 1). McMurtrie (1885, p. 104) refers to the site as the Vallis, and identifies quarries A, B and C along the southern bank of the Mells River, of which the last is Hapsford. Richardson (1911, p. 64) mentions the site as Hapsford-Mills. Since the mills at Hapsford Bridge no longer exist, we follow other authors in using the term 'Hapsford Bridge' instead.

Our work focuses on the Rhaetian bone beds at the Hapsford Bridge roadside locality (ST 76057 49507) which runs parallel to the Mells River (Fig. 2A, locality 1). Other quarries in the Vallis area were also examined (Fig. 2A) and these include two further disused quarries (ST 760494, ST 760493; location 2), the site of the De la Beche unconformity (ST 7557 4918; location 3), and Egford Quarry (ST 7575 4871; location 4).

The geology around Vallis Vale (Fig. 3) comprises mainly Middle Jurassic sediments to the east, with a meandering strip of Carboniferous rocks exposed by the action of the Mells River, and then massively exposed in Whatley Quarry to the west. Mercia Mudstone and Penarth Group sediments occur to the west, and in small patches along the Vale.

2.3. Sedimentary logs

The first detailed account of the Rhaetian at Hapsford Bridge was presented by Moore (1867, p. 490), who gave a measured section from the roadside quarry (here reversed, with oldest rocks lowest):

	ft. in. (cm)
1. Stone in lower corner, lithologically like "White Lias," but without any trace of organic remains, about	2 0 (61.0)
2. Irregular masses of conglomerate	2 0 (61.0)
3. Series of thinly laminated grey marls without any trace of organisms	3 0 (91.4)
4. Irregular conglomerates surrounded by blue pebbly marls	3 0 (91.4)
5. Blue marl with flattened pebbles	0 9 (22.9)
6. Bed of conglomerate	0 6 (15.2)
7. Clay	1 0 (30.5)
8. Clay	0 2 (5.1)
9. Conglomerate	0 9 (22.9)
10. Clay	0 2 (5.1)
11. Stratified conglomerate	0 10 (25.4)
12. Blue clay parting	0 2 (5.1)
13. Rhaetic conglomerate, resting immediately on the above	0 4 (10.2)
14. Carboniferous Limestone with horizontal surface, but very highly inclined	

Richardson (1911, pp. 63–65) benefited from larger exposures after excavation of the rail lines and commercial quarries and was able to provide further details. He reported what he saw in McMurtrie's (1885) three quarries, with 5 m of Carboniferous limestone visible at the south-western end, succeeded by 1.2 m of Rhaetian and 3.7 m of Inferior Oolite. At Hapsford Bridge, he gave a further measured section which agrees with that by Moore (1867), except that he reports *Euestheria* (under the earlier designation *Estheria*) and plant remains in his bed 4, part of the Cotham Member, and he confirms that the uppermost unit is indeed the "White Lias", part of the Langport Member (Boomer et al. 1999, p. 140).

During field work in October 2018, all the Vallis Vale sites mentioned in the earlier literature were identified (Figs. 2A, 4), sedimentary logs were made, and bone bed samples collected. We compare the sections by Moore (1867, p. 490) and Richardson (1911, p. 65) with our measured section (Fig. 5A–C). We found the section was 5–6 m high, along the bank of what had been cut for a railway siding, and now marks the edge of the access road. Only the lower half could be logged, as the upper portion is obscured by a cover of soil and tree roots which was impossible to clear by hand (Fig. 4C). We noted (Fig. 5C) 0.7 m of Carboniferous limestone (Black Rock Limestone Subgroup) at the base, overlain by 2.3 m of Westbury Formation, comprising irregularly bedded limestones, separated by thin blue clays. The Carboniferous-Rhaetian unconformity is marked by a bored hardground, as shown by reworked pebbles (see Section 5), succeeded by 63 cm of muddy limestone showing evidence of storm-bed activity (see Section 6). This is succeeded by a calcareous sandy bone bed with fossil fragments (8 cm thick), 40 cm above which we located a further bone-bearing horizon in a 33-cm-thick muddy limestone. The upper 3 m of this Rhaetian section thins southwards as the unconformity surface at the top of the Carboniferous Limestone rises.

3. Materials and methods

Most of the palaeontological study is based on samples of the basal Rhaetian bone bed collected in October 2018 (Fig. 4). Samples were taken from the measured beds (Fig. 4C), with some 1 kg each of potential bone beds sampled from Beds 2, 3 4, 5, 6 and 8 and small blocks from beds 4, 6 and 8 collected for slab-cutting (Fig. 13). The fossiliferous sediment samples were processed in the Palaeobiology Laboratory at the University of Bristol by Adam Parker. The method of preparation followed that described by Landon et al. (2017). The material was initially treated with a 5% solution of acetic acid in water (total volume of 4 litres) to keep pH consistent and was left for 20 min with a buffer of calcium carbonate and tricalcium di-orthophosphate (4 g and 2 g). The material was then left for two days, by which time the reactions had finished. After acid digestion, the large (>2.0 mm) undigested material was set aside, and the remainder was washed through a series of sieves with gauges of 2.0 mm, 0.5 mm, and 0.18 mm to separate the material into exact sediment fractions.

A hose and a squirt bottle were used to wash each of the sediment fractions into a separate filtration system made of a filter-paper-lined funnel in a beaker, where it was left for 24 h to drain fully. The remaining undigested sediment was placed in a bucket of water for 72 h and was then sieved and filtered using the same process as before. After this, the residue was air dried before being treated with acid again. This process was repeated through a number of cycles until all the sediment matrix had been digested. The acid-digested concentrate fractions were then hand-picked under a binocular microscope and fossils classified and separated into small collection boxes.

The best examples of each morphotype were photographed using a Leica DFC425 C camera on an optical microscope with multiple image-stacking software. Usually, some 20 digital images were taken and then fused, and this minimised depth-of-field effects. The digital images were cleaned and saved at 600 dpi and prepared as plates for the systematic descriptions.

4. Systematic palaeontology

4.1. Introduction

Vallis Vale has been a rich source of fossils from the Rhaetian, Lias and Middle Jurassic. Here, we review the microvertebrates and invertebrates found at the Hapsford Bridge locality (Figs. 6–10), including fossils collected by Michael D. Crane and Rosie H.B. Crane in March and April 1978 for comparison (BRSMG collections; Crane-Copp correspondence; Geology File No. CRA 31, 1–34). In earlier accounts, Moore (1867) and Richardson (1907, 1911) reported extensive collections of invertebrates from the limestone beds of the Westbury and Lilstock formations, which we do not include here. Richardson (1911, p. 65) also reported many lycopod plant remains, and he identified the shark and bony fish teeth in the basal bone bed as well as fish scales in the Cotham Member. The German palaeontologist Erika von Huene (1933) reported the mammal-like tooth *Tricuspes* sp. from Vallis Vale, a genus identified earlier from the German Rhaetian, and possibly belonging to a cynodont (Storrs, 1994). Such a find is unusual in the British Rhaetian bone beds, but much more common at several sites in continental Europe, in Belgium, Luxembourg, and France for example (Lukic-Walther et al., 2019). The specimen is probably BATGM C108 (Storrs 1994, p. 246).

In unpublished work, Copp (1980) reported on all the fossils from the different horizons at Hapsford Bridge, especially the invertebrates, based on collections now in BRSMG. A summary of his main findings is as follows. In the dark-coloured clays at the base of the Rhaetian, Copp (1980, pp. 24–26) reported an abundant fauna including the bivalve *Atreta intusstriata* (common) and *Lopha fimbriata* (fragments), echinoid spines, and neritopsid gastropod opercula. These, he noted, are rare in the British Rhaetian. He also noted rare *Rhaetavicula contorta*, as well as other bivalves, gastropods and brachiopods. Numerous limestone pebbles show borings of *Polydorites* (= *Gastrochaenolites*) and *Trypanites* (see Section 5). In the conglomeratic limestones (his beds 2, 4; the basal

Fig. 4. Hapsford Bridge roadside locality and De La Beche unconformity. (A) The roadside section being measured by (from left to right) Jack Lovegrove, Mike Benton, James Ronan, and Doug Robinson. (B) Jack Lovegrove and James Ronan log the Westbury Formation sequence, lying above Carboniferous limestone at the base. (C) Logging higher in the section, and difficulties of clearing soil and vegetation, with Jack Lovegrove, Joe Flannery Sutherland and James Ronan. (D) Beds 2–6 of the Westbury Formation, showing the basal bone bed, level with the hammer head, overlain by muddy limestone and limestone beds. (E) The De la Beche unconformity, which is slightly overgrown by vegetation, showing the yellow horizontally bedded Jurassic Inferior Oolite lying unconformably on the steeply dipping Carboniferous limestone (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

