



Brackish to hypersaline facies in lacustrine carbonates: Purbeck Limestone Group, Upper Jurassic–Lower Cretaceous, Wessex Basin, Dorset, UK

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Abstract

Sedimentary facies and stratigraphic architecture of non-marine carbonates are controlled by a range of environmental parameters, such as climate, hydrology and tectonic setting, but the few published facies models do not account for this variability. Outcrop and petrographic observations from the Mupe Member of the Purbeck Limestone Group (Upper Jurassic–Lower Cretaceous) in Dorset, southern England, are the basis for new depositional models of non-marine microbialites and associated carbonates in an extensional basin. Ten facies are defined, described and grouped into five facies associations. The Mupe Member is characterised by accumulation of in situ microbial mounds developed around tree remains preserved as moulds and silicified wood. Mounds occur within three stratigraphic units, separated by three palaeosoils, characterised by less-porous, bedded, inter-mound packstone–grainstone that commonly onlap mound margins. Mounds are developed mainly in the shallowest areas of the lake, as indicated by their shapes, facies relationships and association with palaeosoils. These microbial mounds are compared to modern (Laguna Bacalar, Mexico and Great Salt Lake, Utah, USA) and ancient (Eocene Green River Formation, Uinta Basin, Utah, USA) analogues to assess their value as palaeoenvironmental indicators. Facies transitions indicate an earlier, brackish-water lake and a later hypersaline lake for the Mupe Member, both within a semi-arid climate setting in an extensional basin. The fact that the microbialites are covered by evaporitic strata, together with sedimentological, palaeontological and stable isotope data, suggest that there was a sharp change from through-flowing brackish-water, to a closed hypersaline, lacustrine system.

Keywords Non-marine carbonates · Lacustrine · Upper Jurassic–Lower Cretaceous · Microbialites · Purbeck Limestone Group · Facies transition

Introduction

Non-marine carbonates accumulate in basins where the deposition and facies distribution are controlled by a wide range of external factors such as climate, tectonics, source area lithologies, drainage systems and sediment input. Internal factors including hydrology, water-depth, nutrient levels and the ecology of carbonate producers (e.g. plankton, molluscs,

ostracods, algae and microbes) also play a major part (Platt and Wright 1991; Talbot and Allen 1996; Bohacs et al. 2000; Gierlowski-Kordesch 2010). Changes in lacustrine depositional environments and facies transitions can occur rapidly or over longer periods of time, both laterally and vertically, depending on the external controls involved (Platt and Wright 1991; Carroll and Bohacs 1999; Bohacs et al. 2000). The nature of such transitions can be gradual and interbedded or abrupt, within a conformable vertical succession and closely linked to lake-level fluctuations and/or climate/drainage system changes (Carroll and Bohacs 1999). However, there is still debate about the controls on these lake-level fluctuations and the sedimentological response to climatic change or modification of the tectonic regime (Platt and Wright 1991; Talbot and Allen 1996; Bohacs et al. 2000; Gierlowski-Kordesch 2010). Of particular importance for this study, Bohacs et al. (2000) proposed that transitions between lake types appear to be

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driven by climate in balanced-fill and overfilled lakes and by tectonics in underfilled lakes. This paper analyses the nature of the contact between the brackish and hypersaline facies of the lower Purbeck limestones to decipher the dominating external and internal controls on the depositional environment and the observed facies transitions.

Related to this is the question of the possible environmental significance of the occurrence of microbialites. Microbialites are common in lacustrine systems and the associated microbes typically colonise the shallowest areas of lakes with a variety of salinities, from hypersaline to freshwater, and set within various climates from tropical to temperate and from arid to humid (Dupraz et al. 2006, 2009; Della Porta 2015). Whereas there are many studies that indicate that different microbial fabrics occur in different sedimentary environments (e.g. Jahner and Collins 2011, 2012; Chidsey et al. 2015), Della Porta (2015 p. 51) has recently stated in a large review of non-marine carbonate build-ups that “non-marine carbonate fabrics cannot be linked to a specific environment of deposition”. These differing views have been expressed for the origin of microbial carbonates from the lower part of the Purbeck limestones in Dorset since original work by Webster (1826) who described “burrs” encasing in situ tree stumps in the Soft Cap bed at Lulworth Cove. Although originally interpreted as freshwater accumulations (Webster 1826; Buckland and De La Bèche 1835) these units were subsequently interpreted as stromatolitic and forming in hypersaline lagoons (West 1975; Francis 1982). However, more recent work has proposed formation in fresh- to brackish-water lakes (Bosence 1987) or freshwater lakes (Perry 1994). This paper also addresses this aspect by examining the sedimentological, palaeontological and isotopic characteristics of the microbialites and associated facies to assess depositional environments and, through comparison with present-day analogues, propose facies models.

The aims of this paper are: (1) to provide new data on ten non-marine carbonate facies and in particular on non-marine microbial deposits; (2) to interpret these facies in terms of their depositional environments with the creation of two facies models, an earlier brackish-water lake and a later hypersaline water lake; (3) to discuss the different published interpretations of the environments of deposition of the Mupe Member of the Purbeck Limestone Group; and (4) to determine the nature of the contact and the processes that controlled the transition from the brackish to hypersaline facies.

Geological setting of the Purbeck Limestone Group in the Wessex Basin

The Wessex Basin of southern England and northern France (Fig. 1) evolved as an extensional sub-basin within a much larger system of intracratonic Mesozoic basins that covered

much of north-western Europe (Ziegler 1982; Underhill and Stoneley 1998). These basins were inverted during Cenozoic times by south to north directed compression. The original extent of the Wessex Basin has been compiled from both surface outcrop and subsurface data (Fig. 1; Lake 1985; Cope et al. 1980; West 1992; Underhill 2002) and occasional marine connections have been suggested to the southwest and the northeast (Casey 1963; Cope et al. 1992). The Wessex Basin comprises three sub-basins: the Portland-Wight to the south-west (the subject of this paper), the Pewsey to the north-west and the Weald to the east (Underhill and Stoneley 1998) (Fig. 1b).

Deposition in the Wessex Basin is recorded in sandstones, shales, limestones and evaporites ranging from the Permian through to the Cenozoic, where deposits occur in the successor Hampshire Basin, following Cenozoic inversion (Fig. 2; Underhill and Stoneley 1998). The subject of this paper, the Purbeck Limestone Group, occurs within the Permian-Lower Cretaceous syn-rift megasequence (Underhill and Stoneley 1998).

The Purbeck Limestone Group comprises Upper Jurassic to Lower Cretaceous non-marine carbonate, evaporite and palaeosol facies (West 1975; Bosence 1987; Perry 1994). The Mupe Member of the Purbeck Limestone Group, the subject of this paper, is particularly well exposed in its type area along the southern Dorset coast (Fig. 1c) as part of the Jurassic Coast World Heritage Site. The non-marine Mupe Member deposits (Fig. 2) have been studied intermittently over nearly 200 years, and most publications focus on the middle and upper parts of the group that are well exposed in Durlston Bay (e.g. Wimbleton and Hunt 1983; Clements 1993; Horne 2004; Riboulleau et al. 2007).

There have been fewer studies on the details of the lower part of the Mupe Member (Westhead and Mather 1996) that comprises the “Caps” and “Dirt Beds”, the “Broken Beds” and the “Cypris Freestone” of earlier authors (Austen 1852; Arkell 1933; House 1969; Clements 1993). Notable exceptions are West (1975, 1979) and Francis (1982, 1983, 1984, 1986).

Materials and methods

This work is based on examination and logging of successions at 22 localities (Fig. 1c), preparation of 228 slabbed specimens and thin-sections for classic petrography and microscopy. Cathodoluminescence (CL) was also used to identify diagenetic phases, using a Technosyn Cold Cathode Luminescence Model 8200 Mk II coupled to an Olympus microscope BH2 and to a digital camera Zeiss MRc5. Facies descriptions are based on integrated field observations, slabbed specimens, and thin-section microscopy (Table 1).

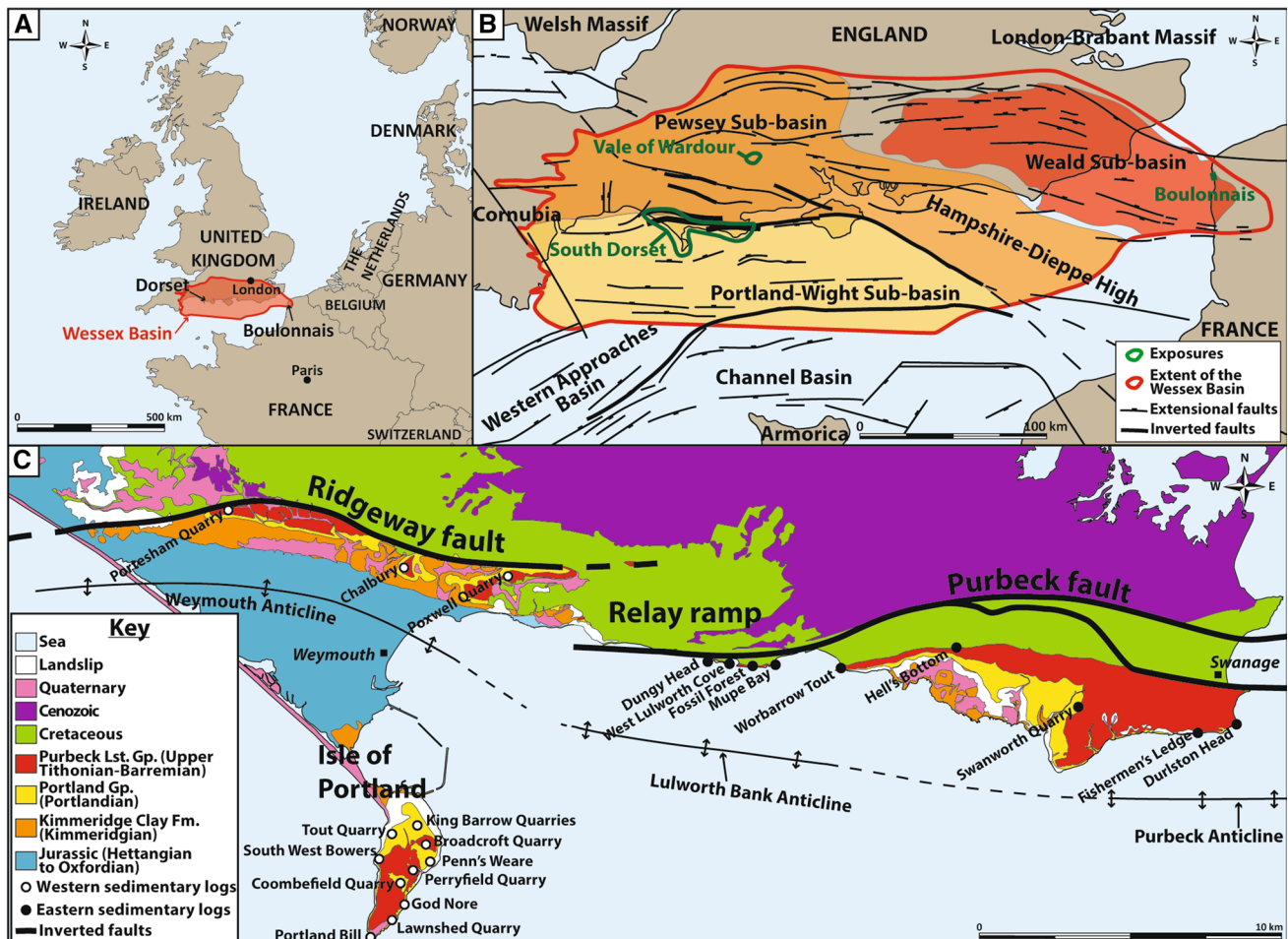


Fig. 1 Location and geological setting. **a** Purbeck Limestone Group exposures in UK and France. **b** Structural map of the Channel and Wessex Basins and sub-basins. The thick lines identify Mesozoic extensional faults inverted during the Alpine orogeny. **c** Simplified geological map of south Dorset with inverted faults (bold black lines)

and associated anticlines. Locations of sedimentary logs measured in this study are labelled as dots. The white dots indicate the western logs and the black dots indicate the eastern logs used for the quantitative analysis of facies transitions

Quantitative analysis of facies transitions was carried out following the methods described in Burgess (2016).

Facies description and succession

Ten facies have been established within the Mupe Member and the details of the facies and their palaeoenvironmental interpretations are given in Table 1 and Figs. 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15. The generalised log (Fig. 3) for the Mupe Member shows characteristic facies of each of the named beds. Although not of formal lithostratigraphic status, the bed names (Fig. 2b), originating from quarrymen's terms, have been used in the geological literature for over 150 years.

The succession has a fine-grained horizon (Wackestone to fine grainstone facies, Fig. 9, Table 1) overlain by three

horizons of mound-forming microbial deposits (Microbialite facies divided into Thrombolite and Stromatolite, and an unusual Burrow boundstone facies, Figs. 4, 5, 6, Table 1) that are interbedded and surrounded by the inter-mound facies (Intraclastic peloidal packstone–grainstone, Fig. 7, Table 1) and capped by three palaeosoils (Conglomerate and Carbonaceous marl facies, Figs. 12, 13, Table 1). These are overlain by either evaporitic horizons (Evaporite facies divided into Evaporite vuggy and Evaporite breccia sub-facies, Figs. 14, 15, Table 1) or packstone to grainstone horizons (Cross-bedded peloidal packstone–grainstone, Fig. 8, Table 1). These two lithologies are interbedded with a Gypsiferous peloidal packstone (Fig. 10, Table 1) and Calcareous sandstone horizons (Fig. 11, Table 1).

The facies succession and bed transitions are described below in stratigraphic order. The Transition Bed (West 2013) erosively overlies the Portland Group at the base of the

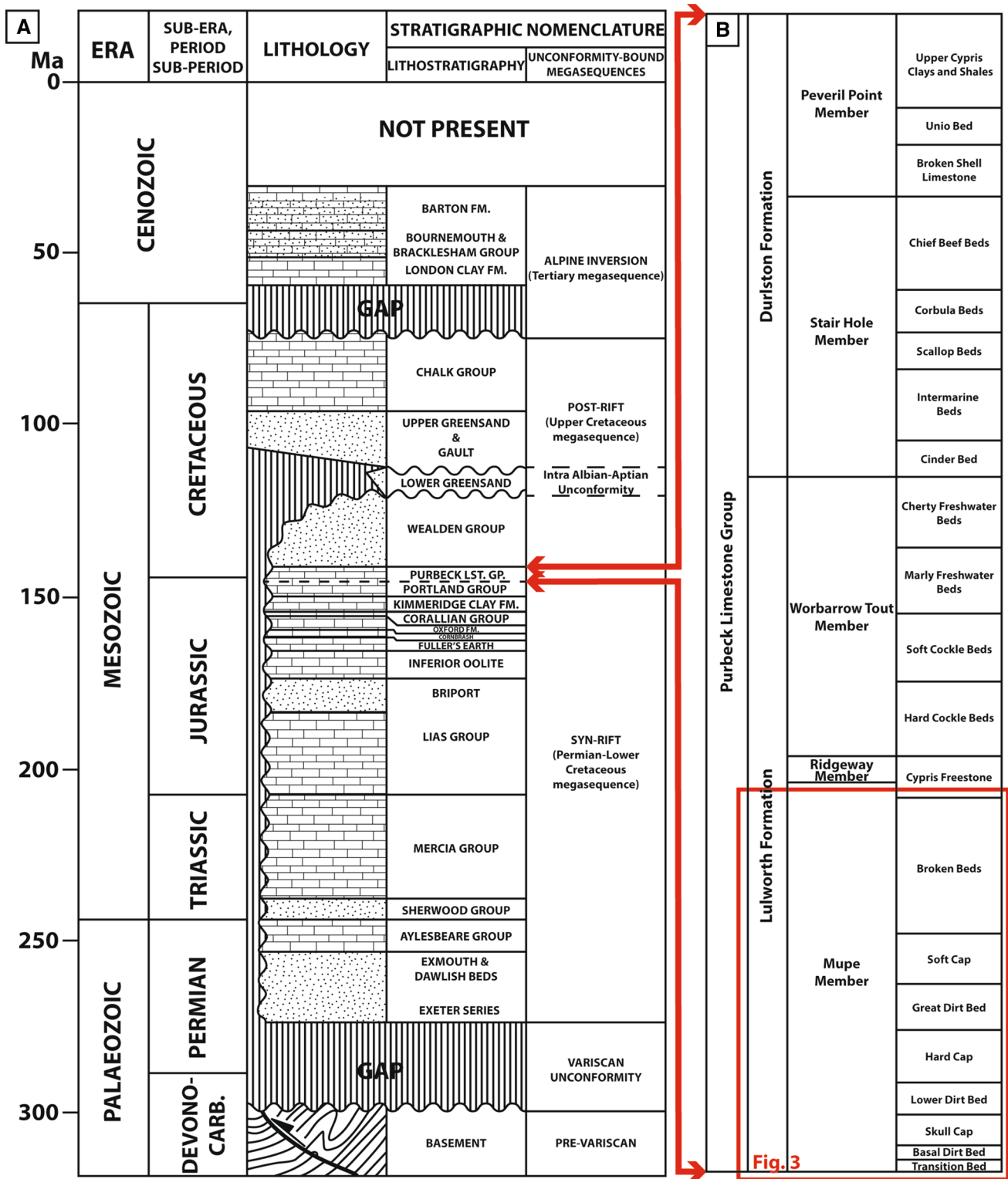


Fig. 2 Stratigraphic divisions of the Wessex Basin. **a** Stratigraphy of the Wessex Basin (modified after Underhill and Stoneley 1998). **b** Detailed stratigraphy of the Purbeck Limestone Group as used in

this study. Formation names from Casey (1963); member names from Westhead and Mather (1996); bed names from Fisher (1856), Bristow (1857), Strahan (1898), Francis (1982) and West (2013)

Table 1 Facies classification of the lower part of the Mupe Member of the Purbeck Limestone Group and interpretation of depositional environments

Facies, sub-facies (bed and location)	Texture	Bed description	Structures, textures, fossils and diagenesis	Interpretation/environment
Microbialite				
Thrombolite (Fig. 4) (occurs within skull cap, hard cap and soft cap beds throughout the studied area)	Clotted	Massive beds with growth layers made of a clotted macrofabric and occasionally columnar structures. In plan view, external growth layer exhibit cerebroid texture or bumpy surface	Angular to sub-angular peloids; ostracod shells; gastropod shells with micritic envelopes; microbial filaments made of micritic walled tubes and micritic threads within a fine-grained to micritic matrix; geopetal sediments at the base of the framework pores; chalcedone spherules; microcrystalline silica replacing clotted texture; and barite cement aggregates with tabular to elongated crystals	The framework with pockets of intramound peloidal packstone–grainstone (see text for full details) contemporaneously deposited with the interdigitated inter-mound facies indicates high hydraulic energy. The occurrence of brackish-water ostracods (Strahan 1898; Anderson and Bazley 1971; Barker et al. 1975; Anderson 1985; Horne 2002) and gastropods (Strahan 1898; Arkell 1941; Clements 1973; Radley 2002) indicate brackish waters. A shallow marginal lacustrine environment is interpreted
Stromatolite (Fig. 5) (occurs within hard cap and soft cap beds throughout the studied area)	Fine grained	Lenticular and mounded beds locally present below the mounds with crinkled laminations and horizontal laminations highlighted by micritic horizons	Sub-angular peloids; microbial filaments of vertical micritic tubules with intervening vertically stacked peloids; and ostracod shells	The peloidal micro-grainstone with some ostracods indicates that these stromatolites most likely developed in rather quiet marginal lacustrine environment
Burrow boundstone (Fig. 6) (occurs within skull cap, hard cap and soft cap beds throughout the studied area)	Packstone–fine grainstone bound by thick-walled burrows	Isopachous sub-cylindrical casing, or collar, around trees. The casing comprises 2–15 cm thick unit bound by complex network of winding and branching tubular, walled burrows	The burrows form a complex sinuous and irregular tubular network with tubes that vary between 0.5 and 1 mm in diameter. The burrows are commonly orientated radially away from the trees but also without any preferential orientation. They have micritic laminated walls with concentric micritic layers of sub-angular to rounded peloids. Inter-burrow areas have locally developed microbial filaments or vertically stacked peloids. Burrow infills are commonly geopetal sediments overgrown by sparry calcite cement. Replacive chalcedony spherules and barite crystal aggregates similar to those described in the Thrombolite sub-facies	The size and morphology of the burrows suggest polychaetes or insect larvae. These invertebrates are thought to have constructed tubes around trees that then bound peloidal sediment to create a cohesive boundstone stabilised by the sinuous burrow network. Peloidal sediments fill the spaces between burrows with occasional influence of calcifying microbes. This resulted in the vertical preservation of the more or less isopachous casing around tree branches, trunks and stumps. The peloidal packstone texture surrounding the burrows indicates intermediate hydraulic energy, possibly in a protected area. Overall, this sub-facies indicates a flooding of lake waters around trees in a shallow marginal lacustrine environment

