

Discriminating between the origins of remotely sensed circular structures; carbonate mounds, diapirs or periclinal folds?

Purbeck Limestone Group, Weymouth Bay, UK

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Abstract

High-resolution, multibeam, bathymetric data from Weymouth Bay (UK) provides remarkable images of numerous, dome-shaped structures within the Purbeck Limestone Group. These 30-150 m across, concave-down structures occur only within the Durlston Fm on the southern limb of the Purbeck Anticline in the southwestern Wessex Basin. Similar structures have not been identified in the extensive outcrops around the Bay. The morphology and geological setting of the circular structures allows some interpretations to be discounted (e.g. pock-marks, dolines, impact structures, diatremes) but three very different interpretations remain. Carbonate mounds, periclinal folds and evaporite diapirs

share similar morphological features, occur in the right setting, and are consistent with aspects of the known geology of the area. Analysis of features of the circular structures' basinal setting and morphology as imaged on the seafloor, and in seismic profiles, is undertaken to discriminate between these three possible origins. This analysis indicates that evaporite diapirs are the least likely origin, then periclinal folds and finally carbonate mounds are the most likely for the origin of the structures. Neither large carbonate mounds, or evaporite diapirs or similar-shaped periclinal folds have been previously recorded in the Durlston Fm outcrops of this internationally renowned geological region.

Many sedimentary rock successions contain plan-view circular structures that are 10s to 100s of metres across such as impact structures, evaporite or mud diapirs, isolated carbonate build-ups, dolines, periclinal folds, monadnocks (erosional remnants) and gas chimneys. However there is debate about how to discriminate between these different origins from remotely sensed data (e.g. Stewart 1999; Burgess *et al.* 2013). This study examines newly discovered 30-150 m diameter circular structures developed in Purbeck Limestone Group limestones and shales exposed on the seafloor of Weymouth Bay. The structures are revealed in a high-quality, multibeam echo sounding (MBES) survey (Fig. 1; DORIS 2017). The MBES data provide an unparalleled one metre resolution, plan-view of Late Jurassic to Early Cretaceous strata deformed by the Purbeck, Lulworth Banks and Weymouth anticlines similar to a time slice from 3-D seismic data. The circular features subcrop (ie. as exposed bedrock on

51 the present-day sea floor) in an arcuate band from the very well-known outcrops
52 of the Purbeck Limestone Group (Purbeck Lst Gp) from the cliffs between St
53 Aldhelm's Head and Durlston Bay to the Isle of Portland in the southwest.
54 Circular structures with a similar size and morphology have not been described
55 from the onshore outcrops in the region despite well over a hundred years of
56 intensive geological research and the inclusion of the outcrops around
57 Weymouth Bay as a World Heritage Site because of their geological diversity.
58 This coastal area is regarded to include the most complete sections of Jurassic
59 to Cretaceous rocks anywhere in the world (Cope 2012).

60 In this study we use the MBES data to map the occurrence of the
61 circular structures, assess their diameters, the dips and strikes of their
62 concentrically arranged beds and their stratigraphic architecture. A detailed
63 stratigraphic correlation to the established lithostratigraphy of the Purbeck Lst
64 Gp is achieved by mapping the resistant intertidal ledges from Durlston Bay to
65 prominent seafloor ridges in Weymouth Bay to determine their stratigraphic
66 level. New field studies and assessment of offshore seismic sections are
67 undertaken to assess possible analogous structures within the Purbeck Lst Gp.
68 Finally, we perform a semi-quantitative analysis of the characteristics of the
69 circular structures to assess potential mechanisms for their formation and
70 conclude that they are most likely to be *in situ* carbonate mounds but that
71 periclinal folds and evaporite diapirs are also possible mechanisms for their
72 formation.

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74

75 **Geological Setting**

76

77 *Stratigraphy.*

78 Previous studies have shown that the seafloor of Weymouth Bay is almost
79 entirely bedrock (Donovan & Stride 1961; Sanderson *et al.* 2017). Gravel
80 patches with dune bedforms occur locally (e.g. The Shambles Bank and
81 Adamant Shoal, Fig. 1), but the majority of the area comprises exposed ridges
82 of strata either locally truncated by Quaternary erosional features (e.g.
83 channels) or covered with weed and/or a thin sediment veneer as seen in
84 seabed photographs (DORIS 2017). The exposed rocks are known from the
85 seabed sampling work of Donovan & Stride (1961) to range from the Upper
86 Jurassic Oxford Clay to the Lower Cretaceous Wealden Gp (Fig. 1).