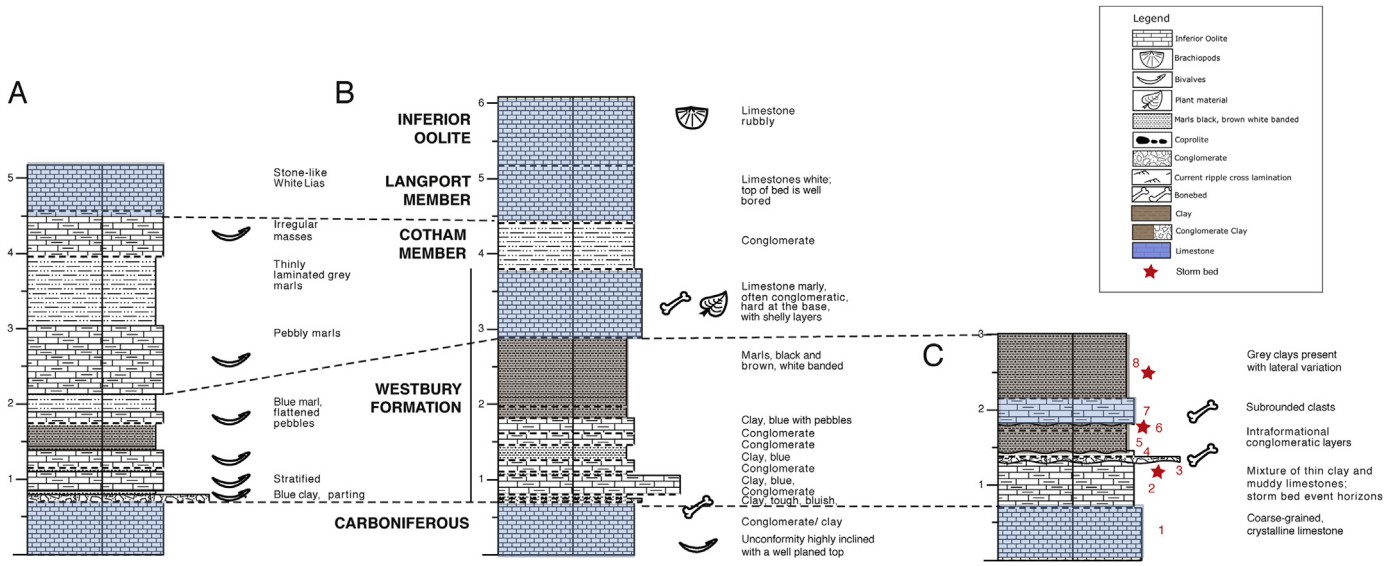

Fig. 5. Sedimentary logs of the Rhaetian beds at Hapsford Bridge, Vallis Vale ST 76057 49507. Log A data from Charles Moore (1867); (B) data from Richardson (1911) and (C) the log we measured in 2018. In (C), we indicate our bed numbers 1–8, and mark inferred storm beds on our section (see Fig. 6). Thicknesses in metres.

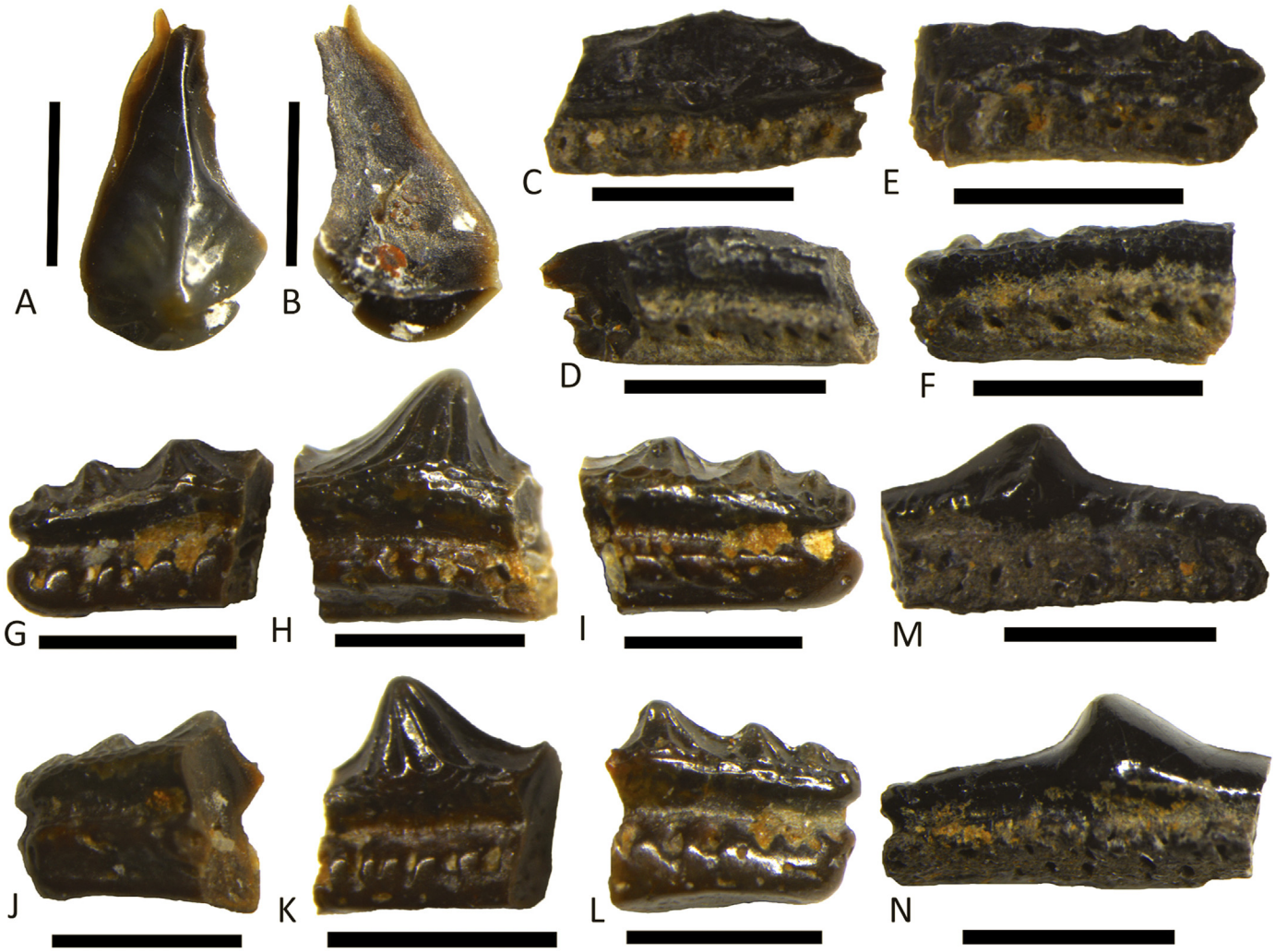

Fig. 6. Chondrichthyan teeth from Hapsford Bridge, beds 4–6. (A–B) *Lissodus minimus* (BRUSG 29954-170) in lingual (A) and labial (B) views. (C–L) *Synechodus rhaeticus*, five teeth in lingual (C, E, G, H, I) and labial (D, F, J, K, L) views: BRSUG 29954-47, posterior tooth (C, D); BRUSG 29954-48 (E, F); BRSUG 20054-73 to 75 (G–L), broken into three pieces, BRSUG 29954-75 (G, L); BRSUG 29954-74 (H, K); and BRSUG 29954-73 (I, J). (M–N) *Duffinselache holwellensis*, BRSUG 29954-72, posterior tooth in lingual (M) and labial (N) views. Scale bar is 1 mm for all specimens.

bone bed), he noted the same fish teeth and scales, bivalves and echinoid remains which we report here, as well as the bivalves *Rhaetavicula contorta* and *Chlamys valoniensis*, borings in pebbles, and insects (although we have been unable to trace the specimens of insects).

In the overlying Cotham Member, Copp (1980, p. 27) noted earlier reports by Moore and Richardson of the conchostracan *Euestheria minuta*, rare insects, and abundant plant remains (*Lycopodites* = *Naiadita*). In the Langport Member, he found only poorly preserved remains of the coral *Montlivaltia* and crustacean burrows in the top bed.

4.2. Chondrichthyans

Four species of shark have been identified from the Hapsford Bridge locality, but identifiable specimens are rare, and they include *Vallisia coppi*, first described from this location.

4.2.1. Lissodus minimus *(Agassiz, 1833-1844)*

One example of this species was found in the collection (Fig. 6A, B). The specimen is over 3 mm in length and is elongate, with a central cusp with a rising vertical tip on the left side which is broken. The specimen in labial view displays some abrasion, and because of incompleteness it cannot be assigned to a particular region in the jaw.