Table 1 (continued)

Facies, sub-facies (bed and location)	Texture	Bed description	Structures, textures, fossils and diagenesis	Interpretation/environment
Intraclastic peloidal packstone–grainstone (Fig. 7) (occurs within skull cap, hard cap and soft cap beds throughout the studied area)	Packstone–grainstone, locally varies from more intraclastic to more peloidal	The bases of the beds are scoured when deposited directly above paleosols and are locally filled with coarser material. The beds can be structureless, with planar lamination or cross-lamination. Facies always associated with adjacent microbial mounds, or interdigitating with them	Sub-rounded microbial intraclasts with clotted macrofabric and/or microbial filaments; sub-angular peloids and a well-sorted texture; ostracod shells either found scattered in the matrix or reworked into ostracod-rich horizons; gastropod shells with micritic envelopes; rare bivalve shell fragments replaced by calcite spar with a micritic envelope; rare fish scales and very rare foraminifer; gypsum pseudomorphs filled with calcitic spar cement only in the hard and soft cap beds from Lulworth area eastwards and as reworked intraclasts at only two locations in the Isle of Portland: King Barrow Quarries and in the soft cap at God Nore; ooids with cortex comprising superficial (one or two layers of radial calcite layers) or mixed (mixture of micritic and radial calcite), and nuclei made of micrite, intraclasts, grapestones or gypsum pseudomorphs	The packstone to grainstone texture indicates moderate to high energy environment that is also supported with the occurrence of ooids. The presence of brackish-water ostracods (Strahan 1898; Anderson and Bazley 1971; Barker et al. 1975; Anderson 1985; Horne 2002), gastropods and bivalves (Strahan 1898; Arkell 1941; Clements 1973; Radley 2002), the stable isotope signature (see text) and the interdigitating with microbial mounds support an interpretation of brackish-water conditions west of the Lulworth area. Furthermore, the presence of gypsum pseudomorphs (even though transported) east of Lulworth area indicates a possible change to hypersaline eastwards. Overall, the depositional environment was a brackish marginal lacustrine system

Table 1 (continued)

Facies, sub-facies (bed and location)	Texture	Bed description	Structures, textures, fossils and diagenesis	Interpretation/environment
Cross-bedded peloidal packstone–grainstone (Fig. 8) (occurs within cypris freestone bed throughout the studied area)	Fine to coarse packstone to grainstone with some wackestone horizons	Beds with wave ripples, cross-bedding, cross-lamination (palaeocurrent directions see Fig. 8), herring-bone cross-stratification, planar lamination. Mud cracks locally present	Three types of micritic peloids: sub-rounded with clotted internal structure, sub-rounded and elongated with a micritic internal structure, and sub-spherical with a micritic internal structure; very thin ostracod shells; gastropods and bivalve shells with a micritic envelope; sub-angular to sub-rounded micritic intraclasts; two types of superficial ooids (one or two radial calcite layers) or mixed (mixture of micritic and radial calcite layers) cortices, and nuclei made of micrite, intraclasts or broken-up ooids; angular detrital quartz; rare foraminifers with a conical shape; and cubic halite pseudomorphs on bed surfaces. Occasional organic-rich interbeds wedging out laterally	The packstone to grainstone texture indicates a moderate to high energy environment supported by the sedimentary structures and the presence of intraclasts and ooids. The presence of brackish to hypersaline ostracods (Barker et al. 1975; Anderson 1985) together with the occurrence of evaporite pseudomorphs indicates hypersaline waters. The association of all these features reveals a variably brackish to hypersaline shallow marginal lacustrine environment. The organic-rich interbeds are interpreted to be reworked and redeposited palaeosols. This lake was subject to winds of variable orientation based on the palaeocurrents and the herring-bone cross-stratification (see text)

Table 1 (continued)

Facies, sub-facies (bed and location)	Texture	Bed description	Structures, textures, fossils and diagenesis	Interpretation/environment
<p>Wackestone to fine grainstone (Fig. 9) (occurs within Transition Bed at Portesham Q., Poxwell Q., Chalbury, Hell's Bottom, Swanworth Q., Fishermen's Ledge, Durliston Bay, God Nore, Lawnshead Q. and Portland Bill)</p>	<p>Wackestone and packstone to fine grainstone</p>	<p>Beds locally with planar laminations</p>	<p>Rounded to well-rounded micritic peloids relatively well sorted; ostracod shell fragments or intact; gastropod shells both a short-spined and more locally more high-spined (Portland Bill) and replaced by calcite cement; bivalve shells with a micritic envelope show two different microstructures, fibrous and prismatic and replaced by chaledony spherules; ooids; foraminifers only found at Portland Bill; rounded microporous <i>Solenopora</i> fragments only found at God Nore and Broadcroft Quarry; echinoderm plates only found at Portland Bill; intraclasts of oolitic and peloidal grainstone with an oolitic coating only found at Broadcroft Quarry and Portland Bill; rectangular bryozoan fragment only found at God Nore</p>	<p>The rather fine grained textures of the sediments (wackestone to fine grainstone) with planar laminations indicate a low energy system suggesting a protected shallow or a deep environment. This low energy system is confirmed with the superficial ooids and the superficial oolitic coatings on some of the clasts. The brackish-water tolerant ostracods and mollusc gastropods indicate a change in the environment from marine of the underlying oolitic Portland Group to the non-marine of the Purbeck Limestone Group. The low diversity of ostracods and gastropods indicate a closed system as suggested by Radley (2002). Occurrences of reworked marine fossils and clasts (red algae, echinoids, oolitic intraclasts, micritised ooids and bryozoans) from the underlying Freestone Member of the Portland Group indicate that the Portland Group was exposed, lithified and eroded prior the deposition of the Transition Bed. Altogether these clasts plus the texture indicate brackish-water conditions and the absence of desiccation cracks and hiatuses specifies a sub-littoral lacustrine setting</p>

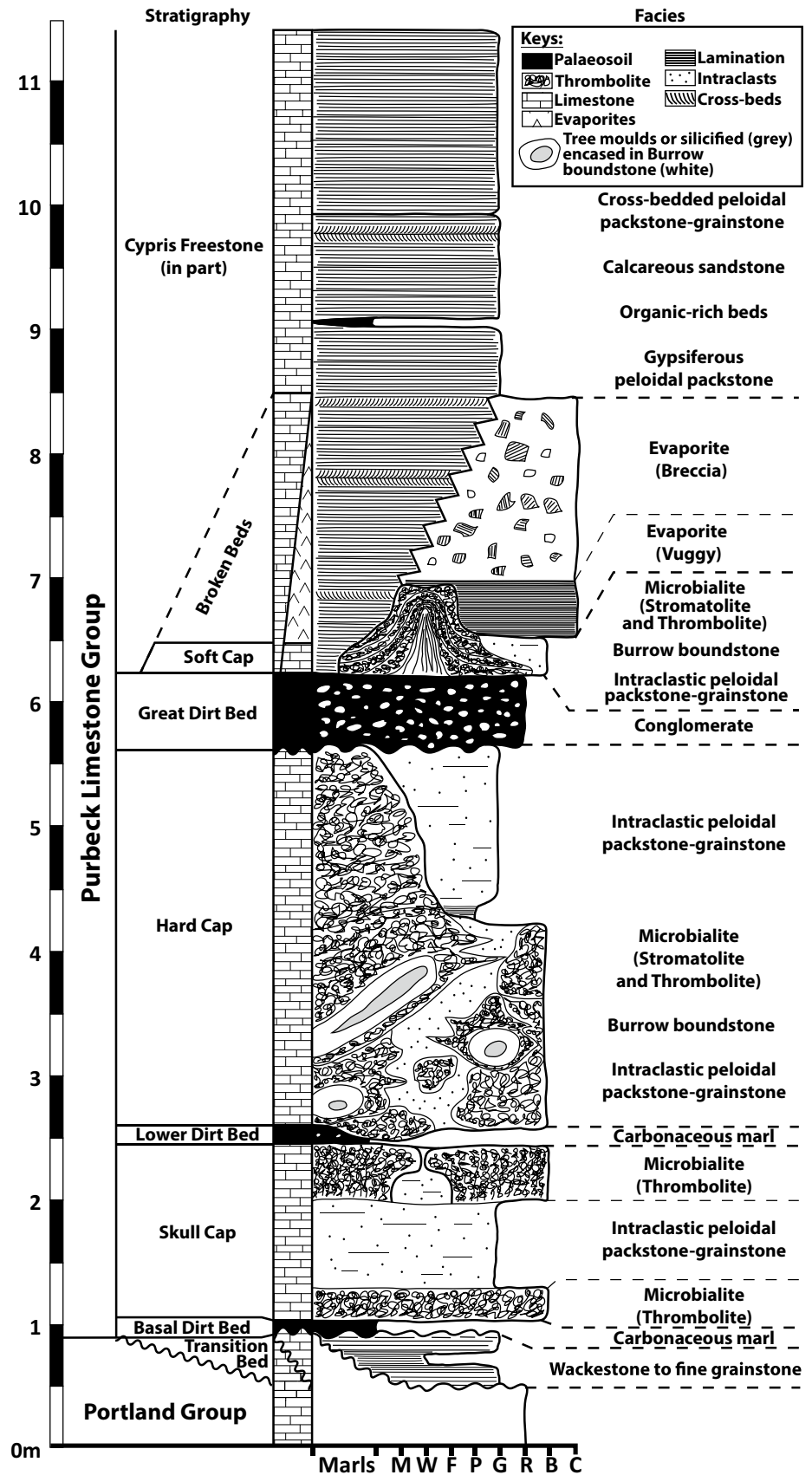
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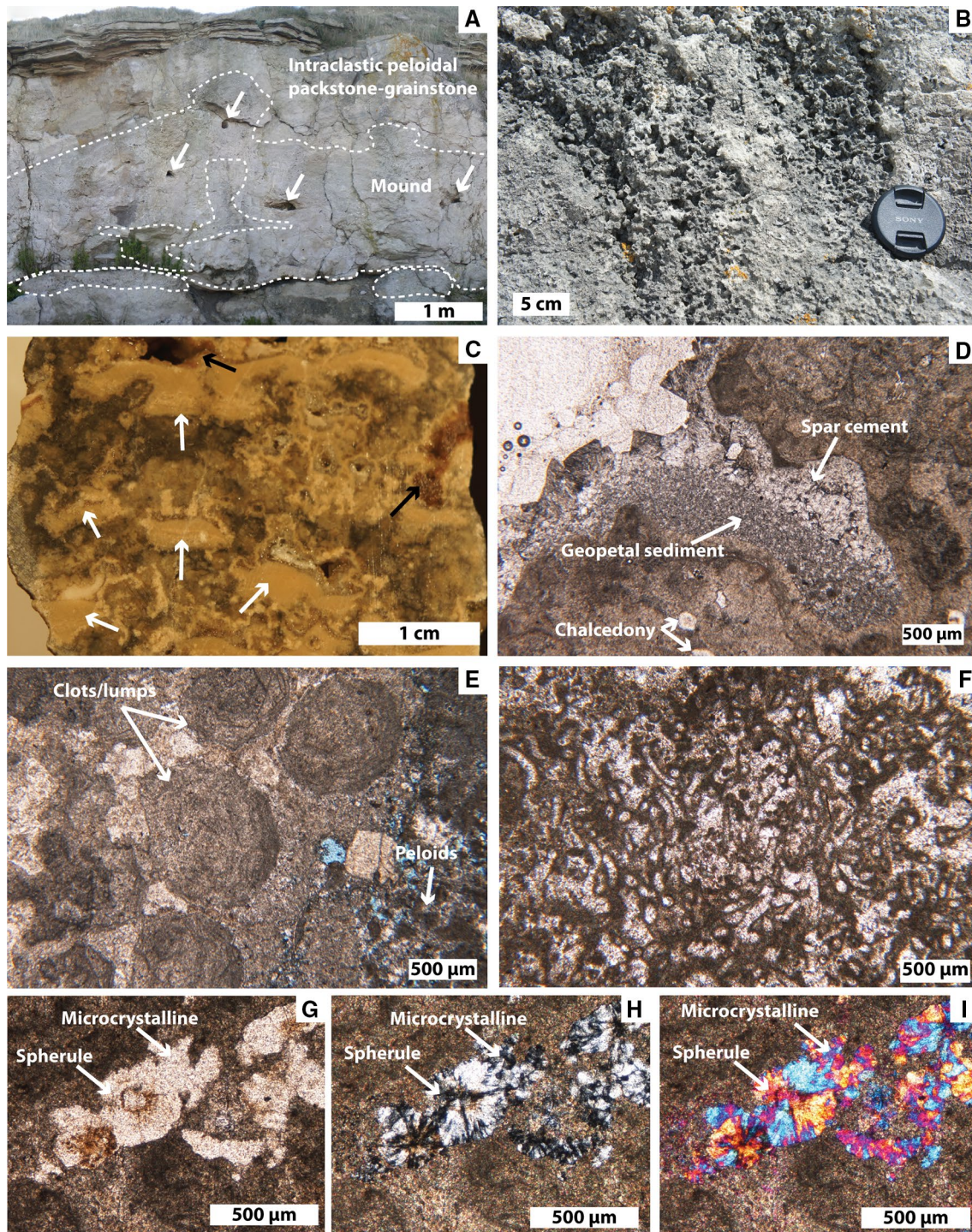
Facies, sub-facies (bed and location)	Texture	Bed description	Structures, textures, fossils and diagenesis	Interpretation/environment
Gypsiferous peloidal packstone (Fig. 10) (occurs within Cypris Freestone beds at Coombefield Q. and South West Bowers Q.)	Packstone	Laminated beds	Sub-angular to rounded prismatic, lenticular/lozenge, and pyramidal shapes, clasts comprising a mosaic of calcite crystals. The clasts are of silt and sand size with a predominance of coarse silt-size crystals; fine silt-size rounded micritic peloids well sorted and micritic patches	The calcite mosaic clasts are interpreted as gypsum pseudomorphs on the basis of their shapes. The fine texture of the matrix indicates low energy. Overall this facies is thought to have been deposited in a protected mudflat of a saline lake with episodic flooding that eroded gypsum-rich beds, reworking and redepositing the gypsum crystals more or less in situ. These are later replaced by a calcite mosaic or drusy infill
Calcareous sandstone (Fig. 11) (occurs within Cypris Freestone beds in Lutworth area)	Grainstone	Beds with planar cross-lamination organised in sets (palaecurrents see Fig. 11)	Well-sorted angular quartz grains comprise more than 50% of this facies. Predominantly very fine sand size surrounded by equigranular microspar cement; sub-angular to rounded micritic peloids with elongated and spherical shapes; few ostracod shell fragments; and rare ooids	The cross-bedded laminations, the sand size of the quartz grains together with the broken ostracods indicate a high energy marginal lacustrine environment. The abundance of angular quartz suggests this facies was deposited near to a clastic supply. The cross-lamination directions indicate a southerly directed palaecurrent and suggests a possible fluvial system running down a slope and bringing siliclastic material from the adjacent footwall block via the relay ramp area (i.e. Lutworth Cove, Fig. 1c)
Conglomerate (Fig. 12) (forms the Great Dirt Bed throughout the studied area)	Conglomerate with carbonaceous marl matrix	Beds with very irregular base	Angular limestone and black pebbles; fossil plant remains; silicified logs; and in situ silicified tree trunks of ancient conifers (<i>Protopressinoxylon purbeckensis</i>) and cycadophytes with roots. The matrix is made of brown to black carbonaceous marl and clay	This is interpreted as a palaeosol, developed over a microkarstic surface with a well-developed carbonaceous A/C rendzina soil profile and to have formed under semi-arid climate of Mediterranean type (Francis 1986)

Table 1 (continued)

Facies, sub-facies (bed and location)	Texture	Bed description	Structures, textures, fossils and diagenesis	Interpretation/environment
Carbonaceous marl (Fig. 13) (forms the Basal and Lower Dirt Beds throughout the studied area)	Marl with rare pebbles	Beds with irregular base with dark planar to undulated lamination	The matrix is made of brown to black carbonaceous marl to clay with silicified logs, in situ silicified tree trunks of ancient conifers (<i>Protocupressinoxylon purbeckensis</i>) and rare white limestone pebbles as described by Francis (1986)	The absence of large pebbles indicates that the underlying beds were not totally lithified before the pedogenesis (Francis 1986). The high content of carbonate and the calcareous parent rocks show that these palaeosoils were immature probably compacted and eroded rendzina soil profiles (Francis 1986) developed over a microkarstic surface
Evaporite	Crystalline with rare microcrystalline dark laminae	Beds with irregular planar lamination and locally, entirely silicified	Calcite crystals form an anhedral spar mosaic or exhibit prismatic shapes more or less elongated with triangular extremities; large prismatic quartz crystals; celestine crystals (Durlston Head) with a euhedral elongated shape; chert spherules; the only carbonate clasts found in this sub-facies are intraclasts either with a peloidal packstone-grainstone or a clotted microfabric; vugs are also abundant and unfilled at macroscale	The planar laminations might indicate a low energy environment also highlighted by the microcrystalline laminae. The prismatic calcite crystals are interpreted to be prismatic anhydrite crystal pseudomorphs as suggested by West (1964, 1975). The large prismatic quartz crystals are replacing either gypsum or anhydrite (West 1964) as is commonly the case in such facies (Hanor 2000, 2004). The vugs are likely to be dissolution vugs commonly occurring in evaporitic sediments after dissolution of gypsum or anhydrite crystals (Warren 2006). Overall, the evaporite pseudomorphs and vugs indicate a hypersaline lacustrine environment
Breccia (Fig. 15) (Broken Beds at the base of the Cyprus Freestone beds from Lutworth area eastwards)	Brecciated with a peloidal grainstone matrix	Very irregular beds not extensive, that locally exhibit north-verging folded structures	Large angular clasts of very coarse sand to boulder size of the Cross-bedded peloidal packstone-grainstone facies some of which are interlocking shapes. The matrix comprises well sorted angular quartz grains and rounded micritic peloids	All the evidence presented in this study confirm West's (1960, 1964, 1975) interpretation that this is a breccia formed as the result of a combination of both tectonic and diagenetic events. He proposed that this is a collapse breccia modified by later tectonic movements

Fig. 3 Idealised log for the lower Mupe Member of the study area indicating beds and facies as classified in this paper (Table 1), and drawn with average thicknesses of each bed (based on 22 sedimentary logs, Fig. 1). *M* mudstone, *W* wackestone, *F* floatstone, *P* packstone, *G* grainstone, *R* rudstone, *B* boundstone, *C* crystalline





Purbeck Limestone Group and comprises the Wackestone to fine grainstone facies (Figs. 3 and 9, Table 1). The Basal Dirt Bed (Francis 1982) is an immature rendzina palaeosol labelled as the Carbonaceous marl facies (Fig. 13) with an erosional surface at its base (Fig. 3). The Skull Cap (Damon 1860) comprises the Thrombolite sub-facies (Fig. 4) and the Intraclastic peloidal packstone–grainstone (Fig. 7). The base of the Skull Cap is a sharp, planar surface over the Basal

Dirt Bed (Fig. 3) and then comprises flat-topped microbial mounds before the transition in the middle part of the Skull Cap to the Intraclastic peloidal packstone–grainstone facies. This unit is overlain by tabular-shaped thrombolitic microbial mounds (Fig. 3). The Lower Dirt Bed (Damon 1860) is also interpreted by Francis (1986) as an immature rendzina palaeosol made of the Carbonaceous marl facies resting on an erosional base (Fig. 3). The overlying Hard