87 A new geological map of the area, based on a subset of the MBES data
88 used in this study, was recently published by Sanderson *et al.* (2017). The
89 showed that the onshore and offshore geology could be integrated based on
90 seafloor mapping of the different weathering characteristics of the Mesozoic
91 units. Shale and shale-sand units (Kimmeridge Clay, Portland Sand Fm, and
92 shales in the Lulworth Fm) and uncemented mudstones and sands of the
93 Wealden Gp are preferentially eroded along the coastline and also form
94 bathymetric lows in Weymouth and Durlston bays whilst cemented limestones of
95 the Portland Stone Fm and Purbeck Lst Gp form ridges and broader highs on
96 the seafloor. The present-day seafloor truncates both limbs of west – east
97 trending anticlines (Weymouth, Lulworth Banks and Purbeck) together with a
98 prominent set of approximately N-S faults (Sanderson *et al.* 2017, Fig.1). The

map prepared for this study (Fig.1) locates the study area for this paper and extends the Sanderson *et al.* (2017) map towards the east. In addition we do not recognise the Portland Sand as a unit with different erosional characteristics on the seafloor from the underlying Kimmeridge Clay. As is shown later in this paper the circular structures come from within the arcuate subcrop of Purbeck Lst Gp from Durlston Bay in the northeast to the Isle of Portland in the southwest (Fig. 1).

Purbeck Limestone Group. This group is divided into the lower, Lulworth and upper, Durlston formations (Fig. 2; Casey, 1963). It is a succession of non-marine limestones, shales and some evaporites outcropping in their type locations in Lulworth and Durlston bays along the Isle of Purbeck coast and, in part, as the uppermost unit on the Isle of Portland (Fig. 1). These strata overlie the marine limestones of the Portland Stone Fm and thicken to the east from 46 m at Stair Hole to 119 m in Durlston Bay and have been subdivided into five members by Westhead & Mather (1996) (Figs 2,3).

The Mupe Member (Mbr), or Caps and Cypris Freestones of West (2013), at the base of the Lulworth Fm and the Purbeck Lst Gp comprises well-lithified, bedded, non-marine limestones, paleosols and microbial mounds (West 1975; Bosence 1987; Gallois *et al.*, 2016, 2017). The Mupe Mbr can be traced through the onshore outcrops with some lateral facies changes becoming thinner towards Portland. The overlying Ridgeway Mbr comprises mudstones and thin-bedded, micritic non-marine limestones with detrital quartz. The remainder of the Lulworth Fm. are ripple laminated limestones and interbedded micrites and limestones of the Worbarrow Tout Mbr (Westhead & Mather 1996).

The Durlston Fm (Figs 2, 3) comprises a lower Stair Hole Mbr (Shelly limestones interbedded with mudstones) including the “Cinder Bed” (West 2013) and an upper Peveril Point Mbr (Coarse grained shelly limestones and mudstones) including the “Purbeck Marble beds” (West (2014)). The Cinder Bed can be traced as a distinctive horizon that halves in thickness from Durlston Bay to outcrops in the west (Westhead & Mather, 1996).

Structure

Folds. The MBES data provide an unparalleled plan-view of the Purbeck, Lulworth Banks and Weymouth anticlines similar to a time slice from 3-D seismic data. The present-day sea floor truncates both the northern and southern limbs of these apparently linked anticlines, together with a prominent set of approximately N-S faults.

The Weymouth, Lulworth Banks and Purbeck anticlines have shallow dipping southern limbs (consistent with 1-2° dips on the Isle of Portland) and steeply dipping northern limbs that are well exposed, and very well known to geologists, on the coast from Weymouth to Swanage (Fig. 1; Arkell 1947; House 1989; Sanderson *et al.* 2017).

These anticlines result from N-S directed Cenozoic Alpine shortening and inversion of the major, inverted Purbeck Fault (Fig.1; Underhill & Patterson 1998; Sanderson *et al.* 2017). The major folds, associated buckle folding and minor fault-related folding mostly formed within the thick syn-extensional hangingwall stratigraphy of the Purbeck Fault, buttressed against the more competent footwall stratigraphy. Stratified limestone units such as the Portland and Purbeck groups contain layering with high mechanical anisotropy and so

readily form complex minor folds within the northern limb and core of the Lulworth Banks anticline, exemplified by the well-studied Lulworth Crumple at Stair Hole and Lulworth Cove (Arkell 1947; Underhill & Patterson 1998).