Lissodus teeth are very common at some localities, such as Charton Bay, Devon (Korneisel et al., 2015), and they occur as anterior, anterolateral, lateral and posterolateral forms, depending on their original position in the jaws (Duffin 1999, pp. 199–201). These are all long and low-crowned, and the different forms vary in length and height of the central cusp.

4.2.2. *Synechodus rhaeticus (Duffin, 1982)*

We identify five teeth of *Synechodus* (Fig. 6C–L) because they bear small lateral cusplets, a heavy ornamentation comprising vertical ridges, and a reticulate ornament on the crown shoulders. When complete, the teeth are roughly symmetrical around a distinctive, pointed, upright central cusp. Because of abrasion, this pointed central cusp, and the lateral cusplets, have been removed.

4.2.3. *Duffinselache holwellensis (Duffin, 1998)*

We identify one tooth of *Duffinselache* (Fig. 6M–N), which is elongate, with crown and root of similar height. The crown may form a single blade with slight crenulations, and there is a definite major cusp as a sloping triangular structure.

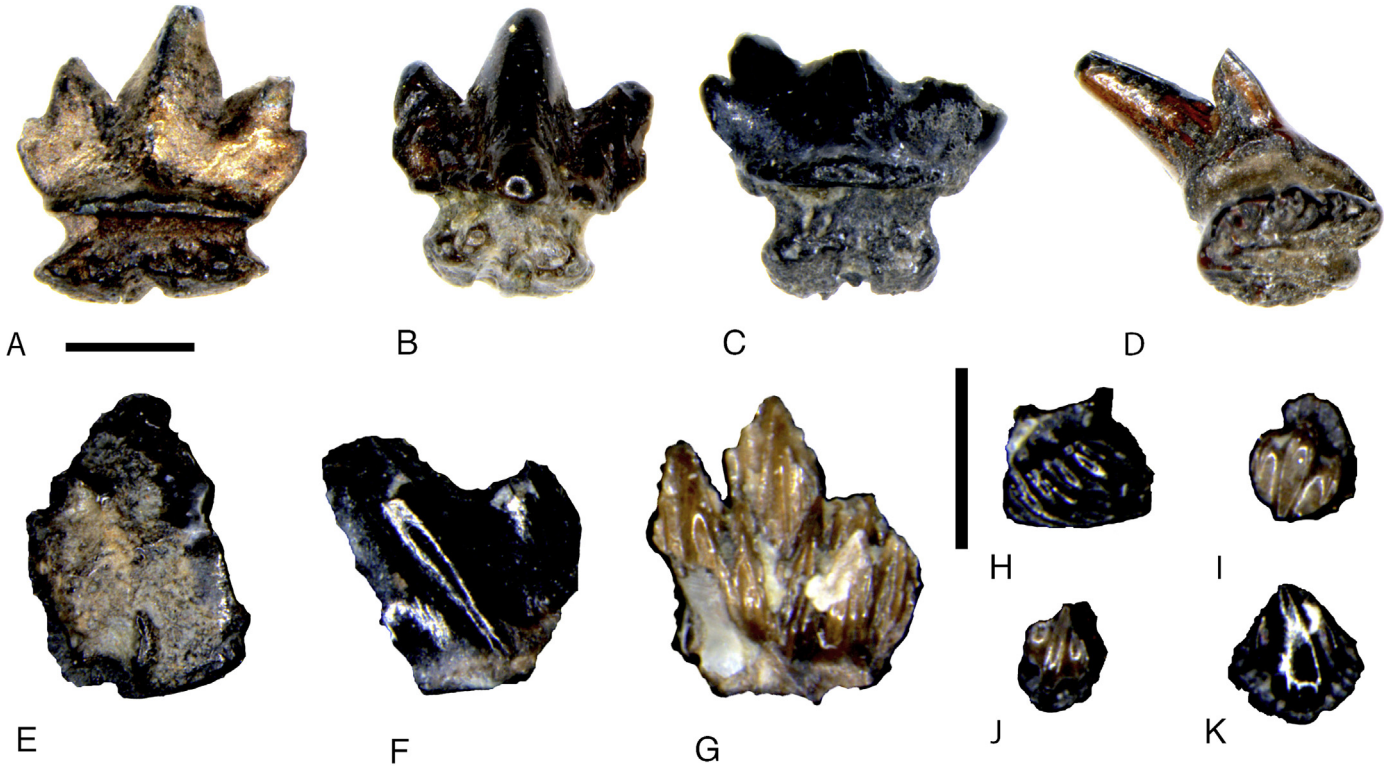

Fig. 7. Chondrichthyan teeth, dermal denticles and scales. (A–D) *Vallisia coppi* teeth. (A) The holotype tooth BRSMG Cc400, in lateral view. (B) BRSMG Cc401, in lateral view. (C) BRSMG Cc402, in lateral view. (D) BRSMG Cc404, in lateral view. (E, F) Fragmentary teeth BRSMG Cd1595 (E) and Cd1596 (F). (G) Ctencanthid scale BRSMG Cd152. (H–K) Dermal denticles BRSMG Cd1526 (H), BRSMG Cd1516 (I), BRSMG Cd1517 (J), BRSMG Cd1520 (K). Scale bar is 1 mm for all specimens.

Teeth of *D. holwellensis* are known only from the Rhaetian (Slater et al., 2016, p. 470), but have been widely reported from most British Rhaetian bone bed localities.

4.2.4. Vallisia coppi Duffin, 1982

We did not find any specimens of this key species in our 2018 collection, but there are examples in the Crane 1978 collection. These specimens (Fig. 7A–D) are 1.5 mm high, with three main upright cusps and two tiny lateral cusplets on a central base forming the crown. The tooth overall is flattened labio-lingually. The central cusp is tallest, and it shows symmetrical faces anteriorly and posteriorly. The flanking cusps are smaller, but also show angled anterior and posterior faces, so all three major cusps show ridges facing labially and lingually. The lateral cusplets are small projections from the two flanking cusps. The surface of the crown is not ornamented. The base of the crown expands and overhangs the root, from which it is separated by a deeply incised groove. The root branches, with flat lobes pointing slightly anteriorly and posteriorly on either side of a medial canal. The surface of the root is roughened, and it bears some large, circular pores.

Some of the Hapsford specimens are complete (Fig. 7A, B), but others are broken (Fig. 7C–F), as commonly seen in previously described examples from Vallis Vale (Duffin, 1982), Manor Farm Quarry (Allard et al., 2015, Fig. 4B), Hampstead Farm Quarry (Mears et al., 2016, Fig. 6k), and Belgium (Duffin et al., 1983). The affinities of *Vallisia coppi* have been debated, with Cuny and Benton (1999) confirming that the ultrastructure of the enameloid is not neoselachian. In a recent review, however, Cappetta (2012, p. 327) classified the taxon as Neoselachii *incertae sedis*.

4.2.5. Dermal denticles

We identified 19 chondrichthyan denticles in the Crane collection (Fig. 7G–K), all of them about, or less than, 1 mm in diameter. These are hard to identify, even though they are generally well preserved. Three small specimens (Fig. 7H–J) are broken, and show distinct ridges and curved grooves, reflecting their original 'hand-shaped' form. One of these (Fig. 7G) is a scale, another (Fig. 7H) is a ctenacanthid denticle, and another (Fig. 7I) looks like a placoid scale. Another (Fig. 7J) is just over 1 mm in diameter, brown in colour, and with clear striations from the base of the denticle upwards. A final example (Fig. 7K) is under 1 mm in diameter, black in colour, and with striations that extend laterally.

4.3. Actinopterygians

Two taxa of bony fish have been identified from collection samples at the Hapsford Bridge locality known from the British Rhaetian.

4.3.1. Gyrolepis albertii *Agassiz, 1833-1844*

These are the most common actinopterygian teeth, with 68 being identified, 15 of which are broken. There are varied morphologies (Fig. 8A–G), but they all share an elongate, sometimes curved, conical shape, with circular cross section. All show the translucent acrodin tip, which is variably long and sharply pointed (Fig. 8C, F, G) or blunt ended (Fig. 8B, D, E), either as a result of wear in use or abrasion during transport and deposition. There is generally no ornament, although some specimens show faint longitudinal ridges.

Gyrolepis albertii is almost always the most common actinopterygian tooth in Rhaetian bone beds, and is reported throughout Europe (Duffin, 1999, p. 213).