Fig. 4 Thrombolite sub-facies. **a** Cross section of a mound with ca. 10-cm-wide tree (i.e. trunk and/or branch) holes (white arrows) and inter-mound bedding of Intraclastic peloidal pack-grainstone facies (Hard Cap, God Nore, Isle of Portland, 50°31'31.41"N; 2°26'22.51"W). **b** Clotted structure and irregular branches in Thrombolite sub-facies (Soft Cap, Fossil Forest, 50°36'58.37"N; 2°14'23.09"W). **c** Geopetal sediment (white arrows) and later barite crystals (black arrows) infilling framework pores (SH1, Sand Hole, Isle of Portland, 50°31'22.42"N; 2°36'34.58"W). **d** Geopetal sediments filling growth framework cavity in mounds in plain polarised light (PPL, CQ2, Skull Cap, Coombefield Quarry, Isle of Portland, 50°31'58.25"N; 2°26'33.65"W). **e** Clots/lumps near the external surface of thrombolite framework (in PPL, BQ8, Broadcroft Quarry, Isle of Portland, 50°32'53.74"N; 2°25'35.07"W), mound on the left and peloidal grainstone (i.e. inter-mound) on the right. **f** Filaments from thrombolite head (HB6, Hell's Bottom, 50°37'11.60"N; 2°6'54.88"W). **g–i** Silica spherules in micritic fabric in PPL (**g**); Cross-polarised light (XPL) (**h**) showing the extinction crosses centred in the spherules and the straight extinction in the microcrystalline silica; and (**i**) with gypsum plate showing a positive retardation in the NE and SW quadrants and negative in the NW and SE quadrants indicating typical extinction of quartzine or length-slow chalcedony (WLC3, West Lulworth Cove, 50°37'1.27"N; 2°14'55.18"W)

Cap (Francis 1983) has a planar contact with the marl and comprises the mound-forming microbialite (Stromatolite and Thrombolite sub-facies, Figs. 3, 4 and 5) and Burrow boundstone facies (Fig. 6) that inter-digitate laterally with the Intraclastic peloidal packstone–grainstone facies (Fig. 3). The transition between the lower and upper part of the Hard Cap bed is marked by finer packstone that onlaps on to the sides of large microbial mounds (Fig. 3). The Great Dirt Bed (Damon 1860) is also interpreted by Francis (1986) as a rendzina palaeosol made of the Conglomerate facies (Fig. 12) with an irregular (microkarstic) erosional surface at the base (Fig. 3). The overlying Soft Cap (Bristow 1857) comprises the third unit of Microbialite facies and Intraclastic peloidal packstone–grainstone facies with a planar surface at the base (Fig. 3). In this bed, the microbial mounds (Stromatolite and Thrombolite sub-facies and Burrow boundstone facies) developed around fallen trees and in situ tree stumps, as seen at the well-known Fossil Forest locality east of Lulworth Cove. Here, domed or doughnut-shaped build-ups, which interdigitate with the Intraclastic peloidal packstone–grainstone facies (detailed in the next section), are exposed in three dimensions. The overlying Cypris Freestone (Fisher 1856) beds comprise mainly the Cross-bedded peloidal packstone grainstone facies (Figs. 3 and 8) with intercalations of Gypsiferous peloidal packstone (Figs. 3 and 10) and Calcareous sandstone facies beds (Figs. 3 and 11). The basal surface is irregular, overlying the Soft Cap. The Cypris Freestone beds are overlain by the Hard Cockle Beds (Bristow 1857) that mark the top of the Mupe Member. In some locations, the base of the Cypris Freestone comprises the Broken Beds (Fisher 1856) that are made of the Evaporite breccia (Figs. 3 and 15) and vuggy sub-facies (Figs. 3 and 14) with an irregular and undulating surface at the base

(Fig. 3). The lower part of these beds is made of the Evaporite vuggy sub-facies that covers the microbial mounds of the underlying Soft Cap bed and is overlain by the Evaporite breccia sub-facies (Fig. 3).

Quantitative facies transition analysis

Quantitative facies transition analyses (Burgess 2016) were conducted for all logs from the western area and, separately, all logs from the eastern area (Figs. 1c and 16). Some facies were grouped to simplify the analysis (Fig. 16). The method defines optimised transition probability matrices that show the probabilities of all facies transitions recorded in all logs from each area, as well as the most optimal vertical arrangement of facies, analogous to an ideal cycle (Burgess 2016). Transition probability values range from zero to one. For example, no transitions occur from Evaporite to Carbonaceous marl, but Evaporites always pass upwards to Cross-bedded peloidal packstone–grainstone facies. These variable transition probabilities suggest preferred occurrence of certain facies vertically and therefore laterally adjacent during deposition, assuming little or no missing time. This is clearly shown on the matrices and optimised successions (Fig. 16) where the Evaporite and Cross-bedded peloidal packstone–grainstone facies are interbedded and are expected to be deposited after all the other facies.

Microbial mounds

The Microbialite facies is subdivided into two sub-facies (Stromatolite and Thrombolite sub-facies), which together with the Burrow boundstone facies formed mounds, commonly around tree trunks, branches and/or stumps (Fig. 17). These mounds are composed of the Stromatolite sub-facies found locally and always at the base of the mounds (Fig. 17); the Burrow boundstone facies that forms a more or less isopachous casing around the tree remains (Fig. 17), and the major, mound-forming Thrombolite sub-facies that initially envelopes the Burrow boundstone and then accumulates upwards and laterally to form microbial build-ups (Fig. 17). The mounds are surrounded by, and inter-finger with, the Intraclastic peloidal packstone–grainstone facies (Figs. 7 and 17). This facies occurs as an inter-mound facies but also accumulates in growth cavities within the microbial mounds and between thrombolite heads and columns. Silicified tree remains (trunks, branches and stumps) are locally found in the Hard Cap and Soft Cap and were rooted in the Lower Dirt Bed and the Great Dirt Bed palaeosols. Francis (1982, 1983) described and identified the trees to be an ancient cypress (*Protocupressinoxylon purbeckensis*).

Figure 18 illustrates the sequence of events interpreted for the origin of the microbial mounds and the

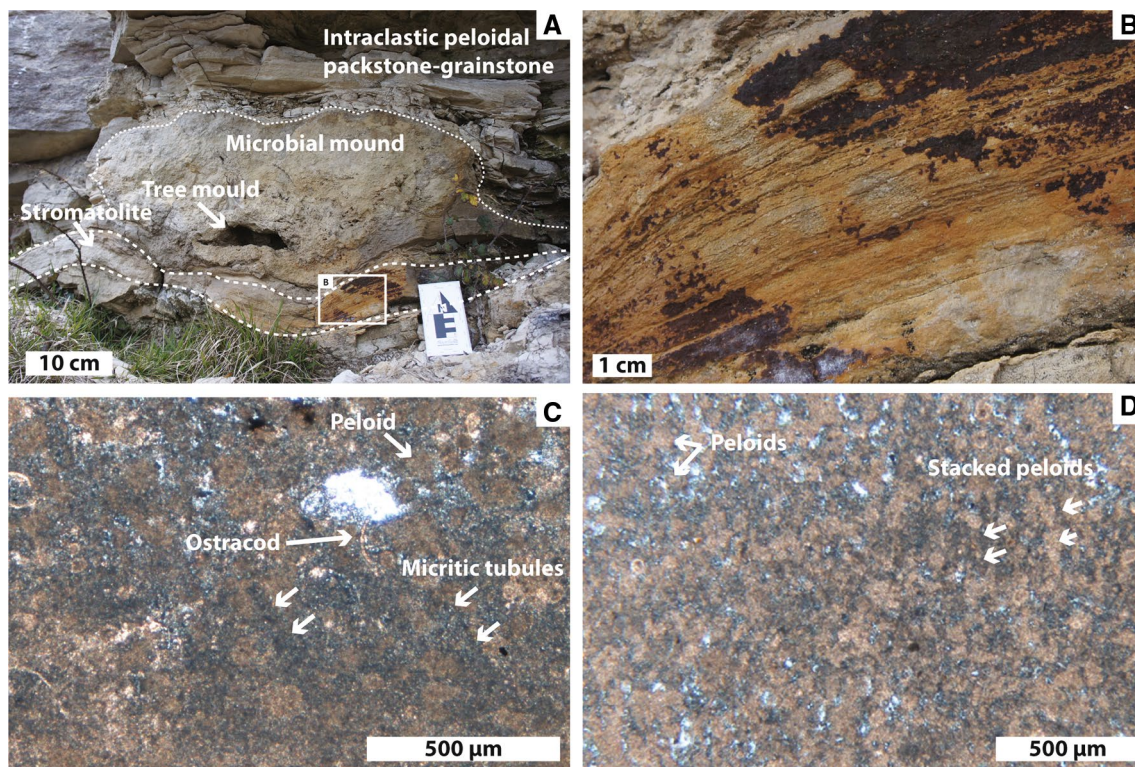


Fig. 5 Stromatolite sub-facies. **a** Hard Cap from Portesham Quarry with stromatolitic bed at the base (50°40′18.03″N; 2°33′8.62″W). **b** Crinkled lamination, close-up view of white boxed area in **a**. **c** Peloidal packstone with micritic tubules in PPL (SWB4, South West

Bowers, Isle of Portland, 50°32′40.06″N; 2°27′10.56″W). **d** Peloidal grainstone with vertically stacked peloids in PPL (BQ4, Broadcroft Quarry, Isle of Portland, 50°32′53.74″N; 2°25′35.07″W)

silicification of the trees. Following the transgression of the lake, the Stromatolite sub-facies (Fig. 18e) accumulated on the lake floor and the soils and trees were waterlogged and killed (Fig. 18b–d), as originally proposed by West (1975) and Francis (1982). Following flooding, the Burrow boundstone facies was constructed around the trees being stabilised by non-marine polychaetes or insect larval tubes (Fig. 18e; Table 1) and locally by microbial filaments. Polychaetes and insect larvae are common in present-day lacustrine environments where they burrow into soft sediment. They create tubes by accreting grains they can find close by to consolidate burrow walls as well as using mucus to impregnate burrow walls (Leggitt and Loewen 2002; Paik 2005; Dashtgard and Gringas; Knaust and Bromley 2012). Contemporaneously with the deposition of the Burrow boundstone facies, the silicification of the wood tissue occurred (Fig. 18e). The silica is considered to be of biogenic origin from the dissolution of planktic organisms that were living in the brackish-water lake or phytoliths (cf. Bustillo 2010). Although diatoms are by far the most common biogenic silica source in the lacustrine environment, their first occurrence is in the Late Cretaceous (Chacón-Baca et al. 2002). Sponges are reported from the Jurassic in lakes (Manconi and Pronzato

2008) and together with phytoliths that are very abundant in non-marine settings. They are the best candidate for the source of silica in the Purbeck lake. This dissolved silica is considered to have been remobilised as a molecular silicic acid (H_4SiO_4), as that is the only form of soluble silica found in nature, and it is the only agent able to penetrate fine wood cells (Siever 1962; Francis 1982). This permineralisation by silicic acid was either a process of filling and impregnation as suggested by Leo and Barghoorn (1976) or the capillary and evapo-transpiration model of Renaut et al. (2002) to silicify in situ trees soon after their death (Fig. 18e, f). At this time, geopetal sediments were deposited in the tubular cavities of the Burrow boundstone facies (Fig. 18e). Francis (1982) measured preferential orientations in moulds of fallen trees in the Hard Cap and Soft Cap and interpreted northerly blowing winds due to their mainly north–south orientations. Relatively strong winds and/or wind-driven currents could have caused the broken-off upper parts of the trees to fall to the lake floor (Fig. 18f). In view of the Burrow boundstone casing around the trees, the broken-off portions are thought to have been heavier than the wood and unlikely to have formed long-distance drifts (Fig. 18f). These broken-off trees then formed the substrates for the accumulation of

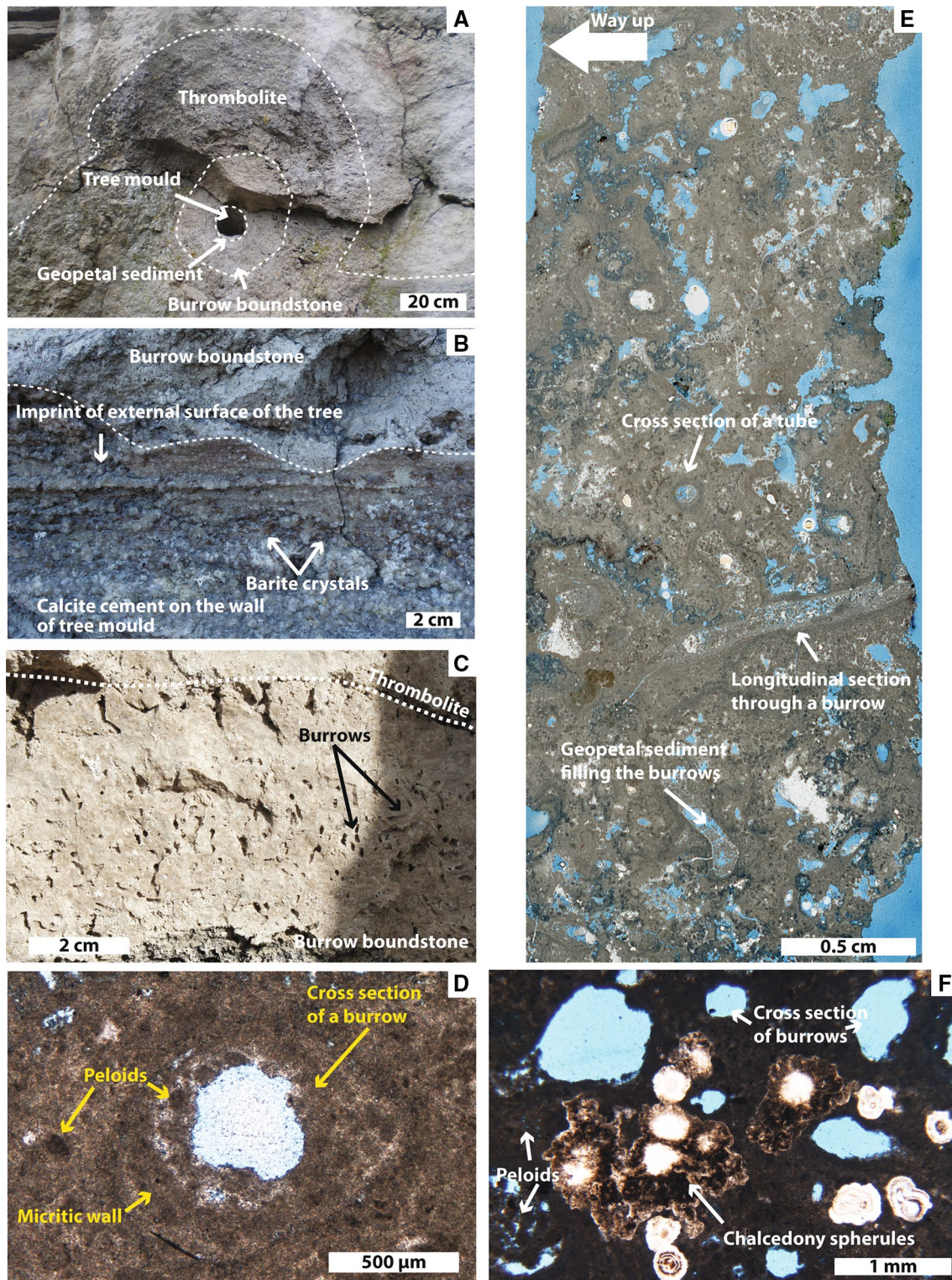
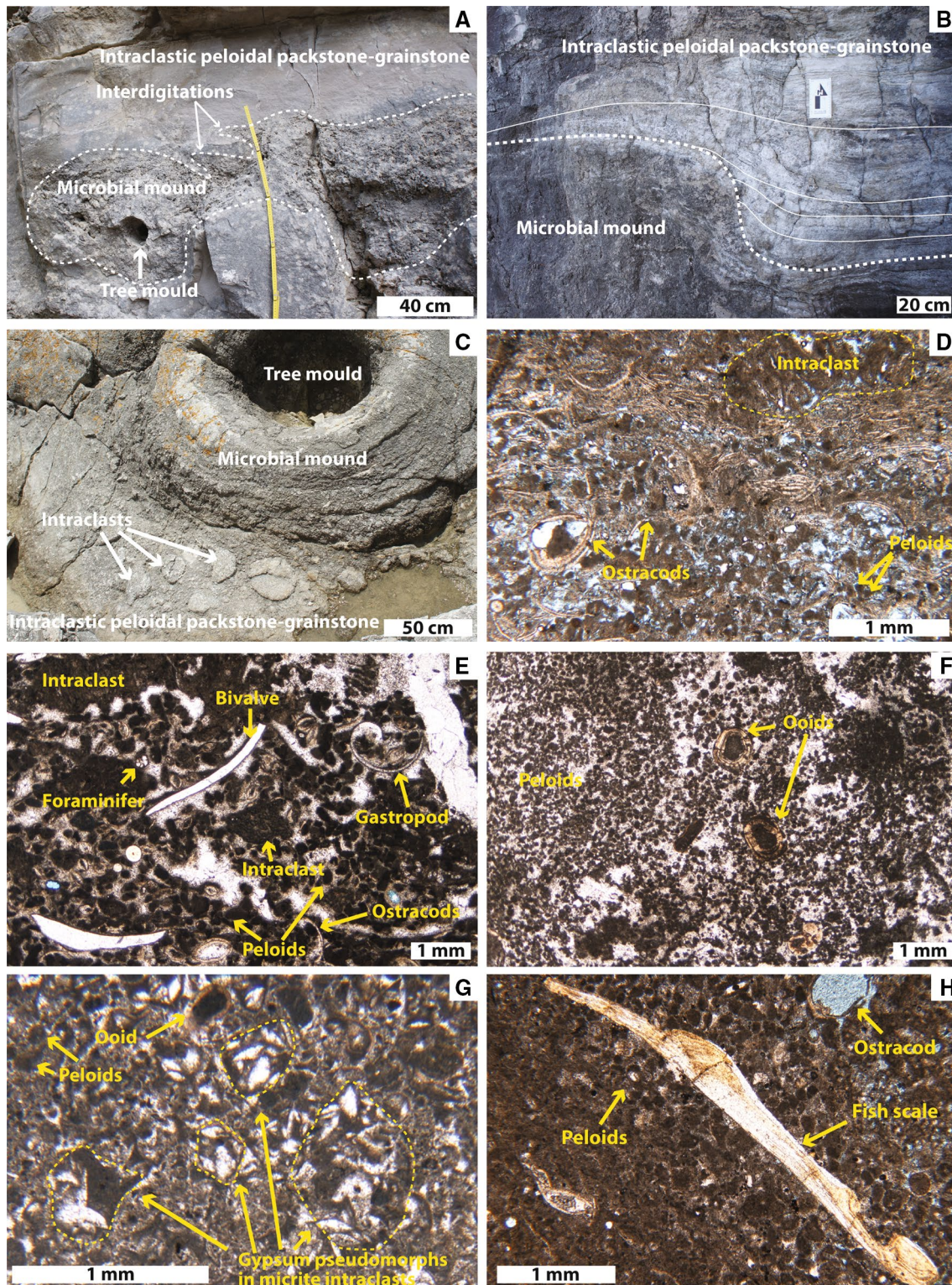


Fig. 6 Burrow boundstone facies. **a** Occurrence of the Burrow boundstone facies between tree (trunk or branch) moulds and Thrombolite sub-facies. **b** Burrow boundstone around tree (trunk or branch) mould with bark imprint, calcite cement and barite crystals (Hard Cap, God Nore, Isle of Portland, 50°31'31.41"N; 2°26'22.51"W). **c** Sinuous cavities interpreted as burrows as seen on quarry surface around tree mould (trunk or branch) mould (Soft Cap, Fossil Forest, 50°36'58.37"N; 2°14'23.09"W). **d** Burrow boundstone with cross

sections of thick-walled, tubular structures interpreted as burrows in PPL (BQ6, Broadcroft Quarry, Isle of Portland, 50°32'53.74"N; 2°25'35.07"W). **e** Thin-section scan illustrating the complex burrow network, burrow walls and geopetal sediment filling the tubes (BQ6, Broadcroft Quarry, Isle of Portland, 50°32'53.74"N; 2°25'35.07"W). **f** Chalcedony spherules developing around peloids in micrite matrix in PPL (E251107, God Nore, Isle of Portland, 50°31'31.41"N; 2°26'22.51"W)



the Thrombolite sub-facies by photosynthetic cyanobacteria as they only developed on the upper surfaces of the fallen trees (Fig. 18g). This explains the non-isopachous morphology of the Thrombolite sub-facies around the trees (Fig. 18a, b, g). In the meantime, a second generation of

geopetal sediments was deposited in the cavities of the Thrombolite sub-facies and in the tubes of the Burrow boundstone facies (Fig. 18g) (cf. Bosence 1987). Later during burial, calcite spar cements were precipitated followed by barite crystals (Table 1; Figs. 4c and 18g).