Inversion-related folds are also known at Osmington Mills, Chalbury and Poxwell (Arkell 1947; West 2012; Sanderson *et al.* 2017) and at Peveril Point (Arkell 1947; Cosgrove & Hearn 1966; Nunn 1992; West 2014). Whilst 2-D cliff sections and BGS maps (Arkell 1947; House 1993) of these minor folds are well known, their plan view aspects are essentially unstudied except for the detailed work of Cosgrove & Hearn (1966) at Peveril Point. Here they mapped a highly localised, northerly verging and thrustfold pair. The anticlinal core has radially outward dips that form a “bulge structure” so that individual beds (eg. Purbeck Marble) can be traced most of the way around the fold on the wave cut platform (Cosgrove & Hearn 1986).

Faults. Numerous faults are imaged on the seafloor of Weymouth Bay (Fig 1), many of which were originally mapped by Donovan & Stride (1961) and are discussed in more detail in Sanderson *et al.* (2017). The faults cut through all of the stratigraphic units in the area. A prominent group of N-S extensional faults (Group 1, Fig. 1C) is believed to have formed during the Cenozoic inversion and compression of the area (Hunsdale & Sanderson 1998, Putz-Perrier & Sanderson 1998).

Earlier, Harvey & Stewart (1998) identified NW-SE and NE-SW conjugate strike-slip faults in nearby Lyme Bay that they also attributed to latest Cretaceous to Cenozoic compression. Harvey & Stewart (1998) further suggested that underlying Triassic salt in Lyme Bay may have facilitated the

development of these strike-slip faults. These are labelled as Group 2 faults (Fig. 1C).

West to east oriented faults (Group 3, Fig. 1C) are only found in Durlston Bay where they strike onshore to form the Zig Zag path and the Durlston Head extensional faults (Fig. 1; Arkell 1947; West 2014). These faults have the same orientation as the inverted Purbeck Fault to the north and are considered to be related to this major fault. The different sense of movement of the two faults is consistent with this interpretation of an inverted fault system.

Methods

This paper uses a range of different methods to investigate the circular structures. We combine an analysis of the MBES data with previously unpublished commercial seismic data, and finally fieldwork focused on resistant coastal ledges and plan view and vertical cliff outcrops of folds in the Purbeck Lst Gp in Purbeck, Dorset. These methods are backed up with the very detailed and extensive literature base for this part of the Jurassic Coast World Heritage Site over the last 70 years (e.g. Arkell 1947 to Sanderson *et al.* 2017).

Multibeam Echo Sounding (MBES)

The data used in this study was collected as part of the Dorset Integrated Seabed Survey (DORIS) in 2008-9 combined with a subsequent MCA survey in 2012 in Durlston Bay. In total 800 km² of seabed was surveyed. The raw bathymetry soundings were reduced to Admiralty Chart Datum using a locally calibrated UKHO “Vertical Off-shore Reference Frame” model and gridded to 1m. This grids was converted from WGS 84 into UTM [Zone 30N] co-ordinates

and loaded into ESRI ArcGIS and IVS Fledermaus software packages. Within ArcGIS two supplementary grids were generated: a slope raster which presents the maximum rate of change of gradient between neighbouring cells and an aspect raster that captures the compass direction of this maximum slope. These were useful for emphasising resistant marker beds which erode to give distinctive ledges; some with “saw-tooth” morphologies on the seabed with long, shallow slopes interpreted to be bedding planes and shorter, steeper slopes between beds. The final bathymetry is shown in Figs 1, 3, 4, 5 & 6).

Subsurface Data

The area is covered by a large number of commercial seismic surveys. However these are of variable quality, vintage and coverage and there are no published wells in the study area that penetrate strata that can be correlated with the Upper Jurassic strata being studied. Horizons were therefore identified in the seismic profiles by tying well data (released through IHS) to a publically available 3-D seismic block in Bournemouth Bay, north of the study area (Fig. 1B). Released seismic data (UKOGL) comprising west - east and then north - south lines were then used to trace top Portland Gp and top Purbeck Gp reflectors from Bournemouth Bay into the study area south of Swanage (Fig. 1B). Three seismic datasets of 2-D data from the 1980s were obtained from CDA (UK Oil and Gas Data) that form grids within the study area: a 1980 Shell dataset (SH802D1019) of 26 E-W and N-S lines, two 1982 BG surveys of 13 and 35 E-W and N-S lines (GC 822D1011 and GC822D1013), and a 1985 Total (OXY852D1004) dataset of 29 dip lines oriented NW - SE. An additional check on the identification of the two mapped horizons, was made by tying horizon

tops to the mapped occurrence of boundaries on the sea floor obtained from the MBES data, which itself, is tied to coastal outcrops (Figs 1,3). The recovery of two offshore seabed samples of ostracod limestones interpreted to be from the mapped subcrop of the Purbeck Lst Gp by Donovan & Stride (1961) further confirmed the interpretation.