4.3.2. Severnichthys acuminatus *(Agassiz, 1844)*

There are ten *Severnichthys* teeth, which show varied morphologies (Fig. 8H–O). Specimens of the '*Saurichthys*' tooth type

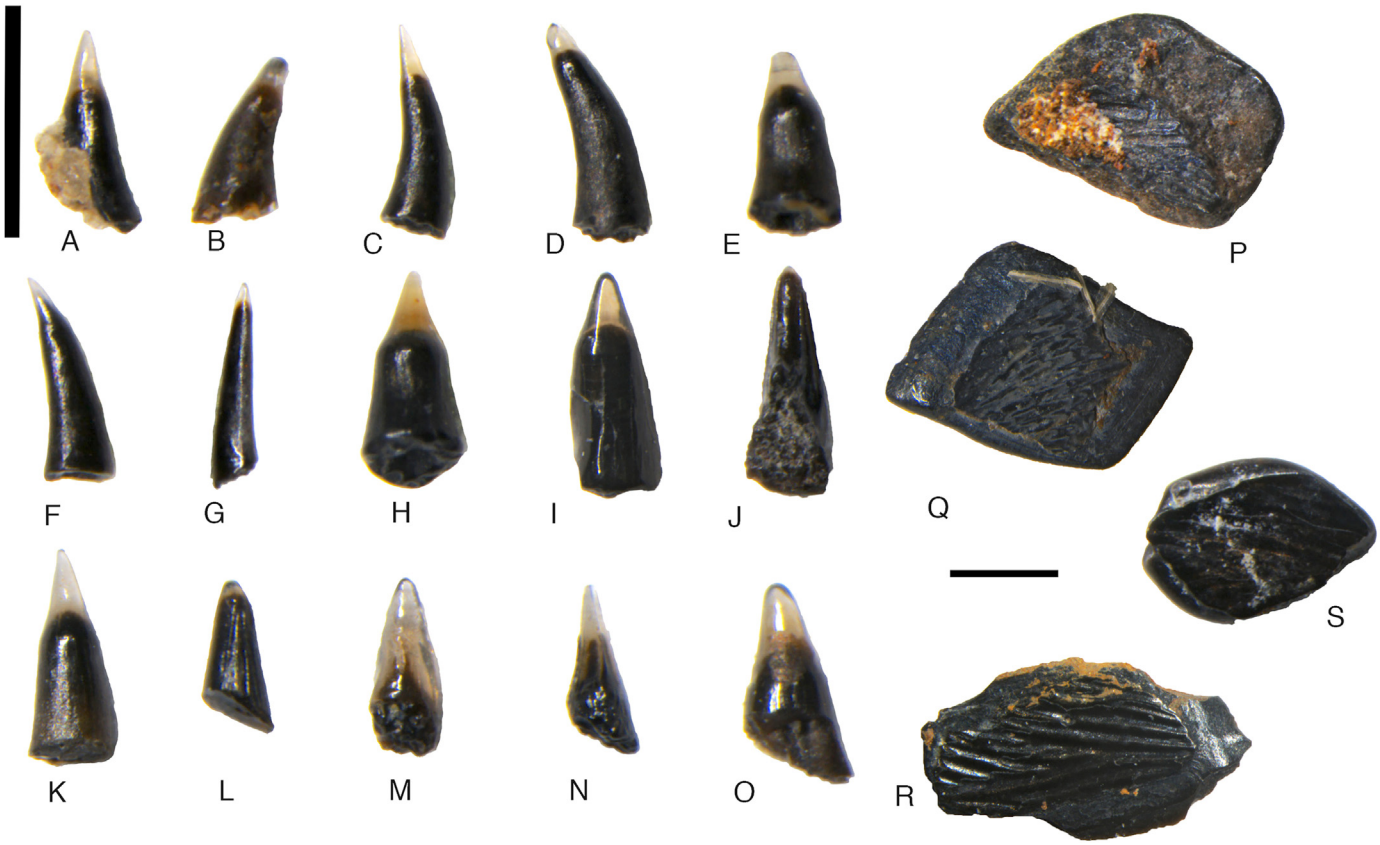

Fig. 8. Actinopterygian teeth and scales. (A–G) *Gyrolepis albertii* teeth from beds 2–3, all in side profile. (A) BRSUG 29954-1. (B) BRSUG 29954-2, very abraded tooth. (C) BRSUG 29954-25. (D) BRSUG 29954-26. (E) BRSUG 29954-27. (F) BRSUG 29954-28. (G) BRSUG 29954-29. (H–O) *Severnichthys acuminatus* teeth from beds 3–5, all in side profile, and showing the two morphs, the '*Saurichthys*' type (H–L) and the '*Birgeria*' type (M–O). (H) BRSUG 29954-38. (I) BRSUG 29954-115. (J) BRSUG 29954-116. (K) BRSUG 29954-117. (L) BRSUG 29954-118, broken specimen. (M) BRSUG 29954-119. (N) BRSUG 29954-120. (O) BRSUG 29954-121. (P–S) Osteichthyan scales with external sculpture beds 4-6. (P) Osteichthyan scale morphotype 1, BRSUG 29954-62. (Q) Osteichthyan scale morphotype 2, BRSUG 29954-110. (R) Osteichthyan scale morphotype 3, BRSUG 29954-111. (S) Osteichthyan scale morphotype 4, BRSUG 29954-140. Scale bar is 1 mm for all specimens.

(Fig. 8H–L) are all conical, ranging in height from 1 to 1.5 mm, and with a small but pointed translucent cap, which in some cases (Fig. 8H, K) is inset above a definite constriction of the tooth. The '*Birgeria*'-type teeth (Fig. 8M–O) are < 1 mm in height and the translucent tip occupies more of the tooth length. All *Severnichthys* teeth lack distinct ridges, which probably reflects their somewhat abraded state: Cross et al. (2018, Fig. 10b, c) shows unabraded examples with distinct longitudinal wrinkles and ridges in the *Saurichthys*-type teeth.

The story of *Severnichthys* has been known for some time, a genus that combines two tooth types that were formerly ascribed to distinct genera and species (Storrs, 1994). As in most Rhaetian bone bed sites, this was likely the largest fish present, a large predatory fish that may have fed as a pike-like, lurking, ambush predator (Duffin, 1999, pp. 215–216).

4.3.3. Other actinopterygian remains

Osteichthyan scales were the second most abundant fossils from the Hapsford locality, with 594 counted. Most of these are fragmentary and abraded quite heavily. Twenty-three of these display the classic *Gyrolepis albertii* ganoin, which is preserved as a black/dark blue surface, though many are abraded and heavily worn. Four morphotypes were identified, but the abraded condition of many scales makes it hard to be sure, and difficult to compare directly with the scale morphotypes identified by Mears et al. (2016, pp. 490–491).

The morphotype 1 scale (Fig. 8P) is over 1 mm in length and possesses a rounded rhomboidal shape. The ganoin layer is hard to distinguish because of abrasion, though traces of the longitudinal ridge-like pattern can be distinguished. The morphotype 2 scale (Fig. 8Q) is around 3 mm in length and less abraded. It features a more rhomboidal shape with a thinner ganoin layer, and the overlap facets are clearly defined at the right-hand end. The morphotype 3 scale (Fig. 8R) is just over 3 mm in length. It features a very thick ganoin layer with defined markings which extend across the scale longitudinally. The morphotype 4 scale (Fig. 8S) is around 1.5 mm in length, and has a defined ganoin layer that is flat, smooth and much more rounded.

There are some better quality *Gyrolepis* scales in the Crane collection (Fig. 9). Some show an encrusted cover of crystalline calcite (Fig. 9A). Others, though, are in less abraded condition (Fig. 9C–E), showing the ganoin cover and antero-posterior longitudinal wavy and branching ridge-groove patterns. These scales also all show the overlap facets along the posterior margin.

4.4. Other fossils

The bone beds include a variety of fossils other than fish remains, including some unusual invertebrates, as well as coprolites.