Fig. 7 Intraclastic peloidal packstone–grainstone facies. **a** Interdigitation of a microbial mound and the Intraclastic peloidal packstone–grainstone facies. The dashed line outlines the boundary of the microbial mound (Tout Quarry, Isle of Portland, 50°33′11.57″N; 2°26′36.83″W). **b** Onlap of plane-bedded Intraclastic peloidal packstone–grainstone (solid lines) onto margin of microbial mound (dashed line) (Fossil Forest, 50°36′58.37″N; 2°14′23.09″W). **c** Centimetre-sized microbial intraclasts adjacent to a microbial mound (Fossil Forest, 50°36′58.37″N; 2°14′23.09″W). **d** Intraclastic peloidal packstone–grainstone with ostracods, peloids, and intraclasts. Note the ostracod-rich horizon above (PPL, PQ3, Portesham Quarry, 50°40′18.03″N; 2°33′8.62″W). **e** Intraclastic peloidal grainstone with mollusc fragments (gastropods and bivalves), intraclasts, peloids, ostracods and rare foraminifer in PPL (WT3, Worbarrow Tout, 50°36′55.95″N; 2°11′11.70″W). **f** Fine-grained intraclastic peloidal grainstone with ooids and peloids in PPL (WLC5, West Lulworth Cove, 50°37′1.27″N; 2°14′55.18″W). **g** Gypsum pseudomorphs (lozenge-shaped) in micrite intraclasts (yellow dashed lines), peloids and ooids in PPL (MB5A, Mupe Bay, 50°36′58.37″N; 2°13′42.20″W). **h** Peloidal packstone with a fish scale, ostracods and peloids (PQ7, Portesham Quarry, 50°40′18.03″N; 2°33′8.62″W)

Facies associations and palaeoenvironments

Five facies associations (FA) are defined on the basis of frequency of facies transitions, the interpreted palaeoenvironments of the facies and their occurrence in the field: Sub-littoral lacustrine, Emergent, Mounded marginal lacustrine, Hypersaline lacustrine and Bedded marginal lacustrine facies associations (Table 2).

Sub-littoral lacustrine facies association

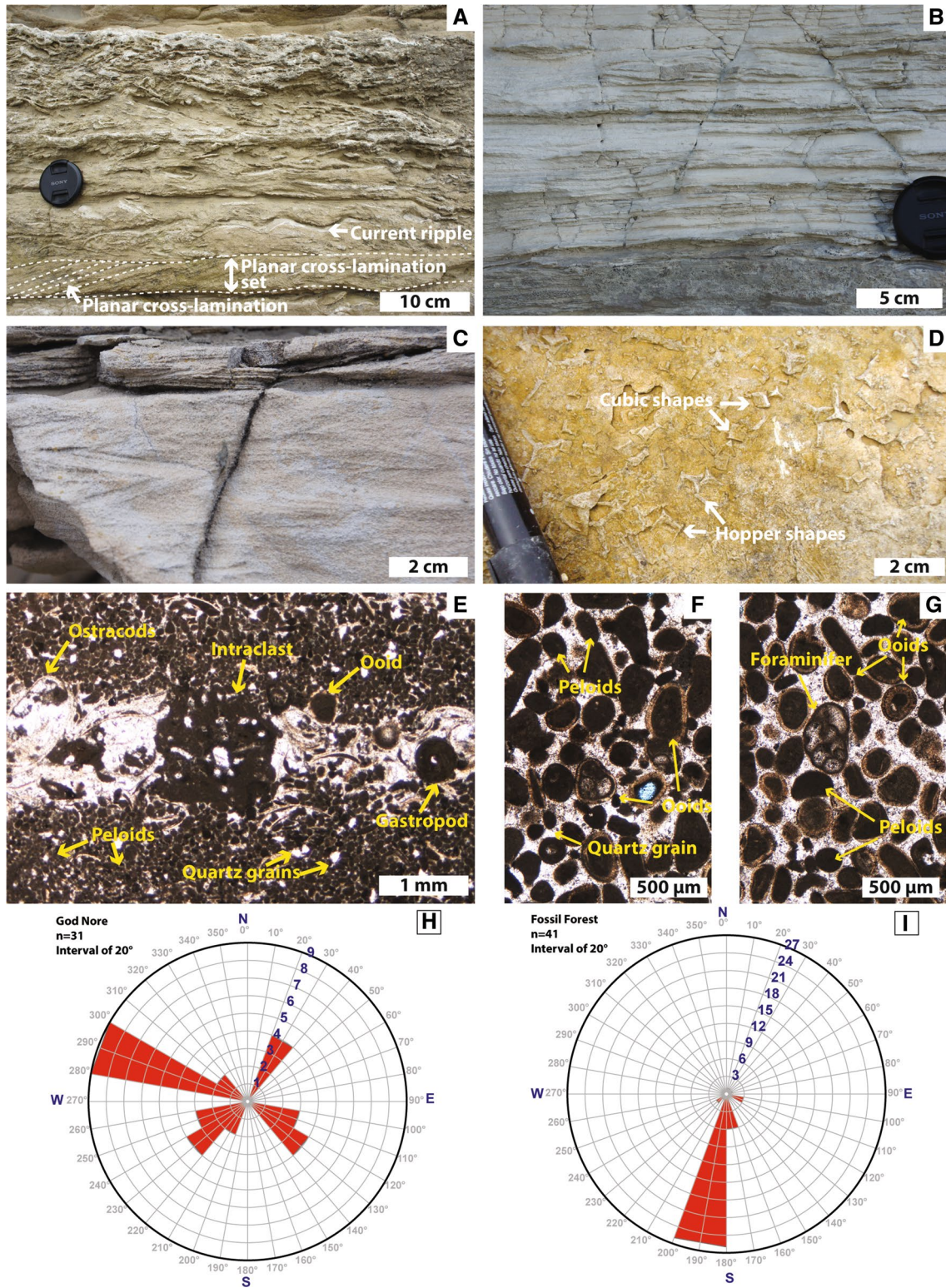
The Sub-littoral lacustrine FA comprises just one rather distinct facies, the Wackestone to fine grainstone facies. This facies is exclusively found at the base of the Mupe Member in the Transition Bed (Table 2; West 2013). It comprises fine-grained peloids and ostracods and lacks sedimentary structures apart from locally developed planar lamination. In view of the fine-grained texture and the quasi-absence of sedimentary structures, this facies association is interpreted to have been deposited below wave-base, between metres and tens of metres of water depth with rare storm reworking to form lamination. On basis of the preserved biotas (brackish-water *Valvata*, *Hydrobia*, and *Loriolina* gastropods; freshwater *Cyrena media* bivalves, and ostracods), the depositional environment is interpreted as brackish-water lacustrine. The erosion of the underlying shallow-marine Portland limestones results in the presence of ooid grainstone intraclasts and marine bioclast fragments (*Solenopora*, bryozoans, echinoids, and bivalves) reworked into this facies.

Emergent facies association

This facies association is found in the three palaeosoils: Basal Dirt Bed, Lower Dirt Bed and Great Dirt Bed, and comprises the Carbonaceous marl and the Conglomerate facies (Table 2). The palaeosoils and their contents were documented in detail by Francis (1983, 1984, 1986) who demonstrated that they have a rendzina profile (mature with profiles A/C for the Great Dirt Bed and immature for the Basal and Lower Dirt Beds). The palaeosoils contain rooted and fallen ancient conifers (*Protocupressinoxylon purbeckensis*, Francis 1983) together with cycadophytes (Fitton 1827; Buckland and De La Bèche 1835). The type of soil and the occurrence of conifer and cycad remains were used as evidence by Francis (1986) to interpret the climate semi-arid Mediterranean-type. This is supported with the occurrence of fossil charcoal, or fusain (Francis 1986) and black pebbles as indicators of past forest fires (e.g. Strasser and Davaud 1983). The palaeosoils commonly accumulated over an irregular surface, interpreted as microkarstic; they have their thickest expression in palaeotopographic lows and are thin or absent over highs.

Mound marginal lacustrine facies association

The Mounded marginal lacustrine FA comprises the mound-forming Microbialite and Burrow boundstone facies and the intermound Intraclastic peloidal packstone–grainstone facies. This facies association is found in all the locations studied, in the Skull Cap, Hard Cap, and Soft Cap (Table 2). The coarse-grained texture of these boundstones and grainstones indicates a moderate- to high-energy depositional environment and a marginal-lacustrine setting is interpreted. This is supported by its close association with karstic surfaces and palaeosoils (Fig. 16) and the presence of tabular and mounded, low-relief microbial mounds, which are interpreted to have grown to lake level in shallow water. The presence of brackish-water ostracods (Strahan 1898; Barker et al. 1975; Anderson 1985; Horne 2002) and gastropods (Strahan 1898; Arkell 1941; Clements 1973; Radley 2002), together with the absence of freshwater charophytes and in situ evaporite minerals suggests that this facies association represents a brackish-water lacustrine (i.e. non-marine) environment. This is supported by stable isotope (carbon and oxygen) data acquired during this project (Fig. 19; Dharmarajah 2015) from bulk samples from the Intraclastic peloidal packstone–grainstone of the Skull and Hard Cap from the Isle of Portland. The $\delta^{13}\text{C}$ data vary between -2.71 and -7.20‰ (with a precision of 0.12‰) and the $\delta^{18}\text{O}$ data between -4.63 and -0.72‰ (with a precision of 0.03‰ ; Fig. 19). Oxygen isotopic signatures of lacustrine carbonate precipitating in the water column, and accumulating



as mud, reflect lake water composition and temperature of precipitation; carbon values are controlled by the source of the CO₂/carbonate (Talbot and Kelts 1990; Leng and Marshall 2004; Tanner 2010). Considering that the Purbeck data

were obtained from bulk samples, their values will reflect a mixture of sedimentological and diagenetic signatures.

Arenas-Abad et al. (2010, Table 2), Della Porta (2015, Tables 1 and 2) and Talbot (1990, Fig. 1) presented isotopic values from abiotic lacustrine and fluvial carbonates and

Fig. 8 Cross-bedded peloidal packstone–grainstone facies. **a** Planar cross-lamination and wave or current ripples (vertical-section, Pondfield Cove, 50°36'57.12"N; 2°11'4.11"W). **b** Planar lamination (vertical-section, South West Bowers, 50°32'40.06"N; 2°27'10.56"W). **c** Herring-bone cross-stratification (vertical-section, Fossil Forest, 50°36'58.37"N; 2°14'23.09"W). **d** Halite pseudomorphs on under surface of bed (Broadcoft Quarry, 50°32'53.74"N; 2°25'35.07"W). **e** Peloidal grainstone with peloids, ostracods, microbial intraclasts, quartz grains and gastropods (WLC8, West Lulworth Cove, 50°37'1.27"N; 2°14'55.18"W). **f** Close-up view of grainstone with peloids, quartz grains and superficial ooids with heavily micritised (possibly microbial) intraclasts and grapestone nuclei (WT12, Worbarrow Tout, 50°36'55.95"N; 2°11'11.70"W). **g** Peloidal grainstone with peloids, ooids and foraminifer (WT12, Worbarrow Tout, 50°36'55.95"N; 2°11'11.70"W). **h** Orientation and direction measurements of the cross-lamination at God Nore with 31 measurements showing a main current direction towards N290 and three secondary directions N030; N130 and N230 (50°31'31.41"N; 2°26'22.51"W). **i** Orientation and direction measurements of the cross-lamination at Fossil Forest with 41 measurements showing a unique direction towards N190 (50°36'58.37"N; 2°14'23.09"W)

Lovelace (2006) values for an Upper Jurassic freshwater lake of the Morrison Formation (Wyoming, USA); these are compared to the Purbeck analyses in Fig. 19. The $\delta^{13}\text{C}$ data of the Skull and Hard Caps are within the range of fluvial and freshwater lacustrine environments (Fig. 19). The negative values suggest depletion in ^{12}C due to photosynthesis and/or constant renewing of surface waters, which indicates an increasing vegetation cover and/or a short-residence time of the waters (Talbot 1990; Talbot and Kelts 1990; Leng and Marshall 2004). The $\delta^{18}\text{O}$ data are within the range of saline and hypersaline lakes (Fig. 19). This suggests depletion in ^{16}O due to evaporation of lighter isotopes, which indicates fresh (but not truly freshwater) to brackish waters in a through-flowing system (Talbot 1990; Talbot and Kelts 1990; Leng and Marshall 2004). In addition, sparry drusy calcite cements are identified in most thin-sections and these are thought to have formed shortly after deposition during early diagenesis. These cements would have been sampled during isotope measurements, and account for the depletion of ^{16}O . However, the fluids that precipitated these drusy cements would have been influenced by overlying lithologies and lake and soil waters.

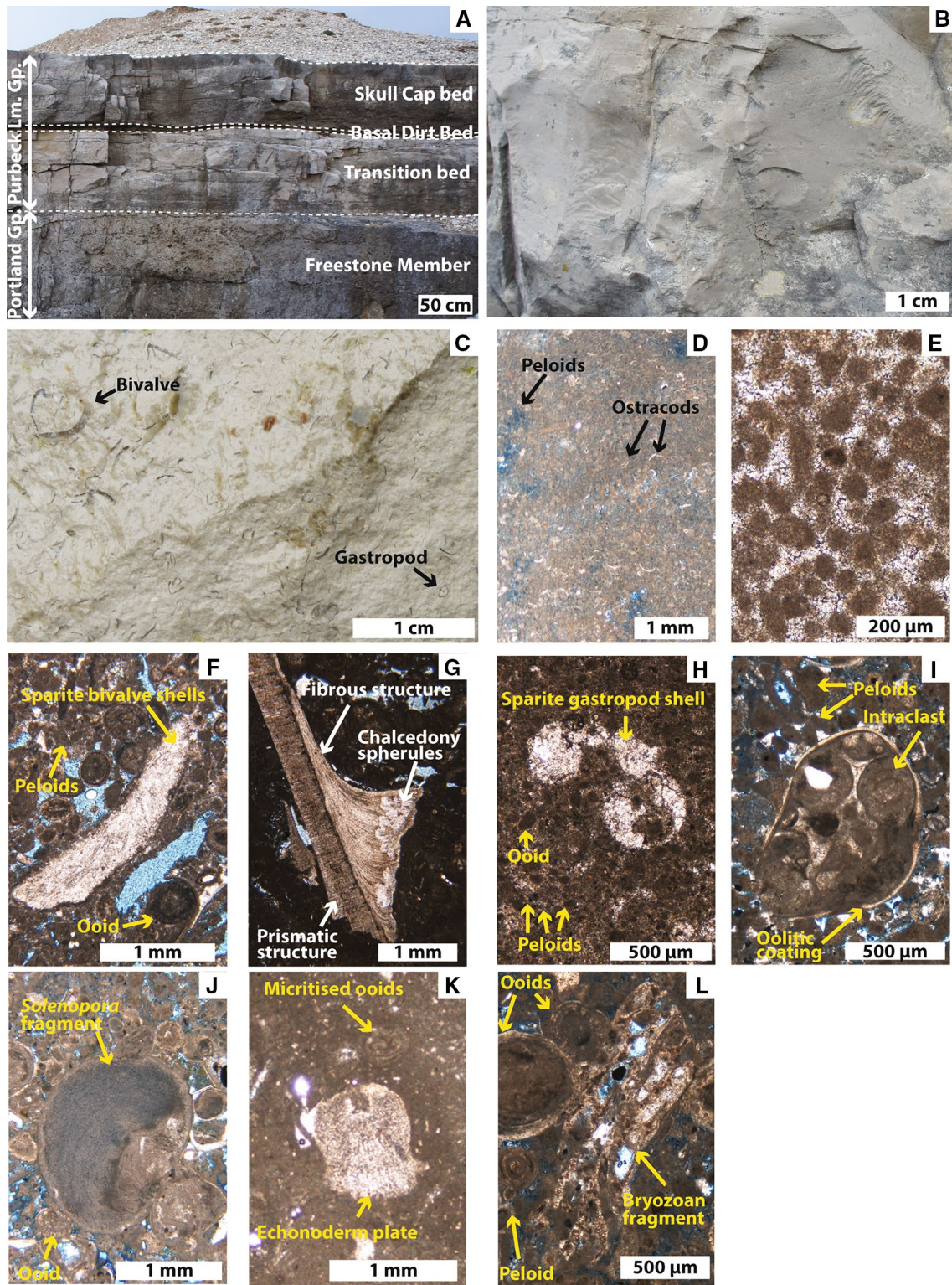
The data from the Hard Cap show more negative values for both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ than in the Skull Cap and these suggest a slight freshening stratigraphically up-section into the Hard Cap and overlying Great Dirt Bed. Talbot (1990) stated that the co-variance between carbon and oxygen data is more common in closed lakes than in open lakes. He proposed that closed lakes typically show greater regression coefficients (r), above 0.8, than open lakes. In this study, the regression coefficients are about 0.11 for the Skull Cap and 0.24 for the Hard Cap (Fig. 19), suggesting an open-lake system. Taken together with the fossil evidence (see above) and the petrographic evidence for the absence of both evaporites

(indicating hypersalinity) and charophytes (indicating fresh waters) in this FA, these data all indicate brackish-water conditions in an open lacustrine system. Taken together, this evidence argues against West's (1975) and Francis' (1982, 1983, 1984, 1986) hypersaline lagoon, Perry's (1994) freshwater origin and Radley's (2002) closed lake system, and supports Bosence's (1987) previous interpretation of a brackish-water lacustrine system. Moreover, the recognition of microbialite deposits around trees provides detail in support of Bosence's (1987) and Perry's (1994) interpretation of tufa deposits as complex thrombolite mounds as opposed to their earlier interpretations as stromatolites (West 1975; Francis 1982).

The textures and structures of the Microbialite sub-facies on their own are not thought to be diagnostic of specific environments. The combination of all these features indicates that this facies association was deposited along the margins of a shallow brackish-water lake that flooded over shorelines and soils vegetated by conifers.

Hypersaline lacustrine facies association

The Hypersaline lacustrine FA comprises the Evaporite and the Gypsiferous peloidal packstone facies (Table 2) and is found at Dungy Head, West Lulworth Cove, Fossil Forest, Mupe Bay, Worbarrow Tout, Fishermen's Ledge and Durlston Head (Table 2, Fig. 1). This facies association forms the evaporite collapse breccia of the Broken Beds and adjacent units at the base of the Cypris Freestone (Fig. 3; Table 2). The presence of evaporite crystal pseudomorphs (anhydrite, gypsum and halite) filled with sediment, and reworked gypsum crystals in the Gypsiferous peloidal packstones indicate hypersaline conditions during deposition, as previously interpreted by West (1975). Anderson (1985) and Horne (1995, 2002) also interpreted hypersaline conditions on the basis of ostracod assemblages in the Broken Beds. In addition, Radley (2002) inferred palaeosalinities on the basis of mollusc assemblages after compilation of data from Arkell (1941), West (1961), Clements (1973), Barker et al. (1975) and his own work. Although sampled molluscs are not precisely located with respect to the more detailed work presented in this paper, the low mollusc diversity helped Radley (2002) propose that the Broken Beds were deposited in a closed lake system with periodic hypersaline conditions. In view of the underlying (mounded marginal lacustrine) and overlying (bedded marginal lacustrine) facies associations reflecting lacustrine environments, this facies association is interpreted to have been deposited in a hypersaline lacustrine system.



