The Wealden Group Wessex Formation (Lower Cretaceous) of Swanage Bay, southern England

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Abstract

The Early Cretaceous Wealden Group of Swanage Bay, Dorset, southern England, comprises two formations, a lower Wessex Formation and an overlying Vectis Formation. Presently only part of the former is exposed and here its stratigraphy, sedimentology and palaeontology are redescribed. Recent work on the Wealden Group of the Wessex Sub-basin has focused either on the Barremian – earliest Aptian of the Isle of Wight, or on the Wealden Group of Dorset in a broader context. Consequently, the Wealden Group of Swanage Bay lacks detailed analysis and description. In the 200 years since the first account of the geology and stratigraphy of Swanage Bay, slumping and vegetation growth have dramatically concealed the upper part of the Group at this previously well-known locality. A stratigraphical framework with assigned marker beds is established here for the first time allowing for the precise placement of new palaeontological discoveries. Analysis of the palaeobotanical and microvertebrate remains recovered from the recorded section permits a more accurate reconstruction of the Early Cretaceous Wessex Formation ecosystem of east Dorset.

Key Words: Early Cretaceous, Wealden Group, Dorset, stratigraphy, palaeoenvironment, palaeobotany, microvertebrates.

1. Introduction

Approximately 700 m of Early Cretaceous (upper Hauterivian – early Aptian) Wealden Group strata underlie Swanage Bay, located on the Jurassic Coast World Heritage site, Dorset (Fig. 1) (Arkell, 1947; Radley, 2006a, 2006b). Presently, a 110 m thick heterolithic clastic succession dominated by fluvial overbank mudstones and fluvial sandstones is well exposed in north Swanage Bay. In common with the coeval Wealden Group of the Isle of Wight, 35 km to the east, the Wealden Group of

Swanage Bay consists of two formations; the Wessex and overlying Vectis formations (Radley, 2006a, 2006b; Radley and Coram, 2011). In Swanage Bay, the exposed Wessex Formation is dominated by thick (> 30 m) sequences of mottled pedogenically altered overbank mudstones, interspersed with moderately thick point bar and sheet sandstones (≤ 7 m), ironstone horizons (≤ 1 m), plant debris beds (≤ 3 m) and sporadic grit horizons (≤ 1 m) (Radley, 2006b). The Vectis Formation and immediately overlying strata, including the previously documented Aptian Punfield Cove Marine band, are currently obscured by landslips (Ruffell and Batten, 1994).

In recent years, studies of the Wealden Group in the Wessex Sub-basin have overlooked the Swanage section in favour of more complete exposures to the west, in Dorset, and further east on the Isle of Wight, (Stewart, 1978, 1981; Hesselbo and Allen, 1991; Radley, 1994, 1998; Radley and Barker, 1998a, 1998b; Insole and Hutt, 1994; Nowell, 1997; Robinson and Hesselbo, 2004; Radley 2006b, Radley and Allen 2012a, 2012b, 2012c; Sweetman and Insole 2010) (Fig. 1). In contrast to the Wealden Group of Swanage Bay, extensive geological and palaeontological investigation has concentrated on the better exposed Wealden Group of the Isle of Wight since the 1800's. Current interpretations of Wessex Formation palaeoenvironments stem largely from the work of Stewart (1978), Insole and Hutt (1994), Allen et al. (1998), Radley and Barker (1998a, 1998b), Radley (1994, 2006b), Radley and Allen (2012a, 2012b, 2012c), Sweetman (2011a, 2011b), Sweetman and Insole (2010) and Austen and Batten (2018). Palaeontological, palaeoclimatic and palaeoenvironmental data obtained from the Barremian part of the Wessex Formation of the Isle of Wight indicate that deposition occurred within a lowland floodplain that supported a diverse fauna and flora (Stewart, 1978; Radley 1994; Watson and Alvin, 1996; Haywood et al. 2004; Sweetman 2009, 2011a, 2011b; Martill and Sweetman 2011). During deposition of the Wessex Formation, Swanage lay palaeogeographically upstream from the Isle of Wight floodplain, some 35 km closer to the Cornubian hinterland. Swanage's closer proximity to these uplands throughout the Lower Cretaceous is evidenced by recurring grits in braid and overbank facies that are not encountered in the exposed Wessex Formation of the Isle of Wight (Stewart, 1978; Insole and Hutt 1994; Radley, 2006b; Radley and Coram, 2011; Radley and Allen, 2012b). Presently, the exposed strata of the Wessex Formation at Swanage Bay provides an important record of an Early Cretaceous palaeoenvironment that is transitional from floodplain to hinterland, and is significant for both its sedimentological and palaeontological record (Radley and Coram, 2011).

Since first described by Webster (1816), the cliff section of north Swanage Bay, formerly very well exposed, has deteriorated. Today the Vectis Formation, Aptian Punfield Cove Marine Band and the Wessex Formation Coarse Quartz Grit are now concealed or otherwise inaccessible (Webster, 1816; Meyer, 1872; Arkell, 1947; Ruffell and Batten, 1994). Similarly, sea defences adjacent to Swanage town have long concealed the lowest beds of the Wessex Formation. This sustained loss of exposure

and lack of detailed description has resulted in the need for a re-examination of Swanage Bay's Wessex Formation geology and palaeontology (Radley and Allen, 2012a). Here, building on the pioneering work of Strahan (1898), Arkell (1947), and the newer syntheses of Radley (2006b) and Radley and Allen (2012a, 2012b, 2012c), as well as the unpublished data of C.P. Palmer, this study provides an up-to-date account of the stratigraphy, sedimentology and palaeontology of Swanage Bay's Wessex Formation. Strata of palaeoenvironmental and palaeontological significance are described in detail and 'marker beds' are designated, to provide a revised stratigraphical framework for the Wessex Formation at this important locality. This new framework allows for the more accurate stratigraphical placement of current and future palaeontological data within the Swanage section. Furthermore, systematic bulk sampling of plant debris beds has permitted the description of the more common elements of both the microvertebrate and palaeobotanical assemblages.