Fieldwork

Studies were focused on obtaining the best possible correlation between the well-known coastal outcrops around Weymouth and Durlston Bays and the sea floor ridges, scarps and hollows visible in the MBES data. Figure 2 indicates the correlation used in this paper between the published outcrop-based stratigraphy and the units mapped in the MBES seafloor data. Distinctive ledge-forming limestones occur in intertidal outcrops in Durlston Bay (Fig. 3A) formed by the Cinder Bed, the Upper Building Stones, the Broken Shell Limestone and the Purbeck Marble units (terminology after West 2013, 2014). These can be traced to correlate with seafloor ridges when Lidar and MBES data are merged (Figs B,C). Digital aerial photographs were downloaded from the Channel Coast Observatory website (http://www.channelcoast.org/data_management/online_data_catalogue/).

In addition, folds within the Purbeck Lst Gp have been studied on the foreshore and cliffs in Durlston Bay and Lulworth Cove on the northern limb of the Lulworth Banks and Purbeck anticlines. Part of one prominent intraformational fold pair (about 14 m x 22 m in outcrop extent) on the east side of Lulworth Cove (West 2005) was mapped in detail to confirm its periclinal

geometry, structural vergence and relationship to adjacent parallel beds. Four 20 m long topographic profiles were measured approximately normal to bedding strike, and bedding orientation measured on each bed with the aim of constructing sequential cross-sections through the folds and statistically determining the fold hinge line. The characteristic Cinder Bed of the Durlston Fm (Fig. 2) was used as a stratigraphic marker horizon to help model the structure in the subsurface.

Circular Structures

Observations from MBES data

In total some 27 circular structures have been identified within the NE-SW trending offshore subcrops of the Purbeck Lst Gp (Fig. 4). Within this subcrop the structures are only seen in a band west of Durlston Head and east of Kimmeridge Bay and are, therefore, confined to the southern, gently sloping, limb of the Purbeck anticline (Fig. 4). Submarine slopes in this region obtained from the slope raster on interpreted dip slopes vary from 2-22° to the SE and SSE and these are consistent with orientations measured along nearby coastal outcrops (Fig. 4). There does not appear to be any regularity in the spacing of the structures within this area and distance to nearest neighbour varies from 150 to 1065m (Table 1). The structures may be cut by the prominent N-S faults and the more minor sets of NW-SE faults that are interpreted to be Cenozoic in age (Fig. 4). The diameters of the circular structures vary from 27 to 147 m as measured by the diameter of the largest circle that could be placed within the circular bedding traces imaged in plan view (Figs 1D, 5). This measurement was chosen as it was considered to be the only consistent way of measuring the

size of these structures. They are minimum diameter measurements because images indicate that stratal orientations are modified around the circular structures by varying amounts laterally away and stratigraphically above, and locally below, their cores.

The majority (20 out of 27) of the structures studied have what we refer to as concave-down domes, or omega, morphologies because of their Ω appearance in the oblique sections (Figs 1C, 5). The structures are underlain by SE-dipping strata with a uniform NE-SW strike producing bedding-parallel ridges on the sea floor. Based on our offshore to onshore correlations (Fig. 3) these are interpreted as limestone shale alternations that are characteristic of the Purbeck Lst Gp. These bedding-parallel strata pass up-section and southeastwards into domed strata with a concave-down morphology and with dips radiating out in all directions (Fig. 5). The central part of the Ω structures is imaged as a sub-circular exhumed or truncated dome, as an inlier, with oldest beds in the centre. These concave-down portions are overlain by strata showing apparent thinning over the apex of the domes and thickening along strike away from the core of the structure before the regional SE- dipping, bedding-parallel subcrop ridges return higher in the succession. Such structures are observed either isolated within the Purbeck Lst Gp or stacked one on top of another, and at one place, stacked within three successive stratigraphic levels within the member (CS 14-16, Fig. 1C). The cores of some structures have little relief above the sea floor, some are eroded out (negative relief as in Fig. 5) and some show positive relief on the sea floor (Fig 1C) so the plan-view morphology of these structures is not controlled by differential erosion of gently dipping strata.