Bedded marginal lacustrine facies association

The Bedded marginal lacustrine FA is composed of the Cross-bedded peloidal packstone–grainstone and Calcareous sandstone facies (Table 2). This facies association is

unique to the Cypris Freestone and is found at all the locations studied. Its true thickness could only be measured at five locations where the contact with the overlying Hard Cockle Beds is exposed (Tables 1, 2). The coarse-grained facies with sedimentary structures, such as cross-lamination,

Fig. 9 Wackestone to fine grainstone facies. **a** Transition between Portland Group and Purbeck Limestone Group (Portland Bill, Isle of Portland, 50°30'53.20"N; 2°27'53.20"W). **b** Close-up view of locally, laminated Wackestone to fine grainstone (God Nore, Isle of Portland, 50°31'31.41"N; 2°26'22.51"W). **c** Close-up view of Wackestone to fine grainstone facies with ostracods and molluscs (Pondfield Cove, 50°36'57.12"N; 2°11'4.11"W). **d** Wackestone with peloids and ostracods (GN2, God Nore, Isle of Portland, 50°31'31.41"N; 2°26'22.51"W). **e** Fine peloidal packstone (PB2, Portland Bill, Isle of Portland, 50°30'53.20"N; 2°27'31.43"W). **f–l** Reworked allochems from the underlying Portland Group. **f** Sparite and fibrous bivalve shell and micritised ooids in a fine peloidal grainstone (BQ1, Broadcroft Quarry, Isle of Portland, 50°32'53.74"N; 2°25'35.07"W). **g** Bivalve shell showing both fibrous and prismatic structures and micritised ooids in a peloidal packstone (PB1, Portland Bill, Isle of Portland, 50°30'53.20"N; 2°27'31.43"W). **h** Gastropod shell replaced and filled by spar cement, peloids and superficial ooids in a fine peloidal grainstone (PB3, Portland Bill, Isle of Portland, 50°30'53.20"N; 2°27'31.43"W). **i** Intraclast of oolitic grainstone with a cortical coating and peloids in a fine peloidal grainstone (GN3, God Nore, Isle of Portland, 50°31'31.41"N; 2°26'22.51"W). **j** *Solenopora* fragment and ooids in a fine peloidal grainstone (GN3, God Nore, Isle of Portland, 50°31'31.41"N; 2°26'22.51"W). **k** Echinoderm plate (with straight extinction in XPL), micritised ooids and ostracod shell fragments (PB1, Portland Bill, Isle of Portland, 50°30'53.20"N; 2°27'31.43"W). **l** Bryozoan fragment, foraminifers, peloids and mixed and micritised ooids in a fine peloidal grainstone (GN3, God Nore, Isle of Portland, 50°31'31.41"N; 2°26'22.51"W)

cross-stratification and herring-bone cross-stratification indicates a high-energy shallow marginal environment.

Herring-bone cross-stratification is known to occur in lakes with a water body large enough to be influenced by gravitational forces (the moon and the sun) as in Lake Superior (about 82,103 km²) or Lake Michigan (about 58,000 km²) in the North American Great Lakes (Mortimer and Fee 1976; Kennish 1986; Mann and Lazier 1991; Mortimer 2004; Trebitz 2006). Alternatively, they can be generated by opposing wind-driven currents as documented by Rusnak (1960) for a hypersaline lake Laguna Merida (about 1230 km²) in Texas (USA) and by Ainsworth et al. (2012) in Lake Eyre (9500 km²) in Australia. They can also be the results of seiche events where two waves of opposite direction are combined to create a unique and larger wave (Sager et al. 1985; Mortimer 2004). With the Wessex Basin being about 45,000 km² (Fig. 1), tides or seiche events would be expected to create such herring-bone stratification. However, the Portland-Wight sub-basin is much smaller (Fig. 1), about 12,000 km², which is a similar area to Lake Eyre (see above) where wind-driven currents may have controlled the formation of herring-bone cross-stratification.

The smooth-shelled ostracods *Fabanella bolonien-sis*, *Mantelliana purbeckensis*, and *Mantelliana cyrtion* were identified at the base of the Cypris Freestone at God Nore, Isle of Portland, and reflect a saline lacustrine environment (Ray Bate, pers. comm., June 2017). Previous records of non-marine biotas such as hypersaline

tolerant S-phase ostracods (Anderson 1985; Horne 2002) and brackish to hypersaline tolerant gastropods indicate a closed lake system (Clements 1973). This is confirmed by the occurrence of sediment-filled, halite pseudomorphs indicating hypersaline conditions (cf. West 1975). Altogether, these features suggest a marginal, shallow hypersaline lacustrine environment.

Facies models for the Mupe Member

The incorporation of these five facies associations into the ideal sequences for facies transition (Fig. 20) is used, together with modern-day analogues, as a basis for the establishment of two facies models for the Mupe Member. The Sub-littoral lacustrine FA, found at the base of the succession, is overlain by the Emergent FA and the ideal sequences (Fig. 20) show that the latter is closely related to the Mounded marginal lacustrine FA as it is mainly found in between palaeosoils. The Emergent FA is most likely to be overlain by the Bedded marginal lacustrine FA as indicated in Fig. 20. These facies associations are interpreted to have formed in a through-flowing brackish-water lake. The Hypersaline lacustrine FA is interbedded with the Bedded marginal lacustrine FA (Fig. 20). This facies relationship enables the identification of two main depositional environments: a brackish-water phase in the lower part of the Mupe Member and a hypersaline water phase in the upper part. The transition between environments is marked by a sharp surface and a random change in facies (as discussed earlier) where the Great Dirt Bed (Conglomerate facies) and the Soft Cap (Microbialite and Intraclastic peloidal packstone–grainstone facies) can be in contact with either the Cypris Freestone (Cross-bedded peloidal packstone–grainstone facies) or with the Broken Beds (Evaporite facies). This was observed at 15 locations; 13 where microbial mounds and inter-mound facies of the Soft Cap are overlain by the Evaporite facies (seven locations) and the Cross-bedded peloidal packstone–grainstone (six locations), against only two locations where the Conglomerate facies of the Great Dirt Bed is overlain by the Cross-bedded peloidal packstone–grainstone facies of the Cypris Freestone. This shows the importance of integrating petrographic and outcrop studies together with facies transition analysis to strengthen the validity of facies relationship diagrams.

Brackish-water phase

The lower part of the Mupe Member is interpreted to have formed in a brackish-water, open-lake system of Talbot and Allen (1996) or a balanced-fill lake of Bohacs et al. (2000), based on the facies, biotas and stable isotope analyses. Figure 21 illustrates the proposed depositional setting of a shallow margin of this lake system based on the integration of

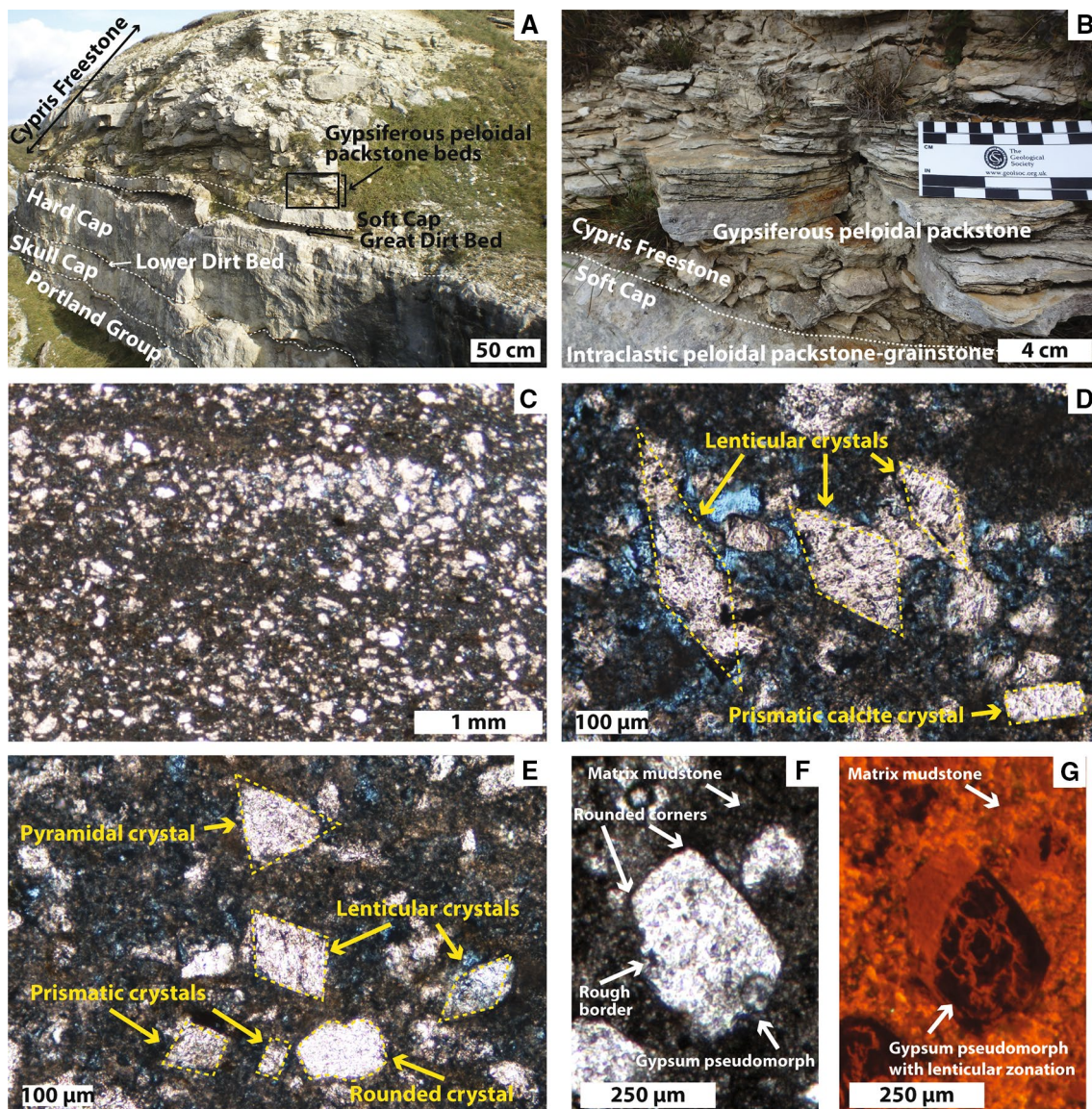


Fig. 10 Gypsiferous peloidal packstone facies. **a** Location of the laminated beds just above the Soft Cap bed and at the base of the Cypris Freestone unit. The black box locates **b** and **c** (South West Bowers Quarry, Isle of Portland, 50°32'40.06"N; 2°27'10.56"W). **b** Laminated packstone beds overlying Soft Cap grainstone (South West Bowers Quarry, Isle of Portland, 50°32'40.06"N; 2°27'10.56"W). **c** Prismatic calcite crystals after gypsum within a micrite matrix (CQ10, Coombefield Quarry, Isle of Portland, 50°31'58.25"N; 2°26'33.65"W). **d** Details of lenticular and prismatic gypsum pseu-

domorphs (highlighted with yellow dashed lines) within a mudstone matrix (TQ11, Tout Quarry, Isle of Portland, 50°33'11.57"N; 2°26'36.83"W). **e** Prismatic, lenticular and rounded gypsum pseudomorphs (highlighted with yellow dashed lines) in PPL (SWB7, South West Bowers, Isle of Portland, 50°32'40.06"N; 2°27'10.56"W). **f**, **g** PPL and CL views of lenticular calcite crystal showing a lenticular dark zone in the centre of the pseudomorph under CL (CQ10, Coombefield Quarry, Isle of Portland, 50°31'58.25"N; 2°26'33.65"W)

work presented in this paper together with facies from a modern analogue, the freshwater lake of Laguna Bacalar, Yucatan Peninsula, Mexico (Gischler et al. 2008, 2011; and observations by the authors in 2014–2015).

Laguna Bacalar lake is about 50 km long, 1–2 km wide, and up to 20 m deep, set in a humid tropical climate (Pérez et al. 2011) in the equatorial zone (Gischler et al. 2008, 2011), with thrombolite mounds along its shores (Fig. 22).

The freshwater is supplied by groundwater from a limestone hinterland through cenotes (Gischler et al. 2008, 2011) and flows towards the north. This differs from the situation that is interpreted for the Purbeck lake. Here, fluvial run-off from the carbonate hinterland in the northern footwall region is considered to be the likely source area and surface waters would have been channelled through the relay ramp in the centre of the study area into the

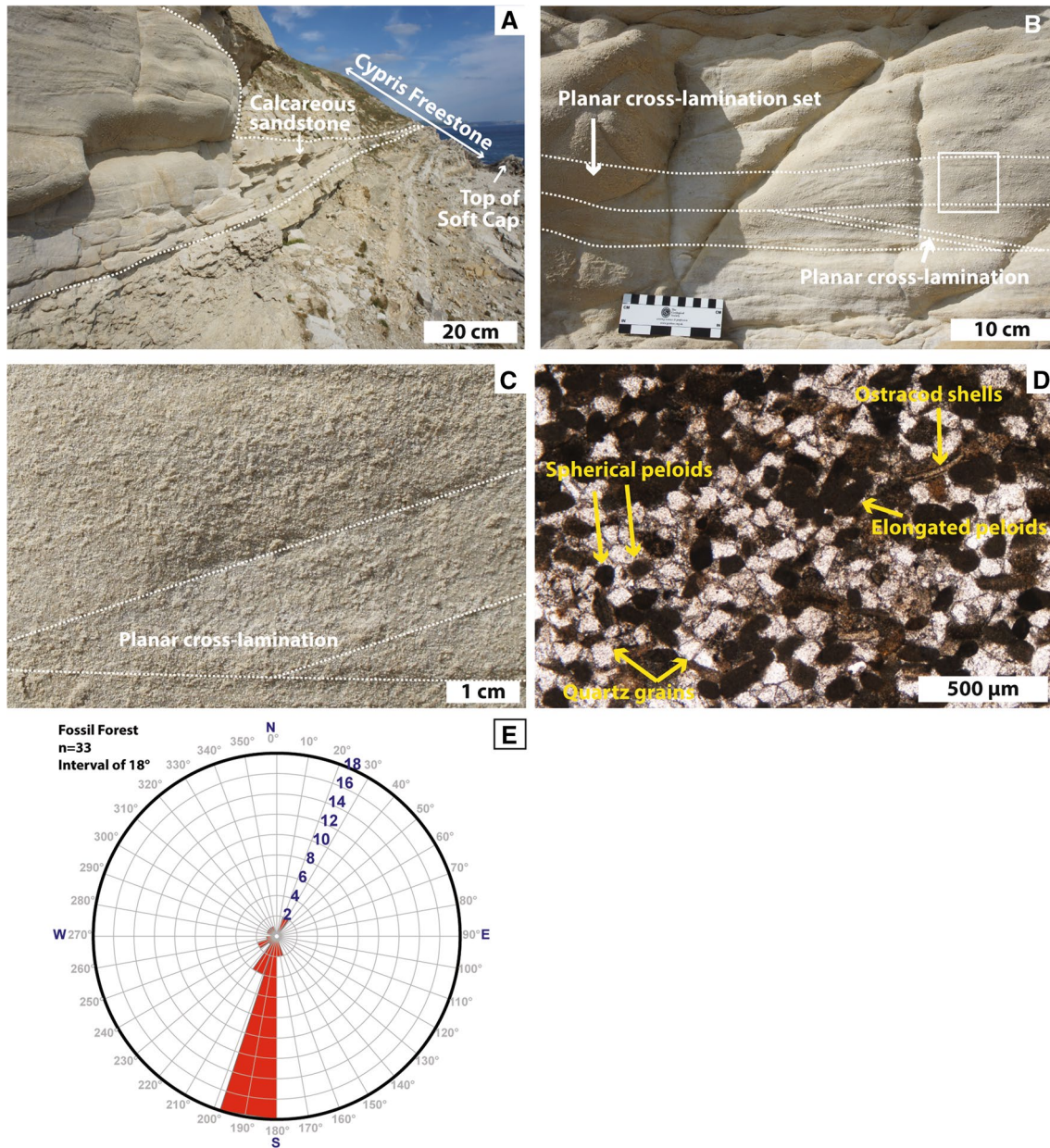


Fig. 11 Calcareous sandstone facies. **a** Location of Calcareous sandstone within Cypris Freestone unit (Fossil Forest, $50^{\circ}36'58.37''\text{N}$; $2^{\circ}14'23.09''\text{W}$). **b** Herring-bone cross-stratification. The white square locates **c** (Fossil Forest, $50^{\circ}36'58.37''\text{N}$; $2^{\circ}14'23.09''\text{W}$). **c** Calcareous sandstone facies in detail with abundant quartz grains weathering out on surface (Fossil Forest, $50^{\circ}36'58.37''\text{N}$; $2^{\circ}14'23.09''\text{W}$). **d** Quartz

grains, elongated and spherical peloids, ostracod valve with calcite cement (WLC9, West Lulworth Cove, $50^{\circ}37'1.27''\text{N}$; $2^{\circ}14'55.18''\text{W}$). **e** Orientation and direction measurements of the cross-lamination at Fossil Forest with 33 measurements showing a main direction at N190 ($50^{\circ}36'58.37''\text{N}$; $2^{\circ}14'23.09''\text{W}$)

Purbeck lake (Fig. 1). However, the carbonate facies and microbial mound sizes, morphologies and internal microstructures in Laguna Bacalar are similar to those in the lower part of the Mupe Member. In particular, the thrombolite mounds found associated with shoreline trees in the shallow lake margins are similarly associated with peloidal grainstone facies with ostracods and molluscs. The internal microstructure of the thrombolites is similar to

that of the Purbeck microbialites, as both have constructed upward-radiating filament moulds incorporating the surrounding sediments and fossils. The modern thrombolites exhibit several sizes and morphologies, microbial mats, small tabular mounds in shallow areas, flat-topped ledges and large mounds (up to 2 m high, Fig. 22) in intermediate depth areas, and microbial mats in deeper areas (> 2 m). The mounds develop along the shores and grow towards

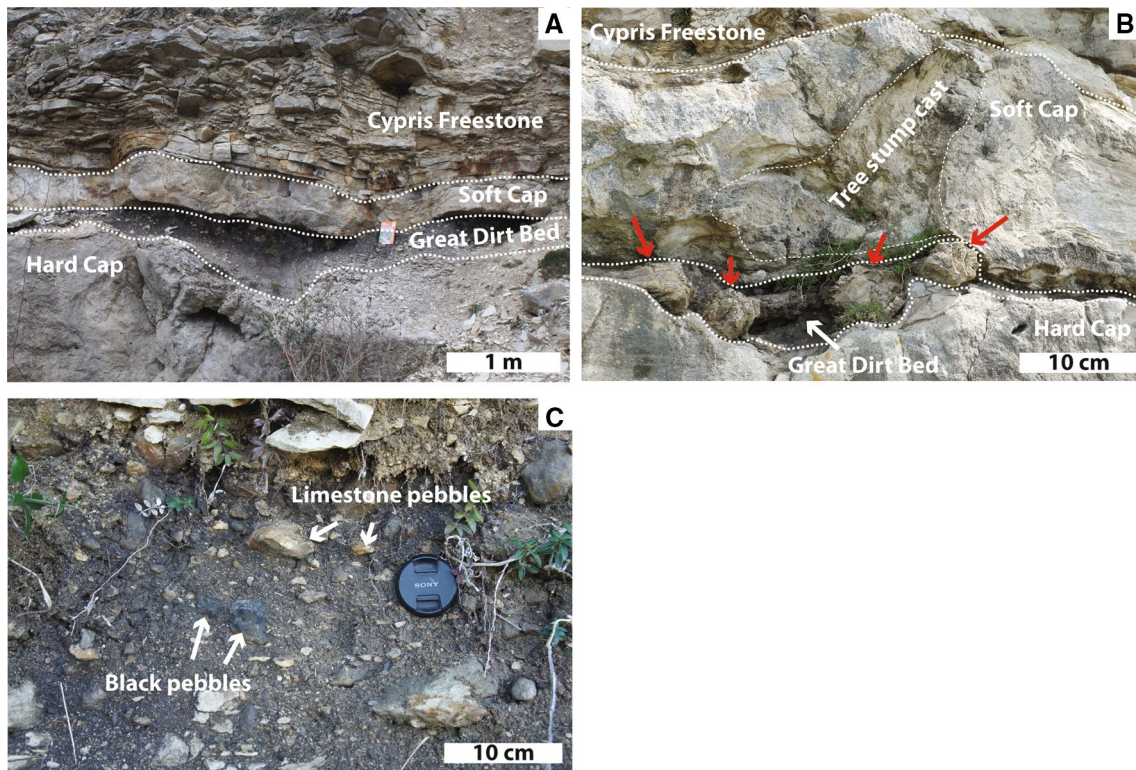


Fig. 12 Conglomerate facies. **a** Location of the Great Dirt Bed with Conglomerate facies (Penn’s Weare, Isle of Portland, 50°32’27.46”N; 2°25’35.31”W). **b** Silicified tree stump and roots (red arrows) within the Great Dirt Bed and stump cast in the Soft Cap (West Cliff, Isle of

Portland, 50°32’2.75”N; 2°27’14.87”W). **c** Conglomerate facies with black and white limestone pebbles (South West Bowers, Isle of Portland, 50°32’40.06”N; 2°27’10.56”W)

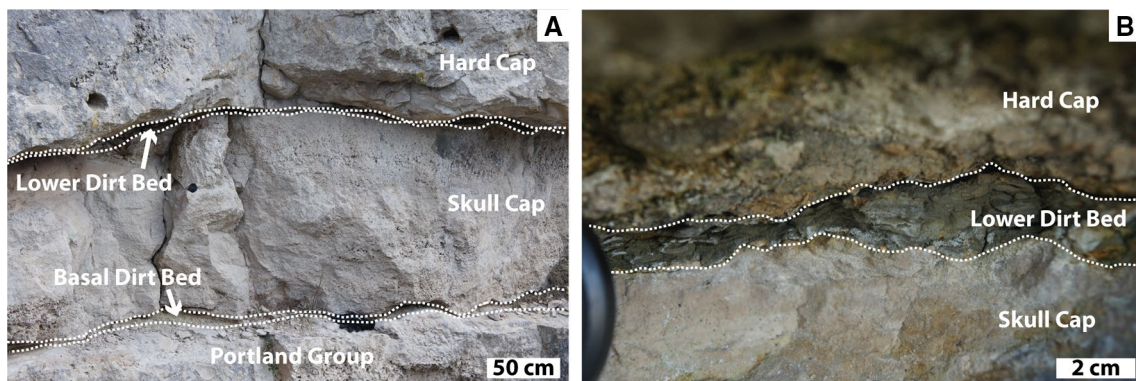


Fig. 13 Carbonaceous marl facies. **a** Location of the Lower Dirt Bed and Basal Dirt Bed comprising the Carbonaceous marl facies (Tout Quarry, Isle of Portland, 50°33’11.57”N; 2°26’36.83”W). **b** Close-up

view of the Lower Dirt Bed, black and brown lamination can be seen in a dark, organic-rich marl (South West Bowers, Isle of Portland, 50°32’40.06”N; 2°27’10.56”W)

the lake basin and are commonly found growing around roots of mangrove trees. The microbialites show very rapid growth rates of up to 1 cm/year as measured during a March 2015 field survey. This rate was measured on stakes in an abandoned harbour built around 25 years ago, where thrombolites have developed a thickness up to 25 cm. In

the deepest part of the lake (2–20 m), fine-grained peloidal carbonates are deposited (Gischler et al. 2008, 2011).