1.1 Historical context

Webster (1816) was first to describe the Wealden Group of north Swanage Bay, drawing comparisons between the Swanage section and that of Compton Bay on the south-west coast of the Isle Wight. Over the next century, the Swanage section was described by such eminent figures in British geology as Conybeare and Phillips (1822), Fitton (1824, 1836), Buckland and De la Beche (1830), Mantell (1827, 1854), Austen (1852), Judd (1871) Lyell (1871), Meyer (1872), Hudleston and Morris (1882), Damon (1884), Bates (1898), and Strahan (1898). Buckland (1835), Beckles (1862) and Mansel-Pleydell (1888) provide the earliest records of dinosaur footprints and bones attributed to the ornithopod *Iguanodon* from the Wealden Group of Swanage Bay.

Studies of the Swanage section continued throughout the 20th century with Arkell (1947) re-evaluating the Wealden Group of Swanage and elsewhere in the Isle of Purbeck. However, no formal stratigraphical framework or stratigraphical log was produced. Oldham (1976) provides a general review of the palaeobotanical content of the Wealden Group describing specimens from Swanage. Over the past three decades notable contributions to the knowledge of Dorset's Wealden Group have been made by House (1989), Hesselbo and Allen (1991), Ruffell and Batten (1994), Robinson et al. (2002), Robinson and Hesselbo (2004), Radley (2006b) and Radley and Allen (2012a, 2012b, 2012c) who provide detailed descriptions of the Wealden Group of Dorset in general and Swanage Bay specifically but, again, no detailed internal stratigraphical framework has been provided. Charles P. Palmer produced a widely distributed, but unpublished lithostratigraphical account of Swanage Bay's Wealden Group. Crucially, this work documented temporary exposures of Wealden strata within Swanage Bay in the late 20th century.

2. Methods

A graphic log of the upper Wessex Formation at Swanage Bay was generated based on field observations and measurements recorded during 2018 and 2019. Analyses of collected samples for micropalaeontological evaluation and sedimentological investigation were undertaken during the same period. In the field, bed thicknesses were measured at beach level. For beds with thickness in excess of 10 m, trigonometry was employed. To ascertain a representation of the entire Wealden Group of Swanage Bay, data from Strahan (1898), Arkell (1947), Ruffell and Batten (1994), C. P. Palmer (unpublished data) and data collected in this study are combined.

Bulk sampling of several plant rich horizons has permitted examination of both microvertebrate and palaeobotanical remains. For the collection of microvertebrate remains, 20 kg of plant-rich mudstone was obtained from Ironstone 2 (see below). The samples were oven dried before total immersion in 10% hydrogen peroxide. After 12-24 hours of digestion, the resulting slurry was screen-washed using 250 μm and 500 μm sieves. Sieved residues were oven dried and picked using light microscopy for the recovery of microvertebrate remains. Beds containing associated plant remains were left in 10% hydrogen peroxide for up to one week; partial evaporation of the solution facilitated the picking of large (30 mm) unbroken sections of delicate coniferous shoots thus preserving their gross morphology. Selected specimens were mounted on adhesive carbon disks, gold- palladium coated and imaged using a Zeiss EVO series MA10 scanning electron microscope.

Institutional abbreviations: IWCMS, Isle of Wight County Museum Service; OUMNH, Oxford University Museum of Natural History; PM Poole Museum.

3. Geological setting

During the Early Cretaceous, the Wessex Sub-basin was undergoing a prolonged phase of subsidence (Chadwick, 1986). A series of east - west trending graben and half graben bordered by active syndepositional normal faults are aligned with pre-existing Variscan basement features (Chadwick, 1986). The presence of newly formed normal faults, coupled with the reactivation of basement faults allowed for a rift phase of subsidence that provided accommodation space for sediment that was being eroded from the isostatically uplifted Cornubian Massif in the west (Fig. 2) (Chadwick, 1986; Underhill and Paterson, 1998; Radley and Allen, 2012b; Westhead et al. 2018). The movement of syndepositional faults within the Wealden Group of Dorset is evidenced by the presence of palaeo-hydrocarbon seeps at Mupe Bay (to the west of Swanage), locally derived upper Jurassic detritus in the Wealden Group of the Wessex Sub-basin, and variation in succession thickness between Swanage Bay and the Isle of Wight (Cook et al. 1995, Wimbledon et al. 1996, Radley, 1998; Underhill and Paterson, 1998; Radley and Allen, 2012b). Some authors have suggested the presence of an Early Cretaceous rollover anticline on the downthrown side of the Purbeck Fault

(Fig. 1) that may have restricted the Wealden alluvial system to a narrow east-west trending valley (Selley and Stoneley, 1987; Underhill and Paterson, 1998; Radley and Allen 2012b). Wealden Group deposition in Dorset occurred approximately 100 km from the eastern margin of the Cornubian Massif (Fig. 2), which was undergoing uplift throughout the Early Cretaceous (Allen and Wimbledon, 1991). Locally within the Isle of Purbeck, the Wessex Formation is rich in detrital grits derived from Cornubian granites; tourmaline-rich sands and grits occur commonly throughout the succession. Within Swanage Bay at least two horizons of Cornubian sourced gritstones occur (Arkell, 1947; Radley, 2006a, 2006b; Radley and Allen, 2012b).

3.1 Post depositional tectonics

The Late Mesozoic strata of the Isle of Purbeck have been incorporated into an east west trending asymmetrical (monoclinal) fold with significant axial parallel faulting (Underhill and Paterson, 1998). This Purbeck monocline and its associated faults dominate the Isle of Purbeck's topography and structural setting today. Miocene compressional tectonics reactivated faults in Variscan basement rocks in both Purbeck and the Isle of Wight leading to reverse faulting and folding of the overlying late Mesozoic and Paleogene sequence in an asymmetric inversion structure (Nowell, 1997; Underhill and Paterson, 1998; Barton et al. 2011). Consequently, the Wealden Group of the Isle of Purbeck is confined to an east west trending valley mostly south of the main axis of the monocline. Here the succession both thins and coarsens westward from Swanage Bay to Durdle Door, thinning of the succession west of Warbarrow Bay is likely exaggerated by the local shearing out of mudstones (Radley and Allen, 2012b; Westhead et al. 2018) (Fig. 1).