A smaller number (7 out of 27) have an irregular, plan-view morphology of concentrically arranged ridges (Fig. 6) rather than the architecture of the Ω structures. These occur in the NE of the area where the dips are shallower (CS 20, 22 and 23-27, Fig. 4, 6) and these have a positive relief on the sea-floor. Shapes in plan view vary from sub-circular through to lobate (Fig. 6). The subcropping ridges pass around all sides of the structures and originate from the regional NNW-SSE and W-E ridges in this area. The structures when viewed with bathymetry and hill shading rasters indicate that the cores of each of these structures have radially arranged dips of domed strata similar to those of the Ω circular structures.

Stratigraphic and Structural context of circular structures

Lithostratigraphic correlation and palaeoenvironmental context

A prominent eastward plunging anticline is seen in the MBES data between Durlston Head and Peveril Point (Figs 1, 3, 4). Mapping of seismic data indicates that this anticline is continuous with the Purbeck Anticline further west. The northern limb of the anticline is cut by a prominent W-E fault (Figs 3, 4) that have seafloor expression and projects onshore to the two normal faults near the Zig Zag path (Arkell 1947) that repeat the Purbeck succession within Durlston Bay. The cliff and foreshore outcrops strike offshore as a series of ledges in Durlston Bay (Fig. 3) and are here used to map four of the most prominent limestones in the Purbeck Lst Gp from outcropping ledges in Durlston Bay, around the plunging faulted anticline to the main NE-SW seafloor exposures of the Purbeck Lst Gp containing the circular structures (Figs 3, 4). This mapping demonstrates that all of the structures occur within the Durlston Formation and,

all bar one of the structures occur between the Cinder Bed and the Broken Shell Limestone (Fig. 2). This places them within the upper part of the Stair Hole Mbr a unit of alternating limestones and shales. They are not associated with the well-known, thick, molluscan rudstones of the Cinder Bed that marks the base of the Stair Hole Mbr or the units of non-marine rudstones of the Broken Shell Lst or the Purbeck Marble beds.

There are no known stratigraphic features that might form plan-view circular structures within the outcrops of the Stair Hole Mbr. The entire unit is made of shales, medium to very thickly bedded limestones (e.g. molluscan rudstones), and locally evaporites. The preserved biota and evaporite minerals indicate these units were formed in a marginal marine to brackish lagoonal environment (El Shahat & West 1983). However, in the lowest member of the Purbeck Gp carbonate mounds are present at three levels in the Mupe Mbr (Gallois *et al.* 2016, 2017) that are variably developed in all outcrops from the Isle of Portland through to Durlston Head. These are concave down, dome-shaped and with sub-circular plan-views (Fig. 7). These mounds are *in situ* constructions by microbial communities that formed positive structures on the floor of brackish water lakes in early Purbeck times (Bosence 1987; Gallois 2016; Gallois *et al.* 2017). They are meters to 10s of metres across and decimetres to metres in height (Gallois 2017). Smaller-scale laminated microbialites (stromatolites) have been observed higher in the succession in the Cypris Freestones on Portland and locally in the Durlston Formation in Lulworth and Mupe Bay outcrops.

347 *Outcropping structural analogues*

348 Periclinal folds with an ellipsoidal plan-view have been described from this area
349 (see Geological Setting- *Structure* above). These are of a larger scale than the
350 circular structures and have different plan-view geometries. However, a small
351 fold pair within the Lulworth Crumple is exposed in plan-view in intertidal
352 outcrops in the east of Lulworth Cove (Figs 8, 9; West 2005) shows a number of
353 similarities with the circular structures of this paper. The folds bring the Cinder
354 Bed, at the base of the Stair Hole Mbr to the surface 3 times on the foreshore in
355 a non-cylindrical, gently doubly plunging, fold pair (Fig. 9).

356 The folds are defined by resistant limestone beds interbedded with
357 recessive shales and are planed horizontally at about modern mean sea level in
358 the cove. The stratigraphy generally dips north at about 40°-50°, except where
359 the fold pair causes gentle to moderate south dips (Fig. 9). The syncline is
360 concave-up, and pinches out abruptly in the west, forming semi-circular bed
361 outcrops. The narrower anticline also tips out where the syncline terminates,
362 apparently leaving uniformly north-dipping strata across the bay towards the
363 Lulworth Crumple in the west (Fig 8A). The syncline is upright, whilst the
364 anticline is broadly north-vergent. The folds are parallel (i.e. layer thickness is
365 preserved), and this may be accomplished by flexural slip along the shale
366 interbeds. Similarly, the abrupt termination of the fold along a thick recessive
367 layer in the north may result from bedding-parallel shearing in shales. The
368 curvature of the exposed beds around the western tip of the syncline
369 demonstrably indicates an easterly plunge, while sixty-nine bedding
370 measurements taken along four profiles across the fold indicate a statistically
371 horizontal to very gently west plunging hinge line – suggesting that the fold is

periclinal. The structure is cut by at least one broadly N-S trending minor fault, smaller than could be observed on either MBES or seismic data.