4.4.1. Barnacle *Eolepas rhaetica* (Moore, 1861)

We found 45 barnacle pieces, all of them phosphatic, black on the outer surface, likely to be from *Eolepas*, but they are all broken (Fig. 10A–D). One example shows the classic pattern of horizontal, parallel growth lines, intersecting a vertical pattern of fine ridges

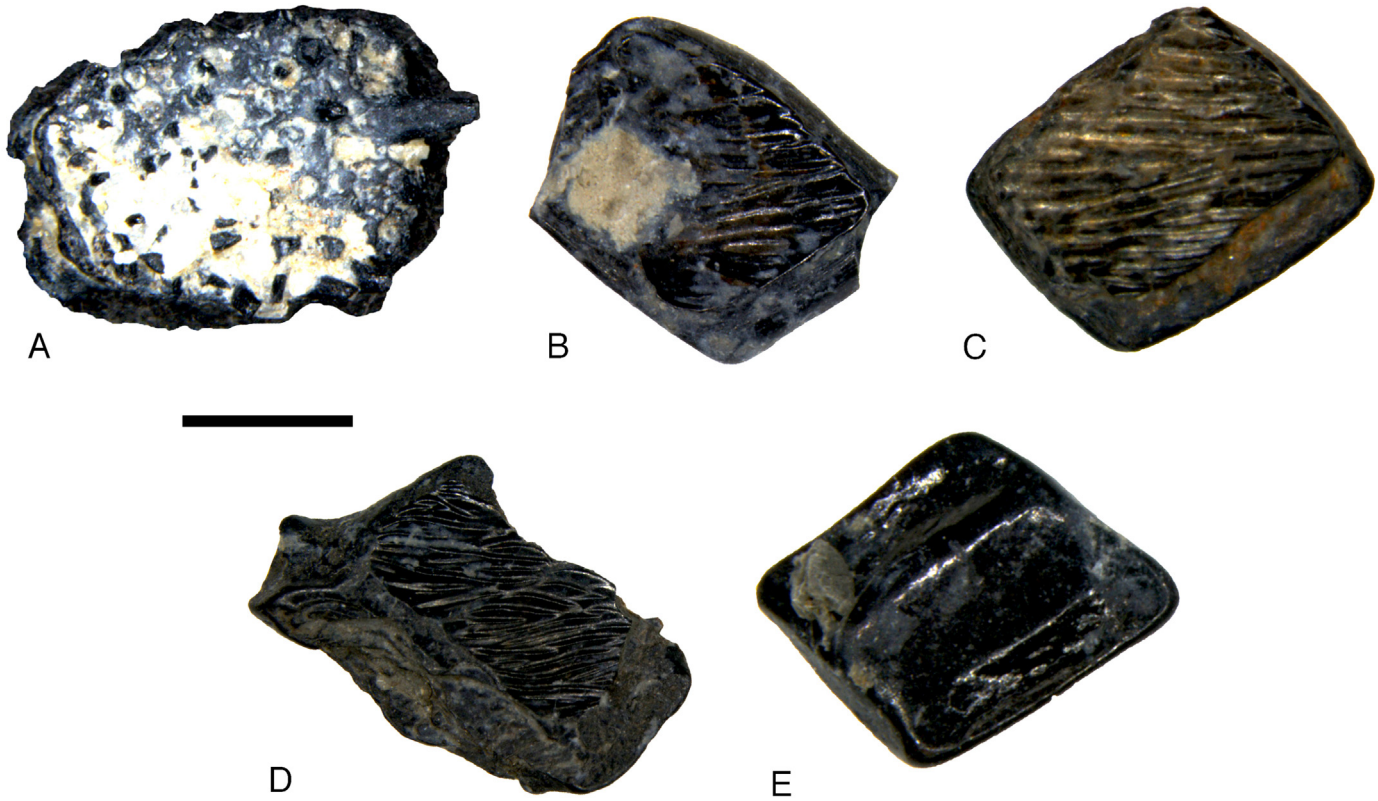

Fig. 9. Bony fish fossils from the Crane collection. (A) Small block (BRSMG CD1588) containing ganoid scales with calcite cement. (B–E) Examples of *Gyrolepis albertii* scales, showing various morphotypes in external (B, C, E) and internal (D) views; BRSMG Cf7846.1 (B) Cf7846.4 (C), Cf7846.2 (D), Cf7846.3 (E). Scale bar is 1 mm for all specimens.

on the outer face (Fig. 10A), but with a smooth inner face (Fig. 10B). Another specimen shows the same external sculpture (Fig. 10C) and a platform and concave shape internally (Fig. 10D). All of the fragments seem to be partial scutum and carina plates.

Eolepas rhaetica was named by Moore (1861), initially as a species of *Pollicepes*, from the Vallis Vale Rhaetian limestones, based on fragmentary and more complete specimens showing entire valves (Boomer et al., 1999, pl. 20, Figs. 5–9). These show the same sculpture patterns as our specimens. In life, *Eolepas* looked something like a modern gooseneck barnacle, with six rhomboid valves of varying sizes enclosing the body, and all ending with a rounded point distally (Gale and Schweigert, 2016). The genus *Eolepas* ranges from the Late Triassic to Early Cretaceous, so *E. rhaetica* is one of the first members of the genus and is indeed the oldest recorded scalpellid barnacle (Boomer et al., 1999).

4.4.2. Bivalve *Atreta intusstriata* (Emmrich, 1853)

Ten examples of bivalves were identified. Some are broken portions of large oysters with heavy zig-zag commissure line, like *Lopha haidingeriana* (*cf.* Ivimey-Cook et al., 1999, pl. 13, Fig. 8). Two (Fig. 10E–F) show the general shape, irregular layering, and radiating pattern of fine ridges seen in *Atreta intusstriata* (*cf.* Ivimey-Cook, et al., 1999, pl. 13, Figs. 3, 4). Both are 5–6 mm in size, and represent incomplete fragments from near the hinge line, showing irregular folds in the shell, and radiating striations.

Atreta intusstriata is commonly found in other Rhaetian shallow water deposits of north-western Europe including Germany and the Tethys, but is rare in the Westbury Formation, occurring more commonly in the Lilstock Formation. It is a dimyoid oyster (Order Ostreoida), typically small (maximum height 12 mm, and width 9 mm) and the right valve was cemented to the rock, presumably close to shore. We identified it also as one of the encrusting bivalves on the uprooted Carboniferous pebbles (Fig. 12D).

4.4.3. Echinoid spines

We identified 14 echinoid spines, possibly those of cidaroids, all of which are elongate and cylindrical, and range in size from 2 mm to over 9 mm in length, and 1–2 mm in diameter. They are all preserved differently, one (Fig. 10G) being grey-coloured and mottled, 8 mm long, another (Fig. 10H) orange, and 6 mm long, and showing some tapering, and a further one (Fig. 10I) grey and tapering, 8 mm long.

Cidaroid spines are frequently reported in sieved residues of the Rhaetian bone beds (Swift, 1999). Our examples are rather featureless when compared to those reported from Hampstead Farm Quarry (Mears et al., 2016, Fig. 17h), which show the basal boss or acetabulum by which they attach to the echinoid test and short pines on longitudinal ridges along the length of the spine.

4.4.4. Possible belemnite

One specimen, originally identified as a cidaroid spine (Fig. 10J), is composed of crystalline calcite which shows a radiating pattern on the broken end. It is hard to identify definitively as either cidaroid or belemnite because of considerable abrasion of the outer surface. Its size (9 mm long) tends to favour interpretation as a cidaroid spine, but the radiating breakage of the calcite looks belemnite-like. If it is a belemnite, however, it would be the first from the British Rhaetian, and one of only a few recorded from the Late Triassic.

4.4.5. Coprolites

We identified only four coprolites in our collection (Fig. 10K–N). They measure 1–2 mm in diameter and 3–7 mm long, but all are broken and incomplete. All coprolites are light brown/grey in colour and show the usual spiral structure. None of them show identifiable remains of plants or fish scales on the surface.

Coprolites such as these are common components of the Rhaetian bone beds (Swift and Duffin, 1999; Mears et al., 2016, p. 496; Slater et al., 2016, pp. 473–474). Previously, a number of classes of coprolites

Fig. 10. Invertebrate fossils from beds 3–5. (A–D) Barnacle *Eolepas rhaetica* (BRSUG 29954-14- 29954-171). (A–B) Specimen BRSUG 29954-14, in outer (A) and inner (B) views, showing external sculpture, and white colour of phosphate internally. (C–D) Specimen BRSUG 29954-171, in outer (C) and inner (D) views, showing external sculpture, and black colour of phosphate internally. (E–F) Bivalves *Atreta intusstriata*, partial specimens BRSUG 29954-17 (E) and BRSUG 29954-175 (F). (G–I) Cidarid spines, BRSUG 29954-17 (G), BRSUG 29954-76 (H), BRSUG 29954-77 (I). (J) Small belemnite or cidaroid spine, BRSUG 29954-78. (K–N) Coprolites, all incomplete and missing their ends, BRSUG 29954-49 (K), BRSUG 29954-89 (L), BRSUG 29954-90 (M), BRSUG 29954-91 (N); coprolites L–N show spiral ornament at different sizes. Scale bar equals 1 mm for (A–N) and 2 mm for (E–J).

have been identified, but ours all appear to be similar, being cylindrical in shape and marked by closely spaced spiral structures. They are likely the ejecta of one of the fishes, possibly a shark.

4.5. Faunal composition and comparison

Our 2018 collection from Hapsford Bridge comprises 1740 specimens. Of these, 763 are identifiable as non-bone fragments, including 76 teeth and 687 other fossil elements. Of the chondrichthyan remains, five teeth belong to *Synechodus rhaeticus*, and one tooth each to *Lissodus minimus* and *Duffinselache holwellensis*. Of the osteichthyan remains, 68 teeth belong to *Gyrolepis albertii* and 10 to *Severnichthys acuminatus*. *Eolepas rhaetica* barnacles are common, with 45 valve pieces being identified. The remaining 977 unidentifiable fossils comprise scales, denticles, and teeth.