The lower part of the Mupe Member comprises three stratigraphic units (the Skull, Hard and Soft Caps) of the Sub-littoral lacustrine and Mounded marginal lacustrine FA deposited between three palaeosoils (Emergent FA). They therefore represent three depositional sequences. The

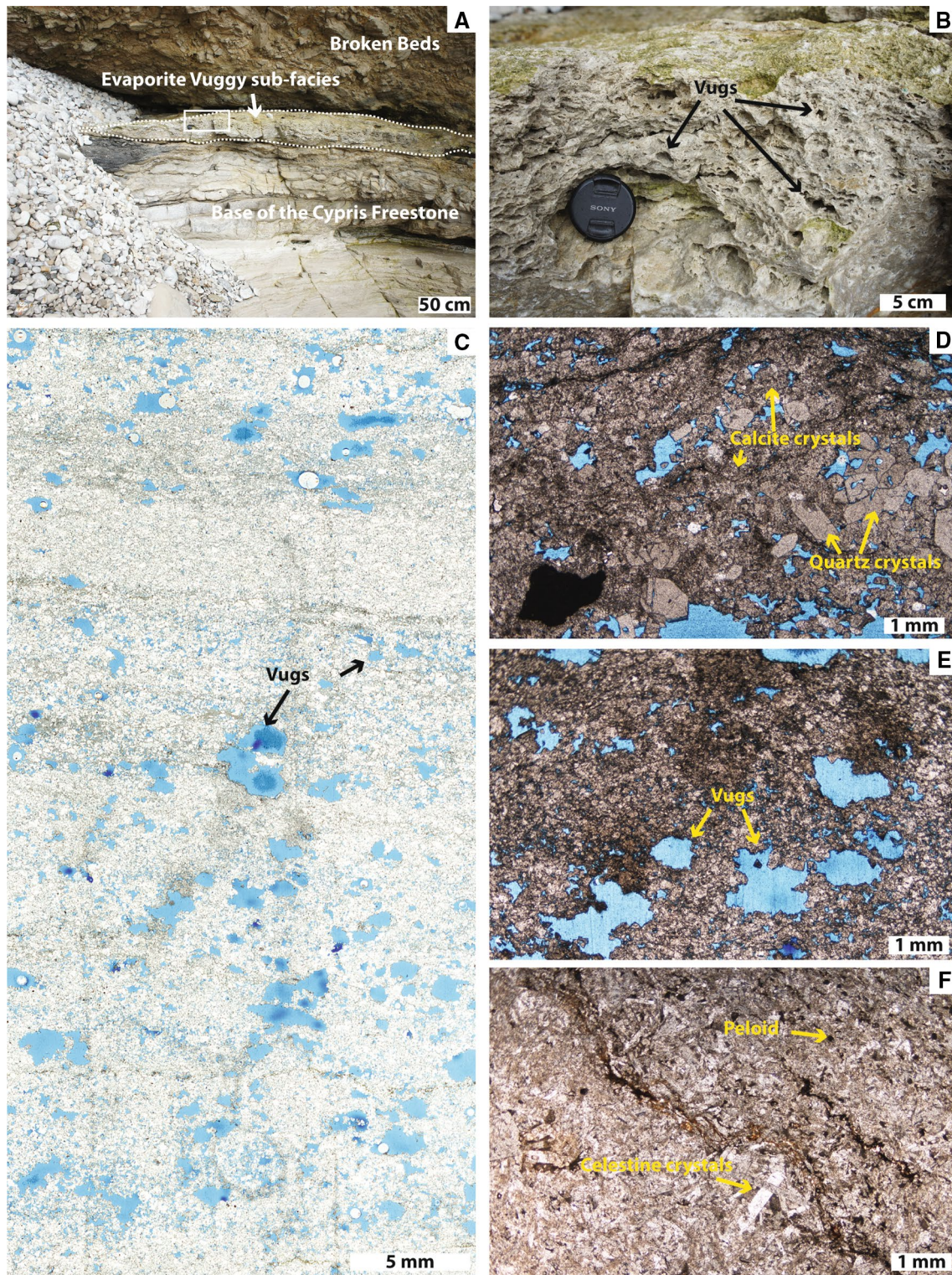


Fig. 14 Evaporite vuggy sub-facies. **a** Evaporitic beds below the Broken Beds. The white box locates **b** (Worbarrow Tout, 50°36'55.95"N; 2°11'11.70"W). **b** Close-up view of **a**, note the vugs up to 1 cm in diameter (Worbarrow Tout, 50°36'55.95"N; 2°11'11.70"W). **c** Thin-section scan with 1–2-mm-sized vugs in a calcite crystalline texture (MB11, Mupe Bay, 50°36'58.37"N; 2°13'42.20"W). **d** Quartz crystals

(between 500 μ m and 1 mm) and calcite crystals replacing original lithology (WT8, Worbarrow Tout, 50°36'55.95"N; 2°11'11.70"W). **e** Millimetre-sized vugs in a calcite mosaic, note squared edges to vugs indicating replacement of former evaporite minerals by calcite (MB11, Mupe Bay, 50°36'58.37"N; 2°13'42.20"W). **f** Celestine crystals and peloids (DH1, Durlston Head, 50°35'43.58"N; 1°57'3.73"W)

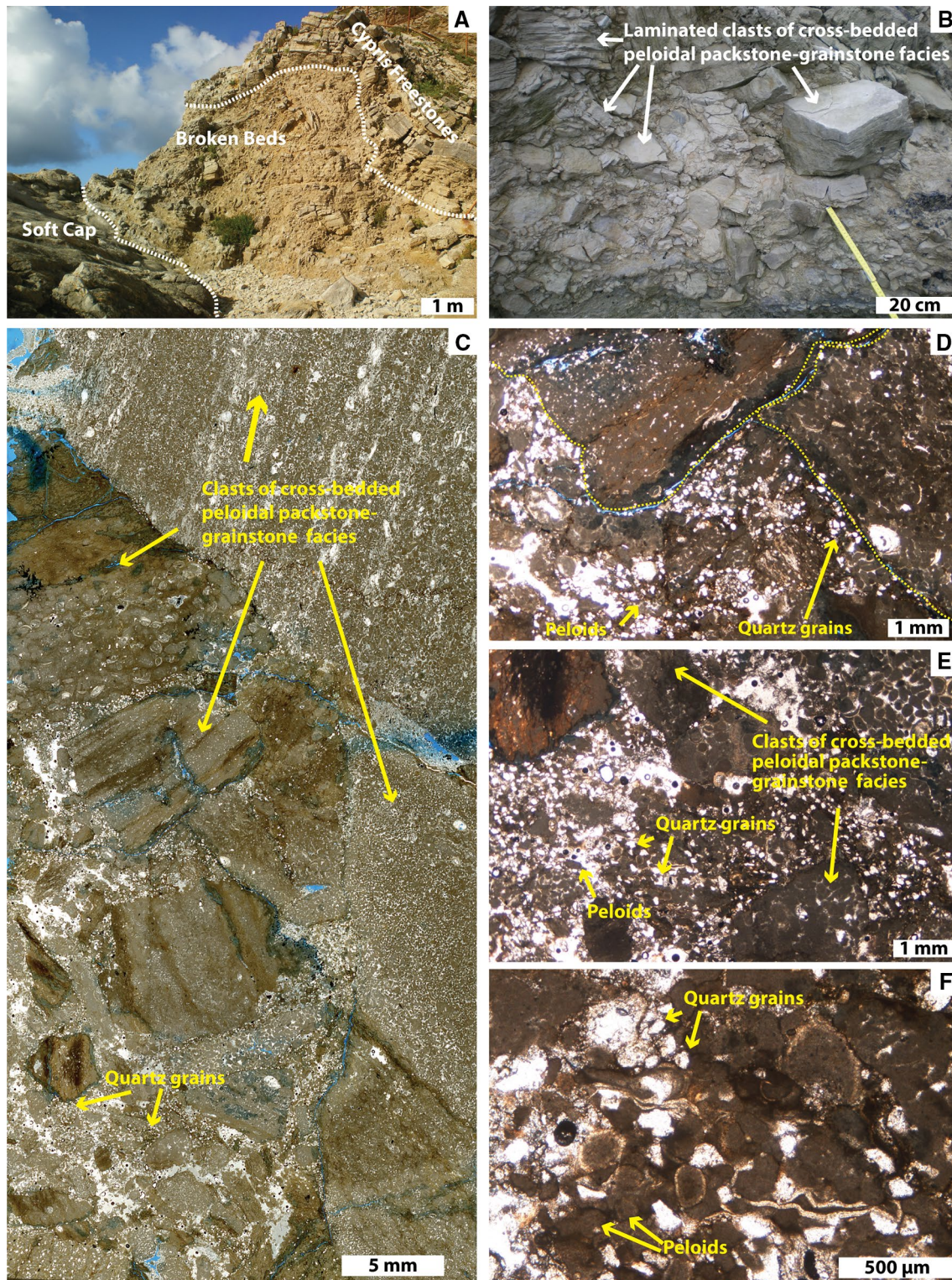


Fig. 15 Evaporite breccia sub-facies. **a** Field view of the Broken Beds unit made of the brecciated sub-facies (Fossil Forest, 50°36'58.37"N; 2°14'23.09"W). **b** Close-up view of the Broken Beds made of cobble to boulder-sized blocks (West side of Lulworth Cove, 50°37'1.27"N; 2°14'55.18"W). **c** Thin-section scan showing relatively large clasts of Cross-bedded peloidal packstone–grainstone facies (WLC7, West Lulworth Cove, 50°37'1.27"N; 2°14'55.18"W). **d** Close-up view

of **a**, the matrix is composed of quartz grains, peloids and ostracods (WLC7, West Lulworth Cove, 50°37'1.27"N; 2°14'55.18"W). **e** Close-up view of **a**, smaller angular intraclasts can be identified within a matrix made of quartz grains, peloids and ostracods. **f** Close-up view of **c** detailing the matrix of the sub-facies (WLC7, West Lulworth Cove, 50°37'1.27"N; 2°14'55.18"W)

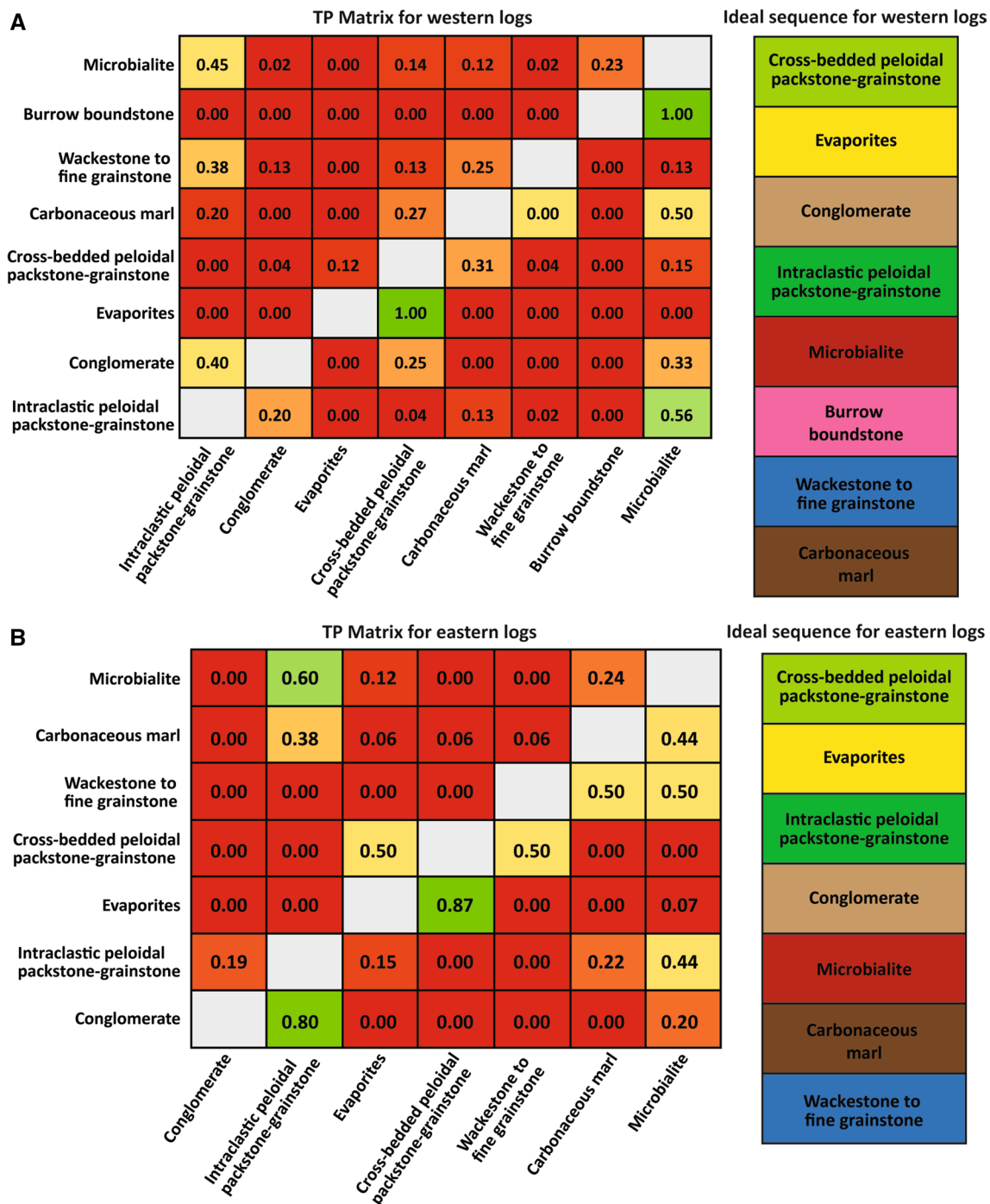


Fig. 16 Optimised transition probability matrices and optimised successions (Burgess 2016) for the Mupe Member in south Dorset from the western area (a) and eastern area (b). Transitions are not equiprobable, suggesting preferred occurrence of certain facies vertically and therefore laterally adjacent during deposition, assuming

little or no missing time. The vertical successions. Note that to simplify analysis, some facies have been grouped, so the Microbialite facies combines the Thrombolite and Stromatolite sub-facies; and the Evaporites facies combines the Evaporite vuggy sub-facies and the Gypsiferous peloidal packstone facies

palaeosoils were deposited after a drop in lake level as indicated by erosion of underlying deposits of either the Portland Group (for the Basal Dirt Bed) or the Transition Bed, the Skull Cap and the Hard Cap beds (Fig. 20). On the emergent

lake margins, the palaeosoils supported a vegetation of ancient cypress trees and cycadophytes. In the littoral zone and shallowest parts of the lake, small, tabular microbial mounds developed either around tree stumps, or associated

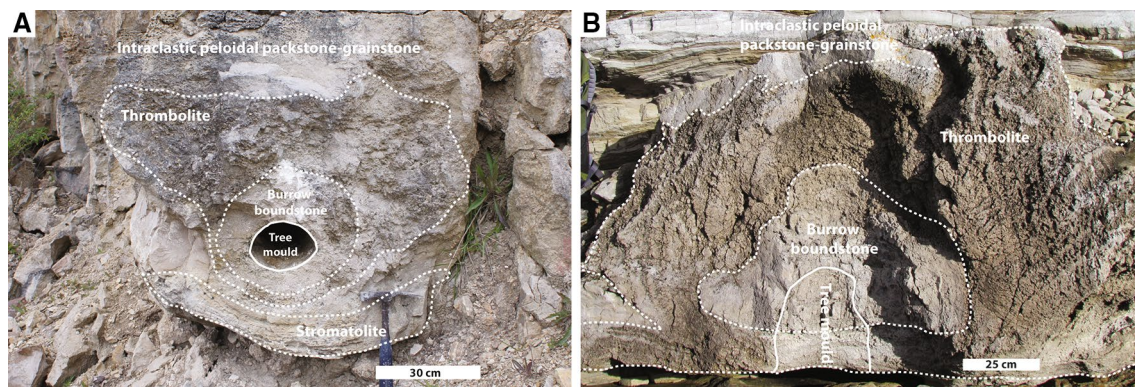


Fig. 17 Microbial mounds at outcrop. **a** Developed around a fallen tree (Hard Cap, Broadcroft Quarry, Isle of Portland). **b** Developed around an in situ tree stump (Soft Cap, Fossil Forest, picture courtesy of Estanislao Kozlowski)

with trees, and surrounded by inter-mound coarse-grained facies (Intraclastic peloidal packstone–grainstone), comparable to those seen in Laguna Bacalar. Where the accommodation space was greater in slightly deeper waters the mounds are higher, more irregularly shaped, thicker and developed around inundated tree trunks and branches (as with the large mounds found in intermediate depths in Laguna Bacalar). These are surrounded by an inter-mound, coarse-grained facies with mound-derived intraclasts, as is also the case in Laguna Bacalar. Deeper into the Purbeck lake, in the sub-littoral zone, microbial activity formed mats alternating with horizons of coarse-grained facies (Intraclastic peloidal packstone–grainstone facies) as represented by the microbial mats found in the deepest part of the margins in Laguna Bacalar. The reason these deeper-water mats did not develop into tabular or complex mounds could be due to one factor or a combination of several factors. A lack of light would reduce or stop the photosynthesis that would decrease microbial growth rate; a lack of sediment or of dissolved carbonate due to a change in water chemistry would reduce the trapping and binding process and the microbialites would not be preserved, and/or an excess of sediment may result in the microbial mats being smothered (Dupraz et al. 2009). As suggested by comparison with Laguna Bacalar (see above) and general lacustrine facies models (Platt and Wright 1991; Bohacs et al. 2000), the Purbeck brackish-water lake of this study most likely had low relief, ramp-type margins, with microbial mounds confined to the littoral zone.

In the deepest part of the lake, the deposition of the fine-grained facies of the Sub-littoral lacustrine FA occurred with no microbial build-ups. Although a lateral transition between the Transition Bed and the Skull, Hard or Soft Caps was never observed in outcrops, the abundance of peloids and microbial intraclasts in the Wackestone to fine grainstone facies of the Transition Bed indicates deposition in adjacent deeper-water settings (see above). As a consequence, the

depositional environment of Sub-littoral lacustrine FA can only be inferred.