Less spectacular, but more common, are gentle open, upright folds seen in vertical cliff sections in Durlston Bay (Fig. 8B) and in Bacon Hole, Mupe Bay (Cope 2012, Fig. 68). The former have wavelengths of a few hundred metres and limbs dipping to the north and south at between 5° to 12°. There are no outcrops indicating the plan-view of these folds; however a strongly 3-dimensional fold has been described from nearby Peveril Point (see above; Geological Setting- Folds).

All the tight, non-cylindrical periclinal folds and the upright open folds are recorded from the more steeply dipping northern limb of the Weymouth and Purbeck anticlines close to the inverted faults. None are seen on the gently dipping southern limb that is extensively exposed in cliffs and quarries on the Isle of Portland.

Subsurface analogues

Despite some processing problems with the seismic data (see above Methods- *Subsurface Data*) stratigraphic and structural features can be identified within the Purbeck Lst Gp, particularly in the shallow subsurface to the southeast of the area where it occurs below the subcropping Wealden Group. The top of the Portland Gp shows erosional truncation whilst the base of the Purbeck Limestone Gp. shows clear evidence of onlap and infilling of preexisting topography of the top Portland surface (Fig. 10 A,B). This indicates an unconformable relationship between these two units that has not been recognised in previous outcrop based studies (*cf.* Townson 1975; Coe 1996).

Subsequent to the onlap surface the Purbeck Gp reflectors are concordant and follow the regional SE dip in the study area. The Purbeck Gp is seen to thicken towards the east and the southeast in agreement with outcrop and borehole data (West, 1975; Westhead & Mather 1996). The overlying Wealden Gp clastics locally show large-scale clinoforms and downlap surfaces and thickening towards the east and southeast. One example of an isolated convex-down structure is observed in an east-west line within the upper part of the Purbeck Gp (Fig. 10B). This is underlain by and passes laterally into essentially horizontal concordant reflectors and the structure climbs through the upper Purbeck stratigraphy. Although nearing the limit of resolution and with an unknown plan-view morphology this structure is consistent in size and morphology with a cross-section through a concave-down, or dome-shaped circular structure.

Associated with the faults in the area are numerous minor folds (Fig 10) that have wavelengths that overlap and exceed the size of the circular structures. These occur as folds within areas of the Purbeck Gp with the regional dip and away from faults but more commonly occur adjacent to the steeply dipping Group N-S and NW-SE faults within the area. The latter are interpreted as compressional, buttress folds related to Cenozoic inversion in the area (*cf.* Sanderson *et al.* 2017) and the former are buckle folds related to north-south compression of the same age.

Within the seismic data none of the criteria commonly associated with evaporite seismic facies (i.e. chaotic), or diapiric structures with associated stratigraphic thinning and arching, have been seen (Warren 1996). This applies to the Purbeck Gp interval as well as to the deeper post Triassic sections.

422

423 **Interpretation of circular structures**

424 *3-D modelling*

425 To understand the 3-D morphology of these structures it is useful to envisage
426 the simplest interpretation of their form as a series of parallel beds overlain by a
427 concave-down hemispheric body that is then tilted and truncated (eroded)
428 horizontally at various levels (Fig. 11). The plan-view morphology of the tilted
429 strata and the truncated dome is controlled by the angle at which the flat surface
430 of the dome is tilted (i.e. the regional dip of the strata) and the level at which the
431 dome is truncated (i.e. the amount of erosion). As such, changes to these two
432 variables can lead to a variety of outcrop patterns in plan or oblique view (Fig
433 11) that resemble the basic morphology of the circular structures imaged on the
434 sea floor. However, when applying this to the structures observed within the
435 MBES dataset, only two of these variables can be measured. These are the size
436 of the structures and the amount of present-day dip and strike that can be
437 extracted from the slope raster. However the latter metric cannot always be
438 reliably measured, despite the precision of the data, due to the variable and
439 irregular erosion of dip and scarp slopes on the sea floor (Fig. 5).