Fig. 1. Here

Fig. 2. Here

4. Wessex Formation of Swanage Bay

Approximately 700 m of Wealden Group strata occur in Swanage Bay (Strahan, 1898; Arkell, 1947) (Figs. 1, 3-4). Neither the lower or upper contacts of the Group are currently visible, however C.P. Palmer (unpublished data), recorded the basal contact with the Purbeck Group at 13 m depth below King's Road East, Swanage. The upper contact with the Aptian Lower Greensand Group was noted under what is now a densely vegetated landslip at the north end of the bay by Ruffell and Batten (1994).

Cliffs below the Grand Hotel (N50.619331°, W1.956257°) (Fig. 3) with inaccessible outcrops of bedded sandstone represent the oldest exposed Wealden Group strata in Swanage Bay, scouring conditions on the foreshore occasionally expose older strata. Following the cliff line north, the beach

defences (groynes) decrease in frequency resulting in an accessible foreshore exposure of variable Wessex Formation lithologies (Fig. 3). The stratigraphical section presented here was recorded along the foreshore exposure between the basal contact of the prominent sandstone at Sheps Hollow (Fig. 1 C-D) (herein referred to as the Ravine Sandstone) and the north-eastern extent of the current Wessex Formation exposure (N50.626651°, W1.949247°) (Figs. 3-5). The logged section equates vertically to 110 m of strata exposed over a horizontal distance of approximately 460 m.

The Wessex Formation of Swanage Bay dips north at between 7° and 29° with a general increase in dip northward (Arkell, 1947). The lithology, lateral extent of the strata and bed thickness is highly variable making correlation with coeval sections to the east on the Isle of Wight and to the west in Dorset problematic (Arkell, 1947). As with the Wessex Formation of the Isle of Wight, two dominant facies are present at Swanage; one facies of overbank origin is dominated by red and variegated mudstones, the other is a fluvial channel facies represented largely by fine-grained sandstones and infrequent caliche conglomerates (Radley and Allen, 2012b, 2012c). Of these, overbank mudstones dominate the section, with sequences in excess of 40 m in thickness. These mudstones evidence small scale localised erosional channels, possible traces of roots, prominent calcrete horizons, plant debris horizons of variable lateral extent and six laterally variable ironstone beds (Fig. 4) (Arkell, 1947; Robinson et al. 2002; Radley and Allen, 2012b). Small-scale, fluvial sandstones of less than 10 m in thickness are interspersed with the thicker mudstones. These sandstones may exhibit a variety of sedimentary structures including linguoid/catenary ripples, trough and planar cross bedding, rip up mudstone clast horizons and a *Scoyenia* type ichnofacies with *Beaconites* burrows and occasional dinosaur footprints at two and possibly more horizons (Beckles, 1862; Radley and Allen, 2012b) (Fig. 3). Although the grain size of the arenaceous units is variable, the majority of the sandstones are very fine to fine grained. Thin grit horizons within sandstones are present, but it should be noted grits are not confined to the sandstone lithofacies; at several horizons, mineralogically immature quartz and feldspar rich grits occur within grey mudstones indicating high energy sheet floods (pers. obs. SP).

Fig. 3. Here

Fig. 4. Here

A systematic description of the logged Wessex Formation of Swanage Bay and the ten assigned marker beds is provided below (Figs. 5-10). These easily identifiable horizons allow for the more accurate placement of palaeontological discoveries within the section and are of significance when interpreting the palaeoenvironment. Thick (>30 m), often structureless mudstones are numbered in stratigraphical order (Fig. 5).

Fig. 5. Here

Fig. 6. Here

4.1 Named marker horizons

4.1.1 *Ravine Sandstone.*

Arkell (1947) and Palmer (unpublished data) (abbreviation R.S), (measured section at N50.623328°, W1.952829°).

Laterally extensive very fine to fine grained yellow-grey sandstone. Grains are rounded and well sorted, with quartz predominating, while feldspars and tourmaline are present in low abundance (90% Q, 5% F, 5% L). Grain size varies ranging between 125 µm – 250 µm. At beach level, the bed is 4 m thick, however south of Sheps Hollow, the bed thickens to approximately 5 m (Fig. 7). Horizons containing angular, pale blue/grey mudstone clasts up to 80 mm in diameter indicate localised bank erosion likely during times of flood. Low angle cross bedding is evident in large sand filled channels. Poorly accessible, meter thick mudstone horizons within the sandstone south of Sheps Hollow contain light grey, sub-rounded pedogenic nodules that are approximately 50 mm in diameter. It is not clear whether these nodules are autochthonous or reworked accumulations (Fig. 7B). The basal contact with underlying red-blue clays is sharp. The upper contact with silty clays is rippled indicating deposition in shallow channels. Large 1-2 m lenticular, silty calcitic concretions stand proud of the Ravine Sandstone and are seen to form ledges during scouring conditions. These concretions contain simple *Planolites*-like burrows without spreiten. Fallen blocks display numerous structures including linguoid ripples, desiccation cracks and, in rare cases, overturned blocks display tridactyl dinosaur foot casts as hyporeliefs.

Fig. 7. Here

4.1.2 *Heterolithic Siltstone and Clay.*

Beds 26 - 40 of Palmer (unpublished data) (abbreviated here H.S.C), (measured section at N50.623869°, W1.952320°)

A prominent, 3 m thick horizon of alternating grey silty sandstones and pale blue mudstones forms a spur in the cliff base 50 m north of Sheps Hollow (Fig. 8A). A minimum of three silty, fine-grained sandstones exhibit low angle, small scale cross and trough laminations. Bed thickness and lateral extent of each silty horizon is variable, being around 150 mm thick on average. Bedding of the silty horizons is disrupted by a low diversity *Scoyenia* ichnofacies that encompasses vertical and horizontal, primarily non-branching burrows and isolated tridactyl *Iguanodontipus* hyporeliefs (Fig.

8D-E). The predominance of a low diversity ichnofauna and dinoturbated, finely cross-bedded sands suggest these beds are of overbank or levee origin. Modern beach sand obscures the base of this unit.