In comparing the six samples, the first (bed 2) did not yield any fossils, the second yielded only 32, but third to sixth were much richer, with 542, 161, 835 and 170 individual microvertebrate fossils in each. The most abundant categories were unidentified fish remains (899 specimens) and osteichthyan scales (594 specimens), followed by *Gyrolepis* teeth (68), barnacle pieces (45), unidentified teeth (44) and denticles (29). Identifiable shark and bony fish teeth were overall quite rare, with generally <10 specimens each. Therefore, comparing the relative proportions of the different categories between the five fossiliferous horizons was less useful than we had expected, unlike in the case of the Hampstead Farm Rhaetian where substantial differences were found in faunal composition up through the section (Mears et al., 2016). Here (Fig. 11), we can say that *Gyrolepis* teeth are generally the most common fossils at all levels, then with main occurrences of *Synechodus* and *Duffinselache* in bed 5, *Synechodus* and *Lissodus* in bed 8, and *Severnichthys* in beds 4–8.

When compared with other Rhaetian bone bed sites, the ranges and proportions of species differ, but our sample sizes are small, and many specimens are abraded. A common feature is the relative abundance of *Gyrolepis* teeth and scales, as here, but *Severnichthys* is usually relatively more abundant. The occurrence of *Lissodus* confirms these are basal Westbury Formation bone beds, based on its temporally confined occurrence at Hampstead Farm Quarry (Mears et al. 2016, Fig. 20). Among the sharks, the absence of *Rhomphaiodon* is surprising, as it is usually the most common shark tooth in other British Rhaetian bone beds (Allard et al., 2015; Norden et al., 2015; Cross et al., 2018). Further differences are the occurrence of the shark *Vallisia coppi* and the barnacle *Eolepas rhaetica* at Hapsford Bridge, taxa that occur only rarely elsewhere; *Vallisia* was reported from Hampstead Farm Quarry (Mears et al. 2016, p. 487) and Manor Farm (Allard et al., 2015, p. 768). Finally, unlike most other Rhaetian bone bed sites, we do not find teeth of the durophagous actinopterygians *Sargodon* and *Lepidotes*.

Of the sharks, *Lissodus* was likely adapted to crushing hard-shelled prey with its long, low teeth. The other sharks, with sharp cusps on their teeth, were presumably predators that fed on other, smaller fishes. The actinopterygians *Gyrolepis* and *Severnichthys* were also predatory, feeding on small to medium-sized prey respectively. As in previous Rhaetian bone bed food web reconstructions (e.g., Cross et al. 2018, Fig. 15), *Gyrolepis* is in the middle of the food chain, probably preying on invertebrates and smaller fishes, and preyed upon by *Severnichthys* and the sharks. The durophagous *Lissodus* fed on molluscs and other hard-shelled prey.

5. The sub-Rhaetian hardground

The planed upper surface of the Carboniferous limestone around Vallis Vale forms a remarkable hiatus in the stratigraphic column. Not only does it mark an important unconformity, but it also records evidence that this surface was a hardground in the Triassic and Jurassic. Reynolds (1912) described the top-Carboniferous surface as uneven and bored in places, and sometimes colonised by oysters. In other places, the surface is simply flat, described by Winwood (1890) as 'planed off almost as level as a billiard table.' Copp (1980, pp. 318–327) emphasized how the surface was smooth and generally not bored or encrusted over most of the Mendips. However, Tedbury Camp Quarry (ST 747489), west of Vallis Vale, shows an extensive, cleared surface of the top of Carboniferous limestone, with bivalve encrustation and intensive borings assigned to three ichnotaxa, *Gastrochaenolites* and two species of *Trypanites*, the smaller being *T.*

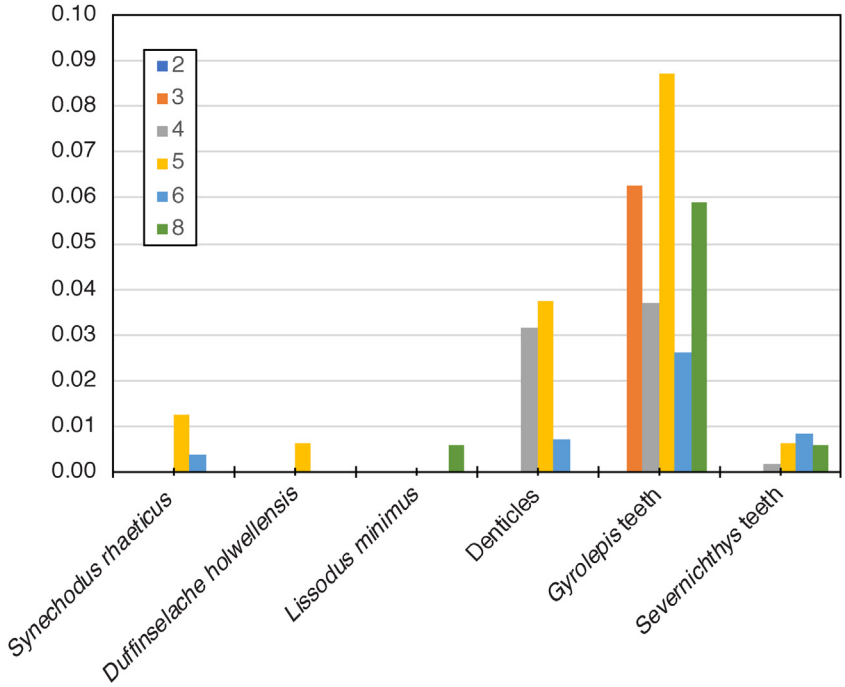

Fig. 11. Relative proportions of key fossils in six fossiliferous samples from beds 2, 3, 4, 5, 6, and 8 (Fig. 4C) respectively.