440 Physical models were constructed from layered and carved plasticine to
441 further understand the likely 3-D morphology from the MBES plan-views (Fig.
442 12). Three geometric scenarios were modelled:

443

- 444 a) Parallel layered gently dipping strata overlain by a hemispheric body with
445 its flat lower surface parallel to regional dip, itself overlain by further
446 layered strata. When a horizontal plane is carved through the tilted

model, the distinctive omega subcrop geometries with oldest strata in the core are formed (Fig. 12A).

b) A periclinal fold plunging down-dip and detached above parallel layered gently dipping strata, and overlain by further layered strata. When a horizontal plane is carved through the tilted model, the omega stratal geometry is approximated, but a circular, dome-shaped, core cannot be replicated (Fig. 12B).

c) Simple, parallel layered gently dipping strata. When an irregular plane is carved through the tilted model, leaving an erosional remnant, or monadnock, omega and circular stratal geometries are formed (Fig. 12C). In this case, the youngest strata form the raised core to the structure and to form a central circle in plan-view. Deep incisions have to cut around the structure to generate this outcrop pattern as is seen in circular structure No. 27 (Fig. 6). However, in this example a dome-shaped core of older strata is imaged.

From this simple modeling it is concluded that the simplest explanation of the circular structures is that concave-down, dome-shaped features are formed within a parallel bedded stratigraphy.

Hypotheses for origin

From the occurrence of the circular structures and our seafloor mapping it is found that they are restricted to the Stair Hole Mbr of the Purbeck Limestone Group and that they are cut by Cenozoic faults. They occur on the gently dipping southern limb of the Purbeck anticline and are not seen in the steeply

dipping northern limbs in the MBES data, or in outcrops. In their simplest form they are concave-down, dome-shaped features formed within a parallel bedded stratigraphy. Within the offshore NE-SW subcrop they only occur in a band whose western limit is a line south from Kimmeridge Bay and its eastern limit extends to a line drawn south from Durlston Bay (Fig. 4).

A large number of plan-view circular structures have been described from sedimentary successions (Stewart 1999; Burgess *et al.* 2013). The size and geometry of some of these structures can be used to discount them as possible analogues for the structures in Weymouth Bay. Impact structures are generally too large at kilometres to 10s of km across and have a chaotic internal structure of breccias etc. Diatremes, again of similar size, can also be discounted for the same reasons and, in addition, there is no known volcanism within the Wessex Basin. The latter observation and their size and concave-up geometry of back filling also discounts circular volcanic calderas. Gas chimneys and dolines, although circular in plan and of a similar size range, generate concave-up structures and do not commonly preserve a layered or domed stratigraphy in their cores. Carbonate build-ups/mounds, periclinal folds or diapirs (evaporite or shale) are all possible interpretations based on the size, geometry and the occurrence of these structures within the Wessex Basin and these are discussed in detail below.

Carbonate Mounds. Mounds or carbonate buildups possess many of the morphological features of these circular structures. The term mound, as opposed to the more general term buildup (*cf.* Bosence & Bridges 1995) is preferred here because mounds are known to occur within non-marine

successions whilst buildups with in-situ frameworks (i.e. reefs) are rare in non-marine settings. Mounds arise from parallel-bedded strata to form a (commonly massive) core with outward radially dipping flank strata that thin into intermound areas. Intermound strata either onlap, or interdigitate with, the mound margins and thin onto the mound (e.g. Monty *et al.* 1995). Overlying strata, or overburden, may also thin over the mound, dip radially away from the mound and may eventually infill the intermound space to return to the regional bedding. Examples of carbonate mound morphology, sedimentology and palaeoecology are published in Monty *et al.* (1995), Kiessling *et al.* (2002) and Bosence *et al.* (2015) and the Ω -shaped circular structures conform to the above characteristics if they were to be sliced obliquely (Figs 11-12A).

In terms of size Phanerozoic marine mounds vary from 10 m to 7 km wide (average 805 m) to 2 – 300 m high (av. 91 m). The global review by Kiesling *et al.* (2002) gives Phanerozoic reef (including mounds) thicknesses as 20 – 140m. Non-marine carbonate buildups (Mesozoic to Quaternary) vary in size from 1-130m wide (av. 63m) to 4-25m high (av. 15m) in papers in Bosence *et al.* (2015). At 27-147 m across the circular structures are within the global field for mounds and also similar to the recorded range for non-marine carbonate mounds. The interpreted environment for the Stair Hole Mbr is consistent with the occurrence of non-marine carbonate mounds.