Pale blue/grey mudstones alternate with the silty overbank /levee deposits. These mudstones represent palaeosols that are rich in well-developed calcretes that likely formed by pedogenic processes in semi-arid, seasonal vertisols (Robinson et al. 2002). Examination of calcretes from the Wessex Formation has given an atmospheric $p\text{CO}_2$ level of approximately 560 ppmV indicating that CO_2 levels were low during the Barremian before rising to the mid Cretaceous 'green house' high (Robinson et al. 2002).

Fig. 8. Here

4.1.3 Middle Sandstone.

Bed 54 of Palmer (unpublished data) (abbreviated here M.S.S) - (measured section at N50.6253566°, W1.9507562°).

A 3.2 m thick, fine-grained, homogenous yellow, quartz rich sandstone exhibits well-developed low angle cross-bedding (Fig. 9). Quartz, feldspar and tourmaline grains are subangular to subrounded; grain size varies with a range of 100 μm – 250 μm (90% Q, 5% F, 5% L). Pale blue/grey mudstone clasts indicate localised bank erosion presumably during times of flood. The Middle Sandstone's basal contact with pale blue mudstones beneath is erosive. Trough cross bedding and trace fossils are rarely seen.

Fig. 9. Here.

4.1.4 Ironstones.

This unit comprises the 'six ironstone group' of Palmer (unpublished data) and are abbreviated here as IRST 1-6 (measured section at N50.626078°, W1.949890° – N50.626503°, W1.949379°). Nearing the northerly extent of the present exposure, plant-rich, pale blue/grey mudstones are interbedded with a minimum of six thin ironstone horizons (Figs. 4D, 10 and 11A). Landslips between Ironstone 1 and 2 (see log) possibly obscure a further Ironstone horizon, this large debris slide contains bedded ironstones likely slipped from Ironstone 2. Presently this landslide obscures strata formerly exposed at the cliff base. Each ironstone is lithologically distinct with grain size and quartz content increasing from Ironstone 1, (lowest) to the sub-conglomeratic Ironstone 6 (the highest in the sequence). Commonly, the bases of the ironstones are erosive with bed thickness ranging from 300 mm to 1.1 m. The lateral extent and fossil content of each bed are highly variable. Lignitic logs

and twigs likely of cheirolepidiaceae conifers are common. Ex-situ or weathered ironstones exhibit casts of degraded branches, twigs and rarely, coniferous cones. Internal moulds of large unionid bivalves, are common and abraded reptile bones are present (Fig. 12A).

Fig. 10. Here

4.1.5 White Quartz Grit.

Bed 72 of Palmer (unpublished data) (abbreviated here W.Q.G) (measured section at N50.626553°, W1.949321°).

The White Quartz Grit is a 6 - 7 m thick, fining upwards sheet sandstone with prominent gritstone horizons near its base (Figs. 10B, 11A-C). The basal contact is sharp, but varies greatly in nature. In the exposed cliff section, it is erosive where it contacts a plant-rich mudstone, whereas at beach level the base is defined by the sub-conglomeratic Ironstone 6, which thickens to the north-east. Near beach level, several inclined horizons of fusain are seen to fan out from a point suggesting deposition may have taken place on an active prograding point bar (Fig. 11C). The coarse grit horizons near the base of the bed (subarkose) are comprised of poorly sorted, immature, sub-rounded to angular quartz, feldspars, tourmaline and mixed sedimentary lithic grains (80% Q, 15% F, 5% L). The maximum dimension of quartz in the lower grit horizon sampled is 12.5 mm. In the cliff section, grains are supported by a fine white kaolinitic powder. The overall composition and appearance of the gritstone is reminiscent of kaolinised granites from the Dartmoor/Cornwall area which may indicate a Cornubian source rock for this bed (D. Bullen, University of Portsmouth, pers. comm.).

Fig. 11. Here

4.1.6 Plant Debris Beds (PDBs)

In Swanage Bay, plant debris beds (PDB's) (Fig. 3D, G, H) comprise approximately 9% of the currently exposed Wessex Formation. Estimates based on the work of Stewart (1978) indicate that approximately 4% of the Wessex Formation of the Isle of Wight is comprised of PDB's (see Sweetman and Insole, 2010, p. 411, fig. 3). However, recent studies suggest that they comprise somewhat more than this (pers. obs. SCS.). Like the Wessex Formation of the Isle of Wight, PDB's are the primary source of fossils in the Wessex Formation of Swanage Bay. These beds mostly represent debris flows generated locally by sheet floods and contain mixed faunal and floral assemblages of fluvial, terrestrial and lacustrine origin (Radley, 1994; Sweetman and Insole, 2010; Sweetman, 2011a, 2011b). Some of the PDB's of Swanage Bay are comparable to coeval PDB's seen on the Isle of

Wight, but differ from them in details of their sedimentology. Further study concerning this is in progress. Distribution throughout the succession is irregular and bed thickness and lateral extent of individual beds is variable. Three plant-rich lithologies can be identified within the Wessex Formation of Swanage Bay: 1) laminated, fine plant material within mudstones; 2) twigs and logs in thick (>1m) mudstones often with ironstone horizons; 3) twigs and logs in high energy clays with grit content and allochthonous pedogenic nodules. The latter most closely resembles PDB,s seen on the Isle of Wight whereas the type 1 lithology of Swanage Bay is rarely encountered there (Sweetman and Insole 2010) and ironstones, with or without plant material, do not occur.