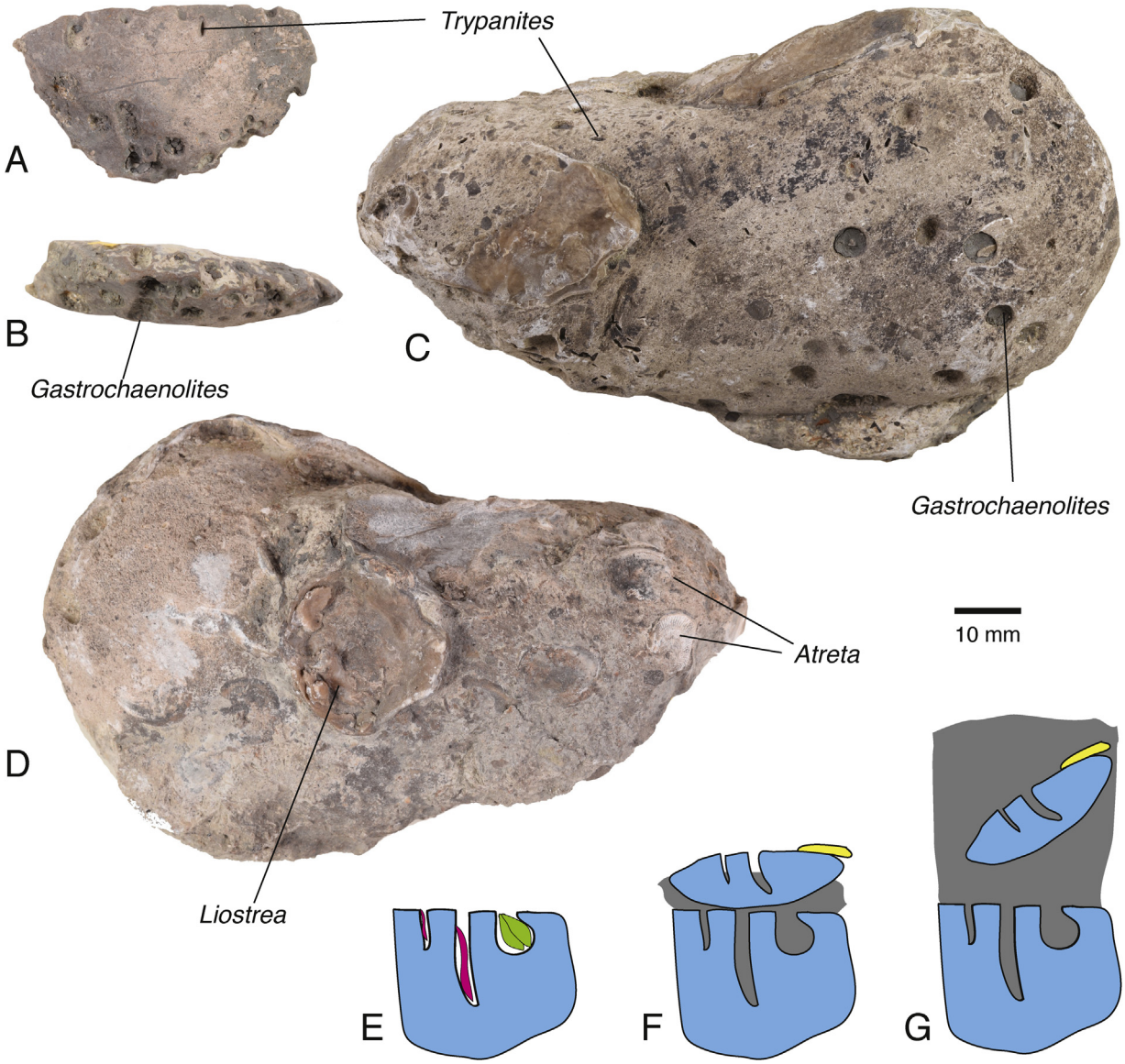

Fig. 12. Reworked pebbles of Carboniferous limestone from the basal beds of the Westbury Formation. (A, B) One pebble (BRSMG Cd384), in upper (A) and lateral (B) views, showing *Trypanites* and *Gastrochaenolites* borings. (C, D) A larger pebble (BRSMG Cd382), in upper (C) and lower (D) views, showing *Trypanites* and *Gastrochaenolites* borings, overlaid by encrusting bivalves *Liostrea* and *Atreta*. Note the Rhaetian grey clay infilling *Gastrochaenolites* borings (C). (EG) Inferred history, as encrusting worms and bivalves make *Trypanites* and *Gastrochaenolites* borings, respectively, presumably in earliest Rhaetian times (E), and then some surface layers of the Carboniferous pavement is stripped off, and the fragments tumbled and abraded, before settling on the seabed and becoming encrusted by bivalves (F), and finally burial in basal Westbury Formation sediments (G).

weisei and the larger *T. fosteryeomani* (Cole and Palmer, 1999). The *Gastrochaenolites* boring is a living crypt of a rock-boring bivalve much like that of modern *Lithophaga*, and the *Trypanites* borings are usually ascribed to worms (Kelly and Bromley, 1984). The planing, boring and encrustation of the surface were dated to the Middle Jurassic by those authors based on the age of the immediately overlying Inferior Oolite, which also infills the borings. Other such exposures with bored hardground surfaces are seen in Torr Works and on the road near Holwell.

The Vallis Vale Rhaetian is also a source of bored and encrusted pebbles of Carboniferous limestone, which occur in the basal mudstones and in the bone bed. Richardson (1911) noted these at several locations, and Copp (1980, pp. 327–340) reported several examples from Vallis Vale. One specimen (Fig. 12A, B) shows numerous borings of two size classes, 0.8–0.9 mm and 3–4 mm in diameter, and both up to 10 mm long. Two or three shallow borings, 4–6 mm in diameter and 6–10 mm deep, have a flask-like shape, broader at the rounded base and with a narrower neck (the 'clavate' shape). Note that the borings occur on one side only of the flat pebbles, suggesting that the boring happened before the clasts were uplifted. These three borings are the two species of *Trypanites* and the one species of *Gastrochaenolites* identified by Cole and Palmer (1999) at Tedbury Camp, confirming the temporal longevity of these trace fossils.

Some of the pebbles (e.g., Fig. 12C, D) are also encrusted with examples of two bivalves, *Atreta intusstriata* and the oyster *Liostrea*, both typical of the Rhaetian (Swift, 1999). This confirms that uplift and tumbling of the pebbles happened in the Rhaetian, when they became encrusted as they lay on the sea floor and before burial.

These pebbles confirm that the Carboniferous limestone top surface formed a hardground under the advancing Rhaetian sea, and here and there the energy of the Rhaetian waters tore up chunks of that hardground, retaining the borings, but tumbling and abrading the pebbles before they were redeposited (Fig. 11E, F). Then, some of them became encrusted by oysters in the shallow

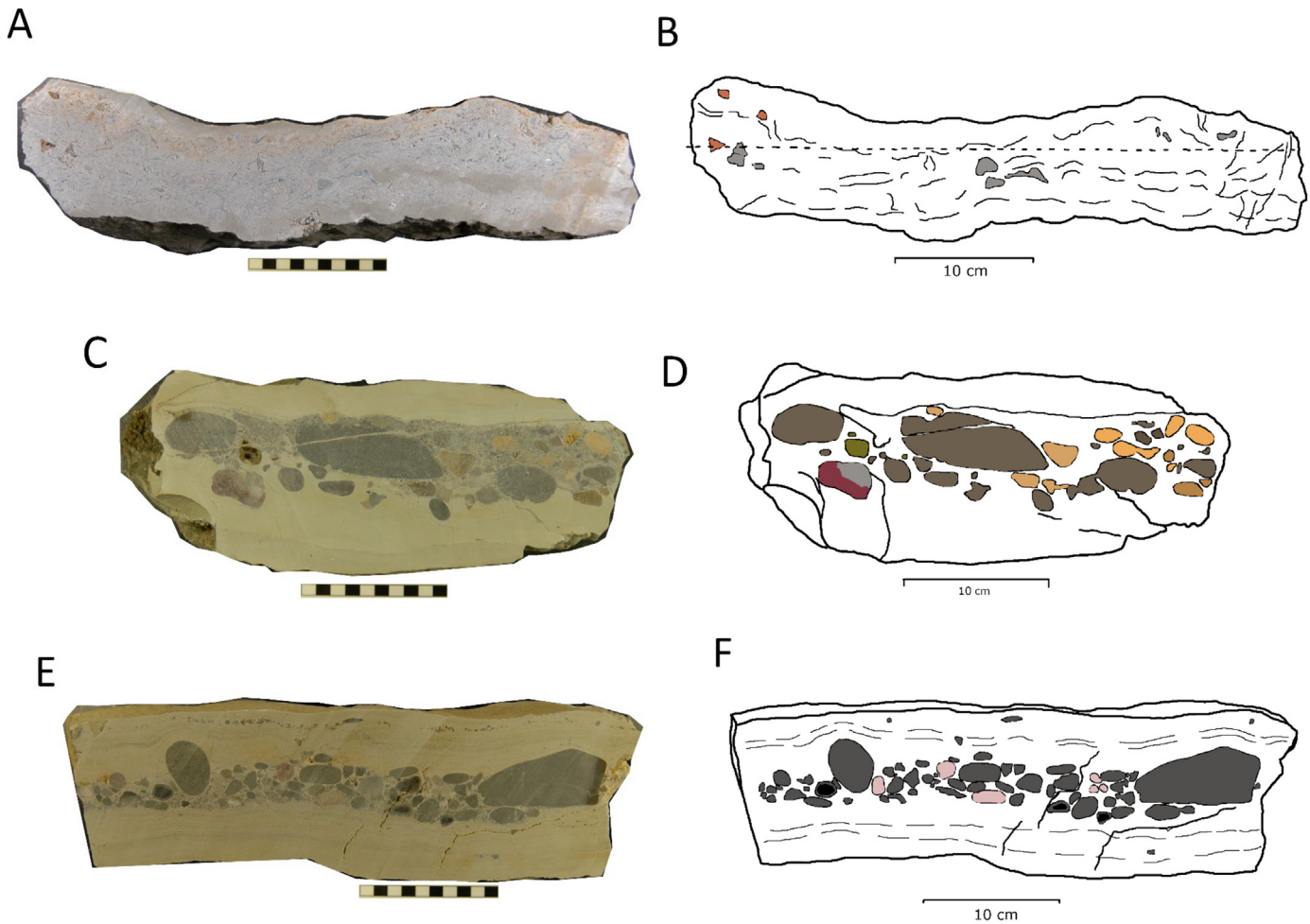

Fig. 13. Inferred storm beds from different levels in the Westbury Formation. (A, B) Bed 4 muddy limestone, (C, D) Bed 6 limestone, and (E, F) Bed 8 conglomeratic mudstone, showing photographs of slabbed sections (A, C, E) and interpretive sketches (B, D, F).

marine waters of the Rhaetian. In detail, the assumed sequence of events, based on our evidence of bored pebbles in the basal units of the Westbury Formation, is:

1 uplift and subaerial erosion of the Carboniferous limestone;
2 flooding by the latest Norian or earliest Rhaetian sea;
3 development of hardground in which bivalves, worms, and others bored into the limestone for protection and to recycle calcium carbonate ions into their own skeletons;
4 influx of rough waters, perhaps associated with the formation of the first conglomeratic bone bed, and tearing of pebbles from the seabed;
5 transport of debris, including pieces of the hardground surface, and deposition together with other debris;
6 encrusting of some pebbles by oysters and other bivalves before eventual burial.