The depositional environments of the Caps and Dirt Beds have been debated since the 19th century when Webster (1826), Buckland and De La Bèche (1835) and Arkell (1947) proposed a freshwater environment because of the trees and their interpretation of the surrounding tufa or “burr” deposits. Later, West (1975) proposed a lagoonal environment with hypersaline waters with algal limestones based on inferred palaeosalinities from biotas and comparison with developments of stromatolites from the hypersaline Arabian Gulf sabkhas. This interpretation had been proposed earlier by Brown (1963, 1964) who worked on the algal limestones and was later supported by Francis’ (1982, 1983, 1984, 1986) work on the Dirt Beds (i.e. the palaeosoils). Brown (1963, 1964) detailed the types of algae associated with the algal deposits to belong to *Ortonella* and *Girvanella* based on preserved filament morphologies and *Solenopora*, and inferred deposition to have occurred in a hypersaline environment. However, this has since been shown to be erroneous, as the first two taxa are now interpreted as sheaths of filamentous cyanobacteria (Riding 1991) that form in a wide range of environments and the *Solenopora* is interpreted to be derived from the underlying Portland Limestone (see above). Francis (1982, 1983, 1984, 1986) demonstrated that the palaeosoils were rendzina profiles at different stages of maturity that supported conifer and cycadophyte forests that developed under a semi-arid Mediterranean-type climate. According to Francis (1982), the hypersalinity of the waters is consistent with this type of climate and with the rapid death and preservation of trees when drowned. It was only with Bosence’s (1987) work on facies of the Cap and Dirt Beds and Perry’s (1994) work on the tufa deposits that the freshwater origin was reconsidered. Bosence (1987) demonstrated that stromatolites are a minor component of the “algal limestones” of previous workers and that

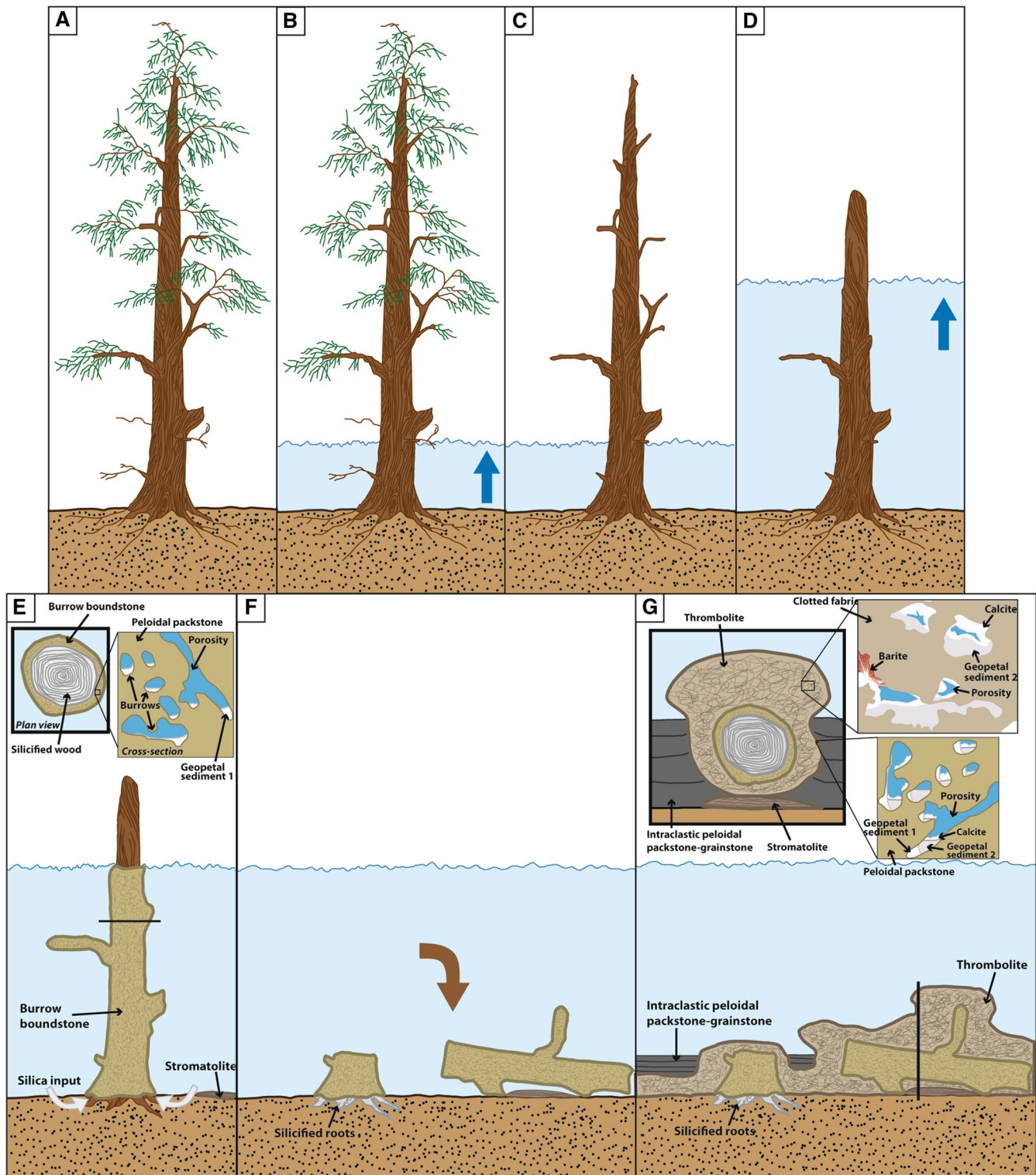


Fig. 18 Reconstruction of events leading to the formation of the microbial mounds. **a** *Protocupressinoxylon purbeckensis* tree growing in Purbeck soil (after Francis 1982). **b** Flooding of vegetated soil with brackish-water lake. **c** Decay of the trees. **d** Lake level continues to rise to at least 4-m depth, which is accompanied by tree decay. **e** Accumulation of the Burrow boundstone facies and Stromatolite

sub-facies. The black line locates the upper cross section. See text for discussion on silica source. **f** The tree breaks with the Burrow boundstone casing and falls near its stump. **g** In situ stump with broken-off tree trunk and branch form substrate for accumulation of Thrombolite sub-facies. The black line locates the upper cross section

Table 2 Main characteristics of facies associations in stratigraphic order from base to top

Facies associations	Facies (subfacies)	Depositional environments	Thickness recorded	Stratigraphic occurrence	Distribution
Bedded marginal lacustrine	Cross-bedded peloidal packstone–grainstone Calcareous sandstone	Marginal hypersaline lacustrine	4.50–10 m	Cypris Freestone	Throughout study area
Hypersaline lacustrine	Evaporite (vuggy and breccia) Gypsiferous peloidal packstone	Marginal hypersaline lacustrine	0–8.70 m	Broken Beds	Dungy Head, West Lulworth Cove, Fossil Forest, Mupe Bay, Worbarrow Tout, Fishermen’s Ledge, Durlston Head
Mounded marginal lacustrine	Intraclastic peloidal packstone–grainstone Microbialite (stromatolite and thrombolite) Burrow boundstone	Marginal brackish lacustrine	1 cm to 5.90 m	Soft Cap Hard Cap Skull Cap	Throughout study area
Emergent	Carbonaceous marl Conglomerate	Soils formed in semi-arid climate Mediterranean-type	0–60 cm	Cypris Freestone Great Dirt Bed Lower Dirt Bed Basal Dirt Bed	Throughout study area
Sub-littoral lacustrine	Wackestone to fine grainstone	Sub-littoral brackish lacustrine	0–1.20 m	Transition Bed	Portesham Q., Poxwell Q., Chalbury Hell’s Bottom, Swanworth Q., Fishermen’s Ledge, Durlston Head God Nore, Lawnshead Q., Portland Bill

they should be referred to as thrombolites originating in brackish-water environments. Perry (1994) supported this idea and interpreted calcite cements coating phytoclasts as more evidence for a freshwater origin. Radley’s (2002) work on mollusc assemblages showed that due to the low diversity of gastropod species and the mixing of low-salinity and marine species (considered to have been brought into the system via rare marine incursions), the environment was most likely a closed brackish-water system that was periodically saline marine. Supporting this are the rare occurrences of small benthic foraminifera within the packstone–grainstones of this study.

Hypersaline water phase

The upper part of the Mupe Member is considered to have been deposited in a more closed lacustrine system of Talbot and Allen (1996) or an underfilled lake type of Bohacs et al. (2000), as indicated by the evaporites and the preserved biota. Figure 23 illustrates the proposed depositional setting of a low-relief margin of this hypersaline, closed-lake. This is based on facies interpretation and a comparison with a modern-day analogue, the northern arm (Gunnison Bay) of the Great Salt Lake, Utah, USA (Chidsey et al. 2015; pers. obs. Gallois 2013).

The Great Salt Lake is divided into a closed, hypersaline, northern arm called Gunnison Bay (240–260 ppt) and a southern arm called Gilbert Bay (120–140 ppt), with freshwater input via four major river systems (Chidsey et al. 2015). In this northern part, microbialites are present but because of the extreme salinity (close to the halite-saturation point, Chidsey et al. 2015), today they are dead and lithified. These microbialites are covered by ooids and microbial intraclasts. Additionally, halite hopper crystals are crystallising on the surface water, sinking when too heavy to float, and are deposited on the lake floor as centimetre-thick salt deposits (Baskin 2014). Consequently, halite crystals can be found encrusted on the surface of the dead microbialites (Chidsey et al. 2015).

The facies model for the upper part of the Mupe Member indicates the lower part of the Cypris Freestone beds as being deposited within a shallow lake margin. This facies model comprises the Hypersaline lacustrine and Bedded marginal lacustrine facies associations. In the littoral to Sub-littoral zones of the lake, cross-bedded, coarse-grained facies accumulated in moderate- to high-energy conditions as indicated by the peloidal grainstones and the presence of well-sorted intraclasts and ooids that were deposited in dunes and ripples. The organic-rich interbeds (Fig. 3, Table 1) are rare throughout the studied area but may be seen

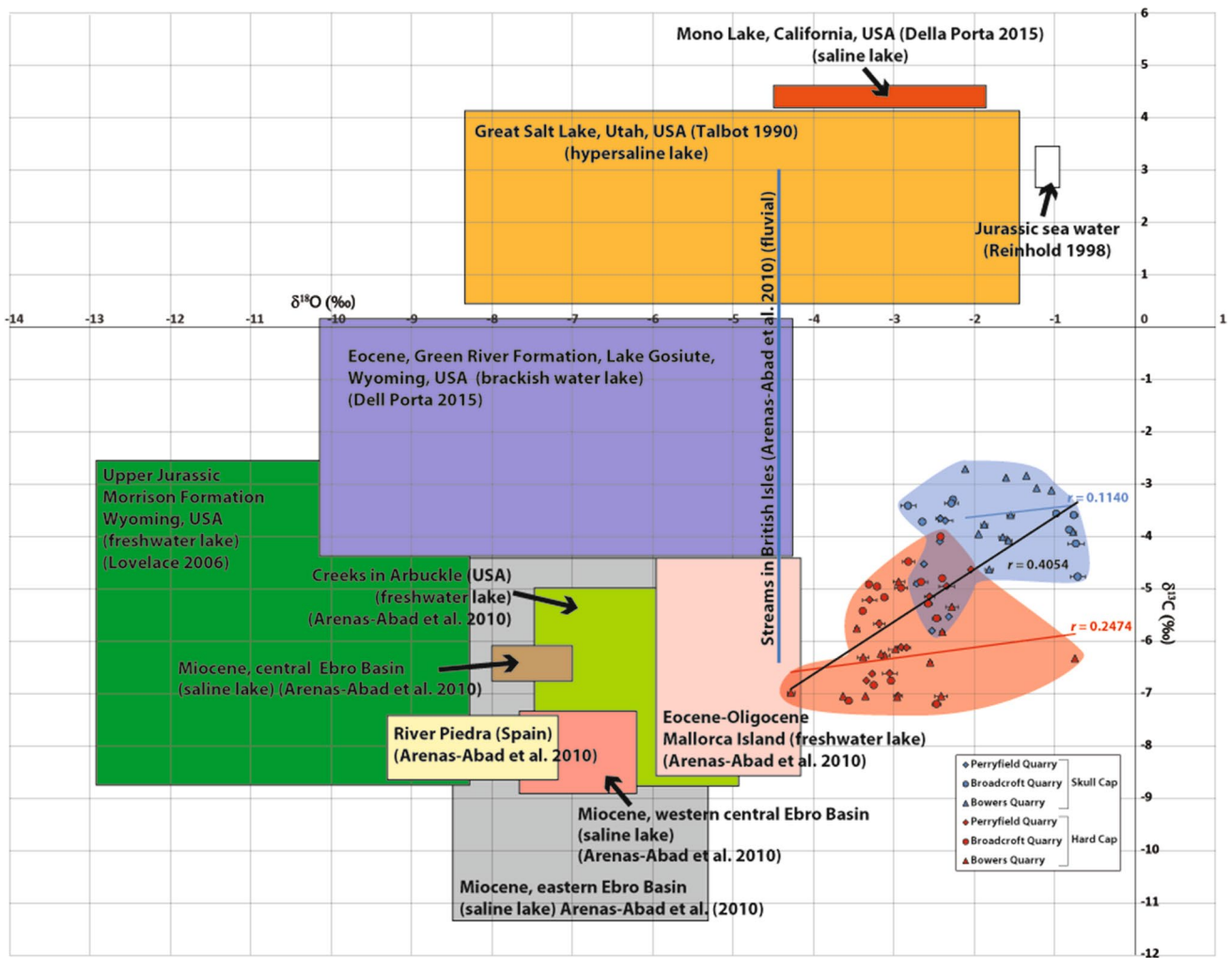


Fig. 19 Cross-plot of $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$ stable isotope data of the Intraclastic peloidal packstone–grainstone facies in the Skull and Hard Cap units compared with data from non-marine carbonates by Talbot (1990), Lovelace (2006), Arenas-Abad et al. (2010) and Della Porta

(2015). Values from Arenas-Abad et al. (2010) were measured on fluvial carbonates; and from Talbot (1990) and Della Porta (2015) on present-day lake deposits

on the Isle of Portland at Broadcroft Quarry, God Nore, King Barrow Quarries and Perryfield Quarry, and are thought to have been deposited in deeper waters from reworked nearby palaeosoils. The evidence of evaporite crystals as calcite or sediment pseudomorphs after gypsum, anhydrite and halite indicates arid climatic conditions and hypersaline waters. The presence of halite pseudomorphs on the top surfaces of beds suggests increasingly arid conditions and desiccation towards the top of the beds (Talbot and Allen 1996). Possible temporary and local freshwater input via river systems provided occasional siliciclastic material from the land that led to the deposition of the quartz-rich Calcareous sandstone facies. Rather more localised and closed areas within this lake provided the conditions for the deposition of the Evaporite facies (Evaporite vuggy sub-facies). Evaporite deposits were formerly more extensive than they appear at

outcrop today, due to their dissolution, and this led to the formation of the Evaporite breccia sub-facies, interpreted as an evaporite collapse breccia (cf. West 1975). In the deepest part (i.e. sub-littoral zone) of the lake, the deposition of fine-grained facies is inferred (Sub-littoral lacustrine facies association) as for the previous facies model. The absence of microbial activity can be explained by two possible processes: either a rise in lake level (i.e. flooding) or a change in the chemistry of the water. A rise in lake level needs to be just enough to stop microbial growth and to be associated with a higher sedimentation rate (sediment input became greater than the growth rate) but not so high as to fill deeper lake areas. This is interpreted from the observations in the modern-day Great Salt Lake (Utah, USA) where microbialites are never found beyond 4 m water depth alongside coarse-grained facies. A change in the chemistry of the water

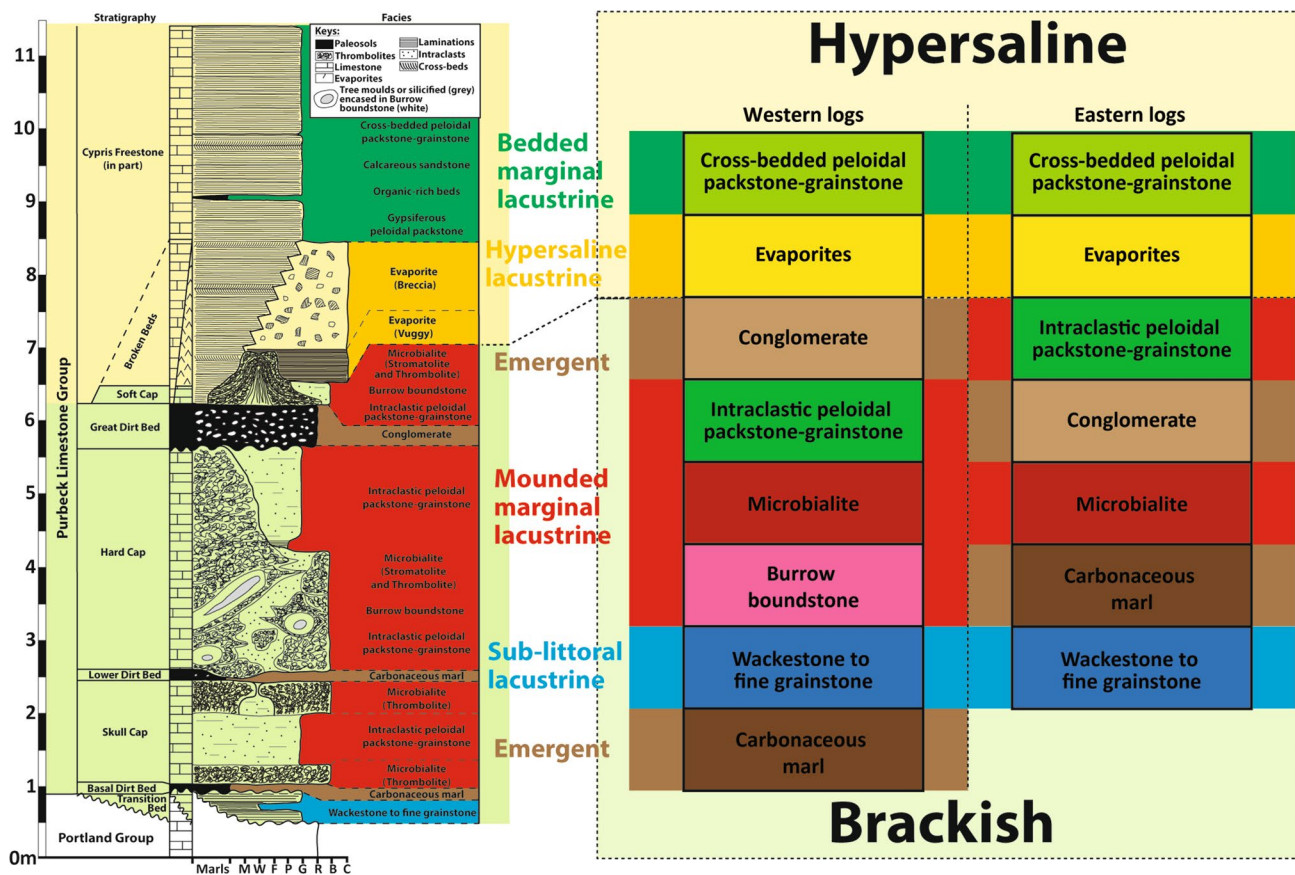


Fig. 20 Ideal sequences with facies associations and depositional environments together with the generalised log