5. Palaeontology

The fossil assemblage recorded from the Wessex Formation of Swanage Bay includes ichnofossils, invertebrates, vertebrates and a moderately rich flora; all occur throughout the section (Mansel-Pleydell, 1888; Oldham, 1976; Radley, 1997; Goldring et al. 2005) (Fig. 12-16). The most abundant fossils in Swanage Bay are friable, lignitic twigs and logs, most probably derived from large cheirolepidiaceae conifers; this material occurs primarily in plant debris beds. Among the trace fossils are coprolites of both invertebrates and vertebrates, termite frass is abundant in almost all micro residues, as it is in those obtained from the PDB's of the Isle of Wight (Batten, 2011, p. 651, text fig.33.3. G). Numerous burrows and trackways occur throughout the succession with *Planolites* and *Beaconites* burrows being common within many of the sandstones (Fig. 8 D-E). Invertebrate remains include the common internal moulds of bivalves. Casts within the ironstone horizons of small bivalves, < 20 mm in length with striated ornamentation are identified as the unionid *Subnippononaia fordii* Barker, Munt and Radley, 1997. Larger bivalves, > 100 mm in length with subtle growth lines show similarities to *Unio mantelli* Sowerby, 1836 (Munt et al. 2011 p.94, fig7.2). Small (~10 mm diameter) ovate impressions of indeterminate bivalves are seen in mudstones above Ironstone 2. Other invertebrates previously recorded from the currently obscured Vectis Formation include viviparid gastropods, ostracods and the oyster *Ostrea* (Judd, 1871). This assemblage is comparable to that of the Cowleaze Chine and Shepherd's Chine members of the Vectis Formation of the Isle of Wight (Judd, 1871; Strahan, 1898; Arkell, 1947; Daley and Stewart, 1979; Stewart, 1981; Radley and Barker, 1998a; Sweetman 2011a). Vertebrate remains include dinosaur and crocodyliform bones and teeth, the majority of which occur as isolated, beach-worn specimens on the foreshore (Buckland, 1835; Mansel-Pleydell, 1888). To date, microvertebrate remains have been recorded from only one horizon, Ironstone 2, and include small teeth of osteichthyan fishes, hybodontid sharks and atoposaurid crocodyliformes (Fig. 13-14). Further sampling is in progress.

5.1 Macrovertebrates

5.1.1 Reptilia

Macrovertebrates have been recorded from the Swanage section for more than 180 years, yet little material has been described. Exceptions include Buckland (1835) and Mansel-Pleydell (1888) who described the first dinosaurs from Swanage Bay, most likely from the Wessex Formation. More recently dinosaurs from the Wealden Group of Swanage have been noted by Benson and Barrett (2009), Barrett et al. (2010) and Barrett and Maidment (2011). The majority of dinosaur material cited is assigned to the ornithopod *Iguanodon*, however this material was mostly collected by Victorian naturalists such as Rev. Bartlett and Colonel White and has since been lost, therefore, its identification as *Iguanodon* remains untested (Buckland, 1835).

Recorded here are two dinosaur vertebrae from museum collections that are undoubtedly derived from the Wealden Group of Swanage Bay (Fig. 12). One specimen, OUMNH PAL-K.67024, is a sectioned vertebra collected from the foreshore of north Swanage Bay (Fig. 12A). This vertebra is typically iguanodontian in its cross-sectional morphology resembling specimens cited by Galton (2009, p.254, fig. 20, g-i) and Martill and Naish (2001, p. 111, Pl. 14). The vertebra is preserved within a typical Wessex Formation, beach-worn ironstone matrix containing sub-angular quart grains that are approximately 1 mm in diameter. A preserved, but incomplete transverse process was clearly broken in antiquity suggesting the vertebra was transported and abraded in a high energy fluvial system prior to final burial. A second bone, specimen PM OI:1040.4, is half of a large indeterminate dinosaur centrum (Fig. 12B) This specimen is most probably assignable to an iguanodontian. The presence of large, water-worn, heavily pneumatized bone fragments from Swanage Bay likely indicate the presence of sauropods, but the absence of clear autapomorphies has resulted in a lack of confirmed records (pers. obs. RC) (Barrett et al. 2010). Buckland (1835) first recorded *Megalosaurus*-like theropods from the Wealden Group of Swanage Bay, but confirmation is not possible as the whereabouts of the specimen is unknown (Benson and Barrett, 2009).

Fig. 12. Here

5.2 Microvertebrates

Bulk sampling of Wessex Formation PDBs for the recovery of microvertebrate remains on the Isle of Wight has significantly altered our understanding of British Early Cretaceous vertebrate palaeobiodiversity (Sweetman, 2009, 2011b, 2016; Sweetman et al. 2014). The extensive Barremian microvertebrate assemblage recorded from the Isle of Wight includes chondrichthyans, osteichthyans, lissamphibians, lepidosaurs, turtles, crocodyliforms, ptersosaurs, non-avian dinosaurs, possible avian dinosaurs and mammals (Sweetman and Underwood, 2006; Sweetman, 2007, 2011b, 2016; Sweetman and Hooker, 2011; Sweetman and Evans, 2011a, 2011b; Sweetman

and Gardner, 2012; Sweetman et al. 2014). Until now, Wealden Group microvertebrates from Swanage Bay had not been recorded. The systematic trial sampling of plant rich horizons has identified one horizon, Ironstone 2, which contains a mixed faunal microvertebrate assemblage that is comparable in part to the coeval microvertebrate assemblages of the Isle of Wight (Duffin and Sweetman, 2011; Forey and Sweetman, 2011; Sweetman et al. 2014; Salisbury and Naish, 2011). The currently recorded Swanage Bay assemblage is restricted in diversity, most probably reflecting the small quantity of matrix processed to date. Osteichthyan remains dominate the Swanage microvertebrate assemblage. However, chondrichthyans, indeterminate lissamphibians and crocodyliforms are also present. Actinopterygian remains representing Lepisosteiformes, Pycnodontiformes and Amiiformes are recorded. Chondrichthyans are represented by hybodont sharks, while neosuchian crocodyliforms include atoposaurids and goniopholidids.

5.2.1 *Elasmobranchii*

Elasmobranchs are represented by the hybodont *Lonchidion*. At least two species, *Lonchidion striatum* Patterson, 1966 and *L. breve* Patterson, 1966 occur (Duffin and Sweetman, 2011; Sweetman, et al. 2014) with a third taxon represented by an indeterminate hybodont tooth morphology (Fig. 13 I-K). The teeth of *Lonchidion striatum* bear distinctive elongate crowns with a robust occlusal crest and well developed, longitudinally vertical ridges on both the labial and lingual surfaces (Sweetman et al. 2014) (Fig. 13 I-J). The teeth of *Lonchidion breve* also have elongate crowns, but differ from those of *L. striatum* in being smooth, devoid of ornamentation and having a low to moderately elevated central cusp (Sweetman et al. 2014) (Fig. 13k) .