6. Rhaetian storm beds

We identified putative storm bed sediments at three levels in the Westbury Formation (Fig. 5C), in the muddy limestone containing the 'basal' bone bed (Fig. 13A, B), in the calcareous mudstone 60 cm above (Fig. 13C, D), and in the muddy limestone a further 43 cm above (Fig. 13E, F). When cut vertically, these muddy limestone blocks show suspended conglomerates. The first example (Fig. 13A, B) shows a limited intraformational conglomeratic layer comprising some mudstone clasts, and abundant shelly debris in an otherwise fine-grained limestone. The second and third examples (Fig. 13C–F) show some large (up to 10 cm diameter), well-rounded clasts of grey brown and yellow-coloured mudstone, all of which match bedded sediments in the Westbury Formation succession. Around these larger clasts, there is a finer mush of 1–3 cm rounded pebbles and debris of < 10 mm diameter. The sediment above and below is fine- to medium-grained muddy and silty limestone.

We interpret these as suspended conglomerates as they are located in the middle of sedimentary beds that lack all sign of grading. Further, they include largely reworked autochthonous debris, and some of it relatively soft sediment that has evidently not been transported far, presumably eroded and deposited from underlying Rhaetian-aged sediments.

There are two kinds of conglomerates at Hapsford Bridge, both indicating storm bed deposition. First, the flat pebbles (Fig. 12) presumably formed part of a flat-pebble conglomerate, a kind of deposit long interpreted as direct evidence of storm wave activity (Bourgeois and Leithold, 1984; Myrow et al., 2004), indicating high energy, churning currents that ripped up pebbles from the seabed and dumped them, often chaotically in basal storm deposits. Second, the intraformational suspended conglomerate layers (Fig. 13) also indicate storm activity. Conglomerates usually show grading, as water currents diminish or increase in energy, but here,

otherwise fine-grained sediments are suddenly visited by a pulse of large clasts from local sources. These are analogous to suspended coquinas, shell beds that unexpectedly occur in the midst of otherwise low-energy, fine-grained sediment beds (e.g., Benton and Gray, 1981; Puga-Bernabéu and Aguirre, 2017), where the storm surge ebb current deposits clasts that had been picked up during the earlier storm surge. This is why clasts are intraformational, sometimes from unconsolidated underlying beds, often heterogeneous and generally a sudden layer, with no sign of grading.

Storm bed deposition within the Westbury Formation has long been accepted (Suan et al., 2012). Indeed, Short (1904, p. 181) was first to propose this model. He noted that the Rhaetian basal bone bed must have been laid down in shallow seas, but that it could not be a strandline conglomerate because it is laterally extensive, although discontinuous. He then proposed that the bone bed is a storm deposit for three reasons: it is not always basal and so is not caused by the 'first inrush of the Rhaetic sea'; the causes must have been similar over England and much of Europe; the water movements were sufficient to transport debris of various sizes, and; it was associated with the death of many fishes and marine reptiles. Short (1904, p. 182) goes on to cite modern analogues where violent storms rushed onshore killing many fishes, and then the ebb current dragged carcasses back down to below wave base.

The storm model for the basal bone bed was elaborated by Macquaker (1994, 1999) particularly to explain the jumbled nature of the fossil bones, in many cases bringing heavily abraded larger bone clasts into contact with smaller, and unabraded material. He presented evidence that storm beds with shells or lacking fossils, as here, correspond to times of shallow water, whereas storm-deposited bone beds correspond to times of water-deepening, where they mark the final phase of a coarsening-upward sequence, when a high-energy flow erodes into pre-existing sediment and the often heavily abraded bone debris is finally dumped. Rhaetian bone beds may be mixed in this way, comprising phosphatic bones, teeth and coprolites that represent multiple cycles of erosion and deposition, as at Aust (Trueman and Benton, 1997; Cross et al., 2018), or they may comprise elements that all show similar amounts of abrasion, as at Hapsford Bridge. Further, as Korneisel et al. (2015) noted, the base of the basal Rhaetian bone bed is often heavily burrowed, and those burrows may be filled with bone bed debris which even shows meniscate structures as evidence that the crustaceans that made the burrows were scrambling through and packing the bone bed debris in them.

7. Discussion

The Hapsford Bridge Penarth Group succession shows the usual marine characteristics as widely seen in the Rhaetian. The lower portions of the Westbury Formation were deposited presumably close to shore, and our evidence (Fig. 13) suggests that storm activity was frequent. Suan et al. (2012) noted five cycles of climate change throughout the time of deposition of the Westbury Formation, each marked by a pulse of organic carbon enrichment. At times of water deepening, abundant phosphate was generated, corresponding to successions of black, anoxic mudstones and rich bone beds, and the phosphate drove enhanced productivity in the oxygenated ocean above. The pale-coloured limestones and mudstones represent shallower waters, often with abundant invertebrate life living on the seabed.

Sharp changes in climate, sea level and carbon cycling through the 1–2 Myr duration of deposition of the Westbury Formation may have been triggered by eruptions of the Central Atlantic Magmatic Province, changing topography of land and seabed, and altering runoff and phosphorus input to the oceans (Suan et al., 2012). Storm beds produced both within the phosphate-rich black anoxic sediments and the oxygenated shell-rich pale-coloured limestones and muds by surge ebb currents are evidence for the sharply changing climates triggered by the first phases of opening of the North Atlantic.

Higher portions of the Westbury Formation may have been deposited under lower energy conditions, represented by fine-grained sediments. These sediments might have been near-shore, as suggested by fossils such as the liverwort *Naiadita* and the conchostracan *Euestheria*, as well as reported terrestrial insect remains (BRSMG collections).

The Hapsford Bridge locality provides new evidence about the palaeotopography of the Mendips area. Farrant et al. (2014) noted a series of unconformities in the Mendips, starting with the Late Triassic Dolomitic Conglomerate, which erodes and recycles Carboniferous limestone fragments, and fills fissures at many localities. Further incursions of the sea in the Early and Middle Jurassic created substantial unconformities, including the De la Beche unconformity and Tedbury Camp, as well as sediment-filled fissures ('Neptunean dykes') formed in the Carboniferous limestone by tectonic extension. Farrant et al. (2014) report Cretaceous sediment unconformably in contact with Silurian and Devonian rocks, and evidence for progressive westward overstep of the Mendip Island, from Frome to Tadhill, the site of the Cretaceous level. Our evidence from Hapsford Bridge provides an older line of overstep that reached a point between Hapsford Bridge and the De la Beche unconformity.

There may have been two or three Late Triassic overstep phases as sea levels rose, depending on the age of the "Dolomitic Conglomerate", a Triassic terrestrial red bed lithology containing reworked Carboniferous (Farrant et al., 2014) as well as two Rhaetian-aged overstep phases, the one reported here at the base of the Westbury Beds, and a second one at the Triassic-Jurassic boundary. There was a younger hardground, reported from the top of the Langport Member (uppermost Rhaetian), on the upper surface of the "Sun Bed", at localities near Bristol, Radstock, and Wells. Copp (1980, pp. 343–357) provides a detailed account of this hardground at Hapsford Bridge, on top of a bed that is 8 cm thick, and bored through by abundant slender *Trypanites*, clavate *Gastrochaenolites*, and burrows and borings that are broader and may penetrate the entire thickness.

Sea levels around the Mendips rose episodically, perhaps interspersed with sea-level falls, throughout the Mesozoic, from the Late Triassic to mid-Cretaceous. The sequential overstep from east to west up the flanks of the Mendip island chain is marked by littoral facies and hardgrounds of Bajocian, Bathonian, Callovian, and Albian age stretching along a 10 km east-west transect from Frome to Tadhill (Farrant et al., 2014, Fig. 8). We now add two Rhaetian levels to the east, both of them lying lower topographically. At each of the hardground levels, whatever the age, the same Carboniferous limestone basement was eroded and planed ('trimmed' by the waves), bored by various animals living in shallow sea waters, and then inundated by high-energy sediment-laden currents, that at times (e.g., Hapsford Bridge, Tedbury Camp) eroded the surface layers and redeposited pebbles of the hardground.

Further work in and around Vallis Vale is likely to shed light on the nature of the Rhaetian Transgression and how it reshaped the landscape over south-western England. It is remarkable that this area provides evidence for five or more stages in the inundation of the landscape, spanning some 100 Myr (35 Myr from Rhaetian to Bathonian, and then 60 Myr from Bathonian to Albian) and all located geographically so close together.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.pgeola.2020.02.005.

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