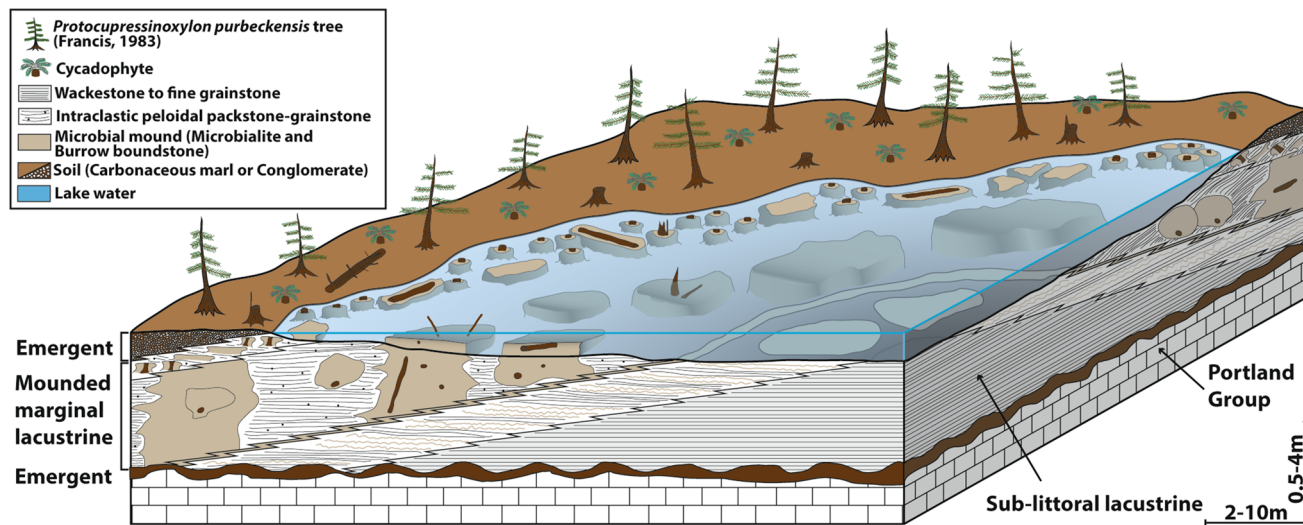


Fig. 21 Facies model for hypothetical brackish-water open-lake margin for the lower Mupe Member, based on the modern analogue Laguna Bacalar (Mexico)

could be due to geographical barriers that reduced flows and increased salinities, which would have provoked the death of the microbial community. This is interpreted from Dupraz

et al.'s (2009) work that proposed that a lack of dissolved carbo associated with either a lack or excess of sediment is deleterious to microbial health and growth. However,

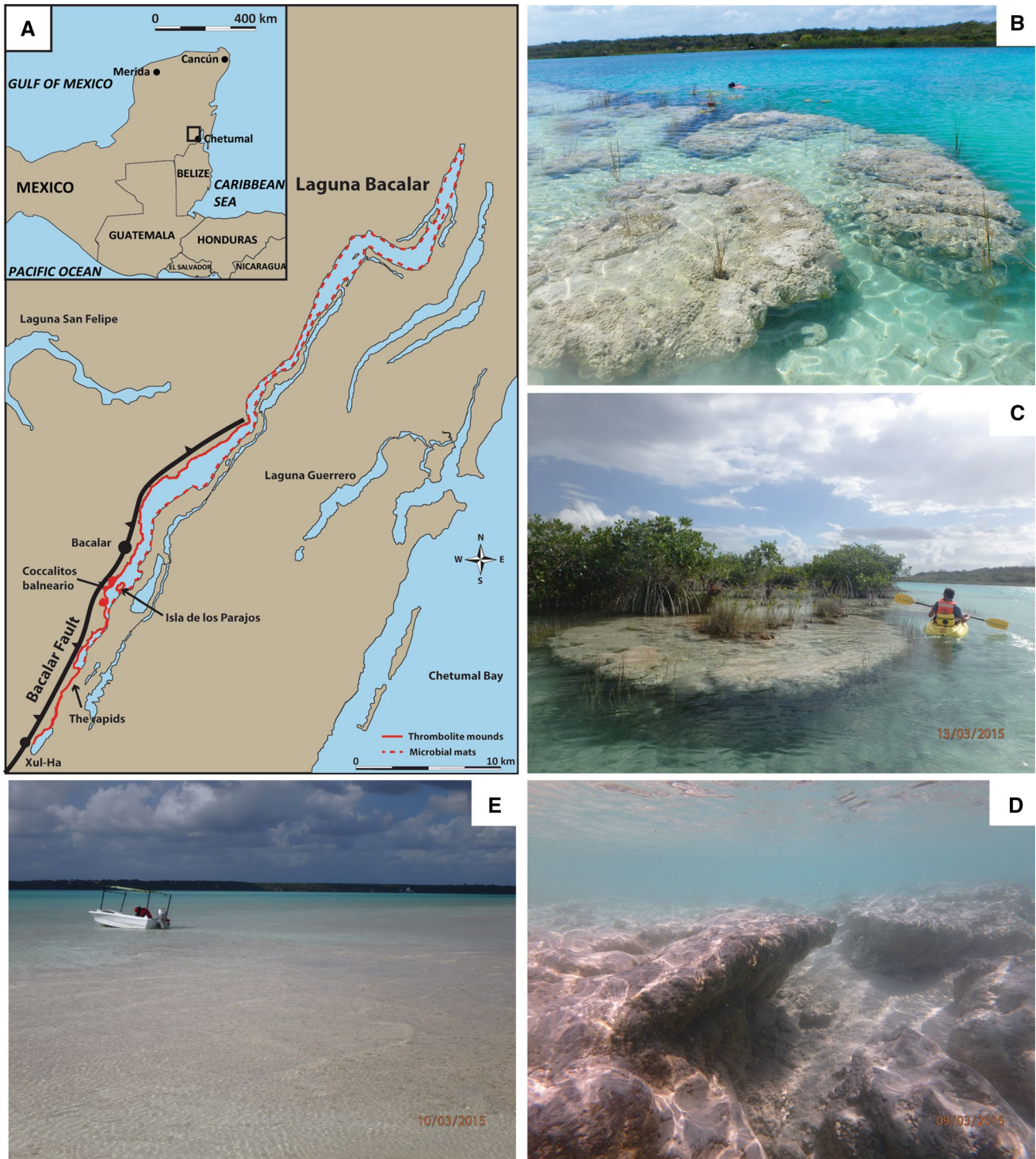


Fig. 22 Laguna Bacalar, Yucatan Peninsula, Mexico. **a** Map of the lake with microbialite occurrence in red (after Gischler et al. 2008, 2011). **b, c** Flat-topped lake margin mounds, south of The Rapids. **d**

Underwater view of lake margin flat-topped ledge mounds, south of The Rapids. **e** Shallow microbial mats, western lake shore

the peloidal packstone–grainstone facies described in this facies model are typical of marginal areas and are similar to

the previous facies model lacking microbial intraclasts and with more ooids. This indicates that the carbonate saturation

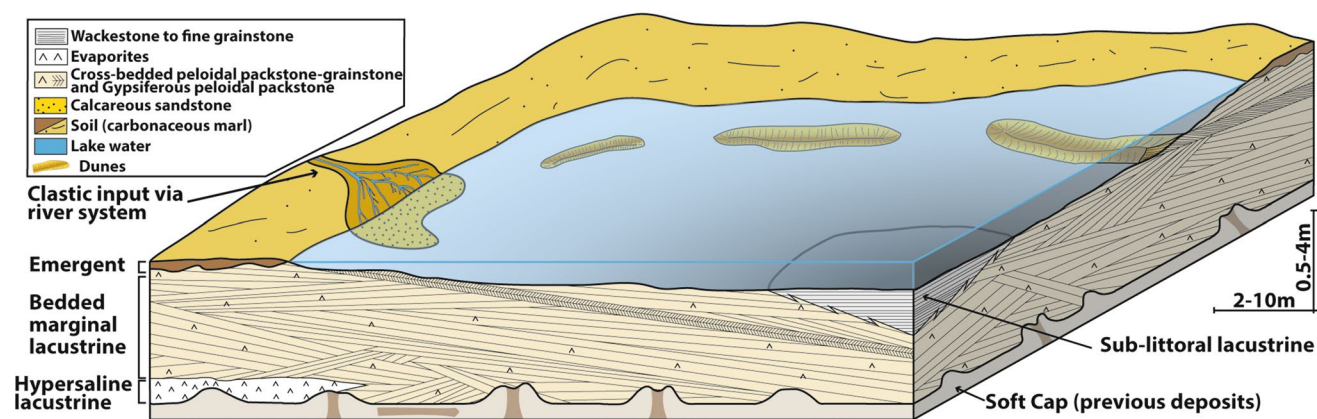


Fig. 23 Facies model for regressive hypersaline water lake margin for the upper part of the Mupe Member. Note that the upper palaeosol is only locally developed compared with the previous model for the lower Mupe Member

probably remained the same or slightly higher, and that an increase in salinity, as indicated by the appearance of evaporite pseudomorphs, is the more likely cause of the death of the microbialites.

In contrast to the brackish-water facies model (Fig. 21), the hypersaline model (Fig. 23) is in agreement with most of the previous interpretations of depositional environments for the Mupe Member and, in particular, with West's (1975) interpretation of hypersaline conditions. Radley's (2002) interpretation of a closed lacustrine system, based on mollusc assemblages (see above), is also consistent with data presented in this study and the hypersaline facies model of Fig. 23.

Discussion

Microbialites as palaeoenvironmental indicators?

Della Porta (2015) compared lacustrine build-ups of a number of modern lakes (Great Salt Lake in Utah, Pyramid Lake in Nevada, and Mono Lake in California in the USA) and ancient lacustrine deposits (Green River Formation, Uinta Basin in Utah and Lake Gosiute in Wyoming in the USA and Ries Crater Lake in Germany) and concluded that internal fabrics of such build-ups are not specific to different lacustrine environments and therefore cannot be used as palaeoenvironmental indicators. By contrast, Jahnert and Collins (2011, 2012) studied the microbial deposits in modern-day hypersaline marine Shark Bay (Hamelin Pool, Western Australia) and Chidsey et al. (2015) studied the ancient microbial deposits of the Green River Formation (Uinta Basin, Utah, USA) compared to its modern analogue, the Great Salt Lake (Utah, USA). Both studies showed an environmental control on microbialite development and demonstrated that

a specific internal fabric reflects a specific water depth and a specific margin type, with stromatolites found in the shallowest part and in low gradient margins and thrombolites in deeper waters and in steeper gradient margins. In the present study, thrombolitic and stromatolitic internal fabrics (cf. Riding 2011) are identified and interpreted to be deposited in a brackish-water lake, compared to modern analogues.

The internal fabrics of the Purbeck microbial facies described in this study show similarities with a range of published data worldwide. Thrombolitic and stromatolitic internal fabrics in the Purbeck limestones are very similar to those found in modern and ancient environments, and five among many others are mentioned here:

The freshwater lake at Laguna Bacalar (Yucatan Peninsula, Mexico, Gischler et al. 2008, 2011) contains thrombolites with their internal fabrics made of heads of upward-radiating filament moulds incorporating the surrounding sediments and fossils.

The hypersaline lake at Great Salt Lake (Utah, USA, Chidsey et al. 2015; Della Porta 2015) contains leiolites to thrombolites (Della Porta 2015) that comprise abundant calcitic spherulites linked with acicular cements and/or microbial filaments (Chidsey et al. 2015) and that can incorporate peloids, detrital grains, ooids, or even bird feathers; the external part is usually encrusted with tubes of brine-fly larvae (Post 1977; Chidsey et al. 2015; Della Porta 2015).

The marine hypersaline lagoon at Hamelin Pool (Shark Bay, Western Australia, Jahnert and Collins 2011, 2012) contains stromatolitic laminated microfibrils of smooth and colloform mounds and thrombolitic clotted microfibrils of pustular domes (Jahnert and Collins 2011, 2012).

The alkaline Mono Lake (California, USA, Della Porta 2015) contains metre-scale pinnacles composed in the central layers of leiolitic and clotted peloidal micrite, dendrites and calcitic spherulites; they are coated in the external layers

with dense micrite laminae, microsparitic crusts and clotted micrite.

The Eocene brackish-water lake of the Green River Formation (Uinta Basin, Utah, USA, Chidsey et al. 2015; Della Porta 2015) contains microbialites with four main internal microstructures: stromatolitic agglutinated made of irregular coarse-grained (peloids, quartz grains and intraclasts) laminae; stromatolitic agglutinated dendritic composed of an alternation of coarse-grained (as for the previous fabric) and dendritic laminae; stromatolitic fine-grained composed of laterally extensive laminae (from metres to tens of metres), and thrombolitic microfibrils characterised by a clotted structure with a micritic matrix incorporating ooids, peloids and quartz grains (Sarg et al. 2013).

This shows that microbial deposits similar but not identical to that of the Purbeck have been found in a range of salinities (from freshwater to hypersaline marine) and all kinds of climate settings (Mediterranean-type to tropical). Therefore, based only on their internal fabrics, microbialites are not thought to be useful as palaeoenvironmental indicators. Interpretation requires the integration of palaeontological, petrographic (stable isotopes) data from penecontemporaneous facies together with comparisons with modern analogues. As mentioned by Della Porta (2015), integration of mound internal fabrics, external morphologies and distribution and their relationships with surrounding facies is critical to enable microbial deposits to be used as palaeoenvironmental indicators.

Depositional environments

This study indicates that the palaeoenvironments were initially brackish-water lacustrine as opposed to the hypersaline lagoons as interpreted by West (1975, 1979) and by Francis (1982). In addition, the two new facies models that depict the two depositional environments proposed in this study indicate that the hypersaline conditions interpreted by West (1975) only appeared in the second half of the Mupe Member (above the Soft Cap). The former brackish-water phase can be classified as a balanced-fill lake type of Bohacs et al. (2003) or an open lake of Talbot and Allen (1996), and the later hypersaline phase as an under-filled lake type of Bohacs et al. (2003) or a closed lake of Talbot and Allen (1996). The transition between the two depositional environments in the Purbeck is sharp, and forms one bedding plane between the Soft Cap and the Cypris Freestone as observed at the Fossil Forest, Lulworth. Here, thinly bedded evaporitic beds overlie microbial mounds and inter-mound facies (Figs. 1 and 23). The thinly bedded evaporitic beds drape the original topography of the mounds and there is no evidence of erosion on this surface. Such a transition is similar to that of modern-day salt-pans where, due to evaporation after closure of the water body, the deposition of gypsum and halite crusts

has resulted in a sharp vertical transition between brackish deposits and evaporitic beds (e.g. Lowenstein and Hardie 1985; Chidsey et al. 2015).

In the lower part of the Purbeck Limestone Group of Dorset, the transition between the brackish and hypersaline environments is sharp, so a climatic control seems unlikely to be the driving mechanism. This is supported by palaeoclimate studies that propose that arid conditions prevailed during the Late Jurassic, from the late Kimmeridgian (*huddlestoni* zone) through to the early Berriasian, with its climax during the deposition of the lower Purbeck beds (Hallam 1993; Hesselbo et al. 2009). As a consequence, channel avulsion (Allen 1965) or tectonically driven change in discharge (Twidale 1971) appear to be the best candidates that might control such a sharp transition. Although no clear evidence for synsedimentary tectonics has been published for the lower Purbeck beds, fluvial input was hypothesised by Underhill (2002) to be through the relay ramp linking the Ridgeway and Purbeck Faults (Fig. 1) and this is further supported by data in this paper (Table 1). A change in the palaeotopography either due to synsedimentary tectonics or to channel avulsion on the footwall blocks or on the relay ramp could have resulted in a river system diversion that would have interrupted the freshwater input into the lake.

Conclusions

This study demonstrates the importance of studying the details of facies and their transitions for the interpretation of shallow lacustrine deposits. Such data are used, together with modern analogues, to erect new facies models for lacustrine carbonates. The main conclusions from this work are as follows:

The study of the Mupe Member of the Purbeck Limestone Group results in ten newly described facies, grouped into five facies associations, all interpreted as marginal deposits in an earlier brackish and a later hypersaline shallow lake.

The Wackestone to fine grainstone facies is exclusive to the Transition Bed locally deposited at the base of the Mupe Member and is interpreted to represent deeper water deposits in a brackish-water lake. The Microbialite facies composed of the Stromatolite and Thrombolite sub-facies and together with an unusual Burrow boundstone facies form microbial mounds that are closely associated with the intermound Intraclastic peloidal packstone–grainstone facies and together with the mounds are found in the Skull, Hard and Soft Cap beds. These facies are interpreted to represent shallow-water deposits formed on the margins of a brackish-water lake. The sub-lacustrine facies are overlain by palaeosoils of the Carbonaceous marl and Conglomerate facies developed under a semi-arid, Mediterranean-type climate. The Cross-bedded peloidal packstone–grainstone facies

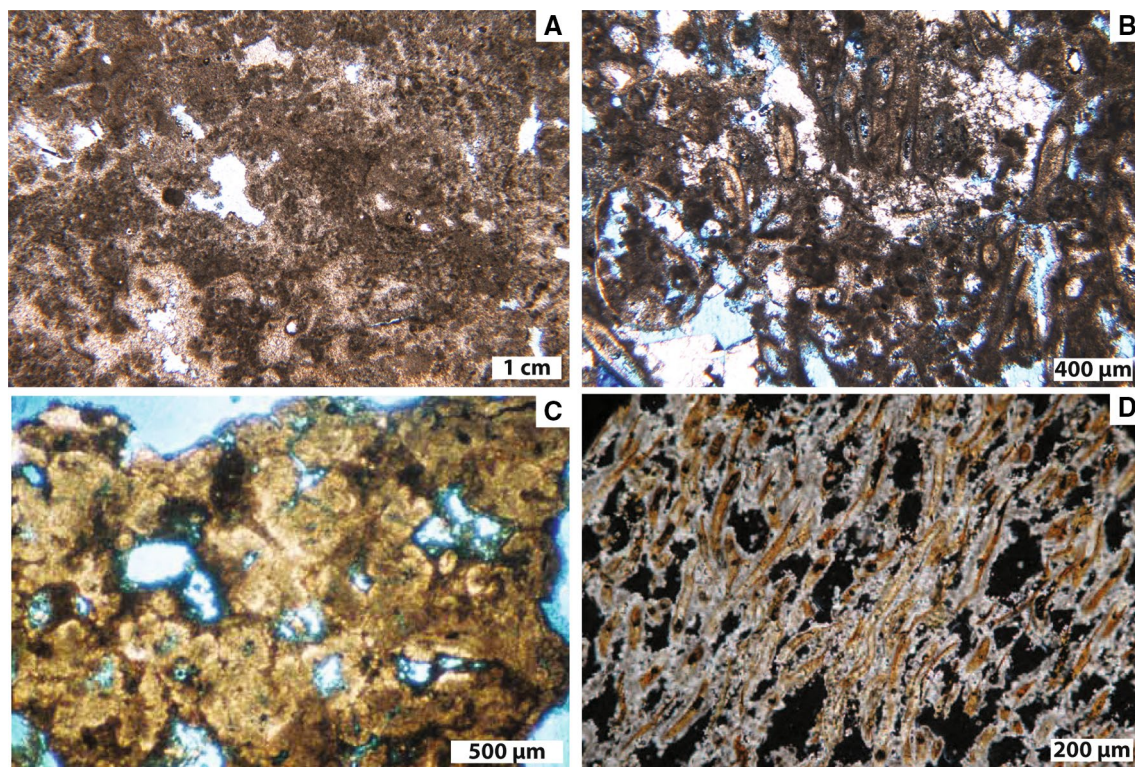


Fig. 24 Microphotographs comparing thrombolitic internal fabrics from Purbeck limestone mounds, Great Salt Lake (Utah, USA) and Laguna Bacalar (Mexico). **a** Clotted texture and cement fringes under PPL from Purbeck (POQ6, Hard Cap, Poxwell Quarry, 50°39'3.84"N; 2°21'52.12"W). **b** Microbial filaments, ostracods and peloids under

PPL from Purbeck (GN4, Hard Cap, God Nore, 50°31'31.41"N; 2°26'22.51"W). **c** Clotted texture and early cements under PPL from Great Salt Lake (Utah, USA, Chidsey et al. 2015). **d** Microbial filaments and early cements under XPL from Laguna Bacalar (Yucatan Peninsula, Mexico, Castro-Contreras et al. 2014)

constitutes the main facies of the overlying Cypris Freestone beds and is interbedded with the Gypsiferous peloidal packstone and Calcareous sandstone facies together with Vuggy and Breccia sub-facies of the Evaporite facies. Together, these facies were formed in a hypersaline shallow lacustrine margin environment.

Microbial mounds are particularly useful indicators of palaeoenvironments, but only when macro- and micro-scale characterisations are integrated with a full description and interpretation of penecontemporaneous facies and biotas.

Similar microbial fabrics of stromatolites and thrombolites are found in modern analogues to the Purbeck limestones such as the freshwater Laguna Bacalar (Mexico, Fig. 24), the hypersaline Great Salt Lake (Utah, USA, Fig. 24) and ancient analogues such as the brackish-water Green River Formation (Eocene) of the Uinta Basin (Utah, USA).

The small-scale characterisation of the vertical facies transition from the earlier brackish to the later hypersaline lake showed that the boundary is marked by a sharp contact where hypersaline, locally evaporitic, deposits are directly overlying microbial mounds. This suggests that the change may have occurred rapidly, most likely due to an extensional

tectonic event (e.g. fault movement, tilting) or a channel avulsion resulting in a reduction in the fluvial discharge into the lake.

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