5.2.2 *Actinopterygii*

Ganoid scales likely from the lepisosteiform *Scheenstia*, are the most common element recovered from microvertebrate residues. Characteristically diamond-shape flank scales evidence two taphonomic grades; scales are either abraded prior to deposition with worn, rounded margins, or are complete, only showing damage due to extraction from the matrix (Fig. 13 A-C). Distinctive conical, spear-like teeth of amiiform fishes are also present (Fig. 13G). Teeth with broken elongate constrictions at the crown root junction flare into spear-like, unornamented crowns flanked by well-defined lateral carinae (see Sweetman et al. 2014, p.888, fig. 11 a-e) indicate a caturid-like fish in Ironstone 2 (Fig. 13G). Pycnodontiformes are represented by fragmentary jaw bones with durophagous dentition similar to *Coelodus* (Fig. 13F) (Forey and Sweetman, 2011; Sweetman et al. 2014).

5.2.3 *Neosuchia*

Two neosuchian families, Goniopholididae and Atoposauridae are reported here from the Wessex Formation of Swanage Bay. Isolated atoposaurid tooth crowns represent the commonest tetrapod

elements among microvertebrate samples; in contrast only one goniopholidid crown (Fig. 14C) has been recovered from samples to date. The larger atoposaurid crown figured (Fig. 14B) measures 0.9 mm mesiodistally and 1.1 mm apicobasally. Teeth are conical, often lanceolate, somewhat labiolingually compressed with well-developed mesial and distal carinae and well-defined apicobasally aligned striations (Fig. 14-B) (Salisbury and Naish, 2011). Goniopholidid teeth are considerably larger, that in Fig. 14C measuring 7.8 mm mesiodistally and 15.9 mm apicobasally. They are typically robust, conical and slightly labiolingually recurved. Striations are defined in apicobasally aligned rows on both the labial and lingual surfaces. Micro enamel ripples flank smooth well defined carinae on both the mesial and distal surfaces (Fig. 14C) (de Andrade et al. 2011; Néraudeau et al. 2012, p.9, fig 7. E-F). Both the atoposaurid and goniopholidid teeth recovered have resorption pits at the base of the crowns, indicating that they are shed. The goniopholidid crown exhibits an apicodistal wear facet (Fig. 14C).

Fig. 13. Here

Fig. 14. Here

5.3 Palaeobotany

The Wessex Formation flora of Swanage Bay is diverse (Oldham, 1976). Conifers, primarily from the Cheirolepidiaceae dominate the section's palaeobotanical record. Cheirolepidiaceae conifers had a near global distribution in the Early Cretaceous and were ecologically important at low to mid palaeolatitudes (Watson, 1977; Alvin, 1982; Srinivasan, 1995; Axsmith, 2006). The Early Cretaceous floras of North America, Brazil, China and mainland Europe closely mirror the Wealden flora of Dorset, where cheirolepidiaceae conifers dominated prior to the radiation of angiosperms (Watson, 1977; Srinivasan, 1995; Sucerquia et al. 2015; Jing and Bainian, 2018). Filicales (Polypodiales) ferns are also present. Robust indeterminate fern indusia are recorded from the ironstone horizons (Pers. obs. SP). In addition, rare silicified 'trunk' fragments of the tree fern *Tempskya* have been recovered from Swanage, these specimens have only been recovered from the foreshore and not in-situ (pers. obs. SP) and may be derived from the underlying Purbeck Group exposed to the south (Fig. 1). Four coniferous, leafy shoot morphologies occur commonly in the Wessex Formation of Dorset; 1) the *Brachyphyllum* type with helically arranged, scale-like leaves, 2) *Watsoniocladius* type closely resembling extant Cupressaceae with decussate scale-like leaves, 3) the 'frenelopsid' type, with long decurrent leaves that give a segmented appearance to shoots, and 4) elongate needle-like leaves resembling those of pine trees (Watson et al. 1987; Watson and Alvin, 1999; Sucerquia et al. 2015).

In the Wessex Formation of Swanage Bay, two conifers, *Pseudofrenelopsis* and *Watsoniocladius*, are found in PDBs of often low floral diversity (Fig. 15, 16E-F, I-K). The botanical content of these beds is highly variable with each horizon often being distinct in its overall floral content. *Watsoniocladius* is

found within a low diversity, laminated plant debris bed that contacts the top of Ironstone 5, in stark contrast, plant-rich mudstones above and below Ironstone 2 are dominated by the conifers *Pseudofrenelopsis* and *Sphenolepis*. Palaeobotanical data from PDBs of the Wealden Group of southern England has proven to be invaluable for interpreting the palaeoenvironmental setting of the Wessex Formation of the Wessex Sub-basin (Batten, 1974; Watson and Alvin, 1996). Xerophytic adaptations, the presence of fusain and uneven growth rings found commonly within wood of the Wessex Formation indicate stressed growing conditions under a Mediterranean-like, semi-arid environment (Batten, 1974; Alvin et al. 1981; Watson and Alvin, 1996). Although morphologically distinct from one another, both *Pseudofrenelopsis* and *Watsoniocladius* possess shared xeromorphic adaptations, thickened cuticle, reduced leaf size and sunken stomata reduce water loss (Alvin, 1982; Watson and Alvin, 1996). Small, ciliate marginal leaf hairs are known to aid condensation capture at night in modern plants, these hairs occur commonly on distal leaf margins of both *Pseudofrenelopsis* and *Watsoniocladius* (Watson and Alvin, 1996). The xerophytic adaptations seen in Wealden taxa are comparable to those of Mediterranean macchia floras where low shrubs and conifers with reduced leaves and sunken stomata thrive in water-restricted environments (Rotondi et al. 2003).

Family: Cheirolepidiaceae Takhtajan, 1963

Genus: *Pseudofrenelopsis* Nathorst, 1893

Pseudofrenelopsis is attributed to the Cheirolepidiaceae on the basis of its association with a *Classopollis* pollen-containing male cone (Alvin et al. 1978; Alvin, 1982, 1983; Watson, 1977). It is one of the better known conifers within the Wealden Supergroup of the UK, having been extensively examined in the Wessex Formation of the Isle of Wight (Alvin et al. 1981; Alvin, 1982, 1983).

Distinguishing characters

Within Swanage Bay *Pseudofrenelopsis* is present in multiple PDBs. Branching is sparse but shown to be alternate evidenced by specimens from the Barremian - Aptian Potomac Group of North America and the Aptian Crato Formation of Brazil (Watson, 1977; Sucerquia et al. 2015). Shoots with a segmented appearance bear striated elongate leaves encircling the stem (Fig. 15C-D, 16E-F). Leaves are adpressed and can be rectangular to triangular in outline. Marginal leaf hairs are present. Stomata are circular, arranged in longitudinal rows and sunken with guard cells. Stomata close to leaf margins where branching occurs become elongate.

Family: cf. Cheirolepidiaceae Takhtajan, 1963

Genus: *Watsoniocladius* (Seward, 1919) Srinivasan, 1995.

Watsoniocladius superficially resembles the extant *Cupressus*, hence its former taxonomic placement within *Cupressinocladius*, a genus erected by Seward (1919) to accommodate leafy shoots of a decussate arrangement that mirrors the morphology of the extant conifers *Thuja* and *Chamaecyparis* of the Cupressaceae (Francis, 1983). Srinivasan (1995) established *Watsoniocladius* to accommodate species of *Cupressinocladius* that possess shared characteristics with cheirolepidiaceus cuticle (Barnard and Miller, 1976; Srinivasan 1995 and Watson and Alvin, 1999). Seward (1895, 1919), Francis (1983), Srinivasan (1995), Watson (1977) and Watson and Alvin (1999) all give detailed accounts of *Watsoniocladius*, formerly *Cupressinocladius*.

Distinguishing characters

Watsoniocladius specimens recovered from within 1 m above and below Ironstone 5 in Swanage Bay (Fig. 6) represent growths from distal leafy shoots (Fig. 15A-B, 16I-K). They branch alternately in a singular plane resulting in a ‘frond like’ appearance (Fig. 15A-B, 16I-K). Two distinct leaf morphologies are present within the shoots: 1) leaves of the axis are appressed with distally flared, free leaf margins crowned by a distinctive projecting spine. These leaves are elongate and encircle the stem in sets of three. Uniformly each leaf expands distally, overlapping the base of the next node. Often, a medial keel extends from the projecting spine towards the leaf base; 2) Scale-like leaves form side shoots that arise alternately from each node. These leaves are somewhat ovate, and arranged in alternating opposite, decussate pairs. Leaves are dorsoventrally flattened and spreading. Multiple small spines flank a medially positioned spine on the leaf’s distal margin, and like the leaves of the axis a medial keel is often seen. Leaf tips are free, with clear grooves separating the leaves. Stomata are 20 µm in diameter and arranged in loose rows near leaf margins. Stomatal pits are surrounded by raised rims with papillae.

Family: Taxodiaceae Warming, 1884

Genus: *Sphenolepis* Schenk, 1871

Leafy shoots of *Sphenolepis* superficially resemble those of the extant *Sequoiadendron*. Specimens recovered from Swanage Bay are morphologically comparable to those figured by Kvaček (1997) from the Cenomanian of the Czech Republic. Fisher (1981) figured and described specimens from the English Wealden, Gomez et al. (2012, Fig 10.3. pp 99 p-q) figured comparable specimens from the Barremian of Belgium.

Distinguishing characters

Three-dimensional leafy shoots show helically arranged, scale-like, adpressed leaves (Fig. 16A-D). Leaf shape is generally rhomboidal. However, the general morphology of leaves changes depending

on the placement of original growth, leaf apices can be rounded or somewhat acute (Fig. 16A-B). Leaves with acute apices and free distal margins have a 'hook like' appearance (Fig. 16C). Currently no stomata have been observed on specimens in this study due to a lack of preserved cuticle.

Fig. 15. Here

Fig. 16. Here

6. Conclusions

Hauterivian to Barremian, Wessex Formation sandstones and mudstones are exposed in north Swanage Bay. Silty mudstones of overbank origin dominate, however, sandstones and well-developed grits evidence active deposition by mixed load, high-energy braid river systems (Radley, 2006b; Radley and Allen, 2012b). Palaeogeographically the section straddles floodplains to the east and hinterland braid plains to the west (Radley, 2006b; Radley and Allen 2012b). Proximity to Cornubian uplands is supported by grits composed of mineralogically distinctive detrital grains derived from granites to the west (Radley and Allen, 2012b) which are not encountered in the Wessex Formation of the Isle of Wight some 35 km to the east.

Deposition of a number of PDBs at Swanage, like those on the Isle of Wight, occurred as a result of locally generated inter-fluvial sheet floods (*sensu* Sweetman and Insole, 2010). Mixed-load debris flows deposited a diverse faunal and floral assemblage into depressions on the Wealden flood plain (Stewart, 1978; Sweetman and Insole, 2010). The majority of fossils recovered from these PDBs show abrasion and varying degrees of disarticulation suggesting a parautochthonous origin, however the presence of delicate, articulated *Watsoniocladius* shoots implies deposition in gentle waters close to the place of growth on at least some occasions. Plant-rich conglomeratic ironstones with channelised bases (Ironstone 5-6) are likely of fluvial channel origin. The presence of well-developed calcretes, desiccation cracks, fusain and highly adapted xerophytic conifers all indicate deposition occurred within a seasonal, semi-arid environment (Robinson et al. 2002; Watson and Alvin, 1996). Both the fauna and flora of the Wessex Formation at Swanage Bay is comparable to the Barremian assemblages of the Isle of Wight (Watson and Alvin, 1996; Sweetman, 2009, 2011b, 2016). Two conifers, *Watsoniocladius* and *Pseudofrenelopsis* dominated the landscape in low diversity coniferous forests. In the rivers, fish flourished with both chondrichthyans and osteichthyans present. Hybodontiforme sharks and neosuchian crocodyliforms represent the top of the preserved food chain in these Early Cretaceous river systems, with spinosaurid dinosaurs such as *Baryonyx* not yet recorded in the Wessex Formation of Dorset. The dinosaurs, although rare, reached enormous size with iguanodontids being the most frequent large herbivore (Fig. 17).

Fig. 17. Here

New data presented here provides additional insight into the environment of deposition and palaeoecology of the central part of the non-marine, Early Cretaceous Wealden Group of the Wessex Sub-basin. The new stratigraphical framework provided allows for more accurate placement of fossil and palaeoenvironmental data within the currently exposed Wessex Formation of Swanage Bay. Future work on the Wealden Group of Swanage Bay and Dorset as a whole will provide an in depth understanding of Early Cretaceous transitional hinterland – floodplain environments which are only encountered in the Wessex Formation of Dorset. The scope for recovering new, significant, palaeobotanical and vertebrate material is considerable and is the subject of ongoing endeavour; further publications concerning the palaeontology, stratigraphy and sedimentology of Dorset's Wessex Formation are to follow.

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List of figure captions:

Fig. 1. A, outline geological map of the Isle of Purbeck. B, outline geological map of Swanage Bay. C, north Swanage Bay showing the area described. D, cliff profile showing the Wessex Formation and marker beds. R.S, Ravine Sandstone., H.S.C, Heterolithic silts and clay., Ms1, Mudstone 1., M.S.S, Middle sandstone., Ms 2, Mudstone 2., W.Q.G, White Quartz Grit. See text below for a description of exposed units.

Fig. 2. Palaeogeographic map of southern England during deposition of Wealden Group strata showing generalised lithofacies (modified after Allen 1981, Fig 11).

Fig. 3. Wessex Formation sandstones and mudstones of north Swanage Bay exposed south of the Purbeck Monocline (see below).

Fig. 4. Lithologies of the Wessex Formation of Swanage Bay. A-B, erosional channel within laminated mudstones; C, laminated mudstone showing high energy silty horizon with small scale laminated cross bedding; D, plant debris beds above and below an ironstone horizon; E, channel and point bar fine-grained silty sandstones; F, thick mudstone sequences with sheet sandstones above; G, a plant debris bed comprised of twigs and small logs capped by laminated plant material; H, laminated plant debris bed with arrows depicting logs below.

Fig. 5. A generalised lithostratigraphical log of the Wealden Group of Swanage Bay. Adapted from Strahan (1898), Arkell (1947), Ruffell and Batten (1994), Palmer (unpublished data) with data from this study included. Ages taken from the International Commission on Stratigraphy (Cohen et al., 2019).

Fig. 6. Log of the exposed Wessex Formation of Swanage Bay showing named marker horizons of palaeontological and palaeoenvironmental significance. Each division represents one meter.

Fig. 7. A, Ravine Sandstone at Sheps Hollow., B, Ravine Sandstone south of Sheps Hollow.

Fig. 8. A-E, Wessex Formation Heterolithic Siltstone and Clay. A, section showing the pale blue siltstone and clays of this marker horizon. B, alternating siltstones and pale blue clays. C, calcrete in pale blue clays. D, silty sandstone with tridactyl hyporelief dinosaur print. E, cross bedded, bioturbated silty sandstone. The hammer for scale is 29 cm long.

Fig. 9. A, Cliff section showing the Middle Sandstone., B, low angle planar cross-bedding in the Middle Sandstone.

Fig. 10. A-B, location of ironstone horizons 2-6. A, position of Ironstone 2-6 (IRST 1 is left of a large landslip). B, Ironstone 5 and 6 showing the White Quartz Grit above.

Fig. 11. A-C, White Quartz Grit. A, Exposure of the W.Q.G. with respect to IRST 6; B, fusain and lignite rich laminae in the base of the W.Q.G.; C, coarse grit horizon near the base of the W.Q.G. containing subrounded quartz, feldspar and tourmaline grains in an off-white kaolinitic matrix. Hammer in lower right of B is 330 mm in length.

Fig. 12. A, Cross section of an iguanodontian dorsal vertebra showing evidence of abrasion possibly due to transport, north Swanage Bay (OUMNH PAL-K.67024). B, indeterminate dinosaur vertebra from the Wealden Group of Swanage Bay (PM Ol:1040.4).

Fig. 13. A-H, Actinopterygian elements. I-L, Elasmobranch teeth. A-C, ganoid scales of *Scheenstia* sp. D-E indeterminate branchial teeth. F, pycnodont tooth ?*Coelodus* sp. G, indeterminate caturid tooth. H, semionotiform-like hemicentrum. I-J, *Lonchidion striatum* in lingual view. K, *Lonchidion breve* in labial view. L, c.f. *Lonchidion* sp. All of the above derived from Ironstone 2, Swanage Bay. Scale bars represent 200 µm for A-H and 500 µm I-L.

Fig. 14. A-B, IWCMS..... scanning electron micrographs of two atoposaurid crocodyliform teeth from Ironstone 2, Swanage Bay. A, accession number, in mesial and B, accession number in lingual view. C, OUMNH PAL-K.67025, normal light photograph of a goniopholidid tooth from Ironstone 2, Swanage Bay, in mesial view showing an apicodistal wear facet. Scale bars for A and B represent 500 µm, Scale bar for C represents 5 mm.

Fig. 15. IWCMS..... Coniferous plant remains from the Wessex Formation, Swanage Bay assigned to *Watsoniocladius* and *Pseudofrenelopsis*. A-B, accession number, *Watsoniocladius*, dark grey showing axial leaves, light grey showing shoot leaves, scale bar represents 2 mm. C-D, *Pseudofrenelopsis*. C, accession number, *Pseudofrenelopsis* type morphology showing branching; D, accession number, two leaves of *Pseudofrenelopsis* showing longitudinal stomatal rows. Scale bar represents 1 mm.

Fig. 16. Accession numbers Palaeobotanical remains from the Wessex Formation of Swanage Bay. A-D, *Sphenolepis*., E-F, *Pseudofrenelopsis*., G, ?*Brachyphyllum*., H, ?*Pseudotorellia*., I-J, *Watsoniocladius*. Scale bar for A-H, J-K = 500 µm, scale bar for I = 1 mm.

Fig. 17. Hypothetical palaeoecological reconstruction of the Wessex Formation of Swanage Bay.

Figure 1

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