The restricted east - west occurrence of the circular structures within the NE - SW trending subcrop is understandable if these features are mounds. Non-marine carbonate mounds are commonly depth restricted in their occurrence in lacustrine settings. From regional palaeogeography it is known that more basinal environments occurred to the east and that the palaeo-shoreline lay to

west and to the north of the Purbeck fault within the study area (Casey 1963; West 1975). If the mounds were only forming in intermediate water depths (e.g. Lake Tanganyika, Cohen & Thouin 1987) this could explain their absence in subcrops to the east (too deep) and the coastal outcrops to north, near the sub-basin bounding Purbeck fault, and to the west (too shallow).

Arguments against a mound origin for the circular structures are that, despite the extensive coastal and quarry outcrops in the study area there are no known mounds in the Stair Hole Mbr, or indeed, in the Durlston Fm. The coarse molluscan rudstones of this member are all parallel bedded at outcrop and do not form biogenic or physical bedforms as has been described, for example, from the Middle Jurassic of Dorset (Palmer 2006). However, microbialite mounds are known, albeit of smaller size (<20m width and <4m high), in the underlying basal parts of the Purbeck Lst Gp (Gallois *et al.* 2016) and these are within the global size field for non-marine carbonate mounds. Microbialites with centimetre to decametre-scale morphology do occur in outcrops of the upper Purbeck Lst Gp (see above) but they are not mound forming.

Periclinal Folds. Folding may also generate sub-circular structures in plan-view as, for example, in the Poxwell and Chalbury periclinal folds near the inverted Ridgeway Fault (Fig. 1; Arkell, 1947, House 1974, 1989). These were described by Sylvester-Bradley (1948, p. 147, Pl. 13, Fig. 16) as “perhaps the finest small scale example of a dissected pericline in the country” when viewed in aerial photographs and pieced together from small outcrops and topographical features. However, they are not well-exposed and involve thicker stratigraphic successions from the Kimmeridge Clay through to the Purbeck Lst Gp. These

periclinal folds have elliptical geometries in horizontal section with the short axis parallel to maximum stress generating kilometre-sized folds, developed in the inverted hanging wall to the Ridgeway Fault. They are, therefore, both significantly larger than the circular structures, are elliptical rather than circular in plan-view and in a different stratigraphic and structural setting.

Smaller-scale, non-cylindrical buckle folds are known from the Stair Hole Mbr of the Purbeck Gp that deform its interbedded limestones and shales. This is the same unit that develops the circular structures in Weymouth Bay. These outcropping folds are best known from the Lulworth area and their non-cylindrical nature is described above and in figures 8 and 9. The unique outcrop in eastern Lulworth cove (see above and figure 9) indicates that in plan-view such folds are highly non-cylindrical and softer shale layers facilitate flexural shearing between competent limestone layers as well as ductile flow from fold limbs to hinges. An omega morphology is developed and the fold may terminate upwards against an overlying, north-dipping, bedding-parallel fault or shale-cored shear zone. If the offshore circular structures were periclinal folds then these shale filled limbs would represent the apparent onlap seen on the MBES images (Fig. 5E). Unfortunately the entire fold in eastern Lulworth Cove is not exposed so its complete plan-view morphology cannot be assessed and it may well have the common elliptical shape of other periclinal folds in plan-view. When compared with the circular structures the folds therefore have a similar size, are in the same stratigraphic unit and have some morphological features that are comparable. Open buckle folds with more gently dipping limbs similar to the circular structures are also seen in 2-D quarry and cliff sections in the

Durlston Fm of the Purbeck Lst Gp. (Fig. 8B) where limestone-shale alternations are common, however their shapes in plan-view are not known.

Folds are seen on the 2-D seismic reflection profiles from the area but these are invariably associated with faults or are typically present as a fold pair, or a series of anticlines and synclines rather than occurring as isolated structures separated by strata with a regional dip (Figs 4, 5). The folds seen at outcrop and in seismic sections cannot be proven to be sub-circular in horizontal section and other outcrop analogues, and minor folds associated with the Purbeck anticline have typical elliptical plan-view sections rather than circular geometries (Figs. 1, 4; Sanderson *et al.* 2017, Fig. 4). If the circular structures were periclinal folds, underlain by SE dipping, bedding parallel faults, and plunging down-dip on the SE limb of the Purbeck Anticline then a similar omega-shaped structure could be developed. However, this would not generate a circular, dome-shaped core and no NE-SW compressive event is known in the area despite many structural studies (e.g. Sanderson *et al.* 2017 and refs therein).

Diapirs. These commonly form sub-circular structures in plan-view and can form from the mobility of evaporites or mudrocks soon after burial or during subsequent extensional tectonics. Despite the occurrence of the Kimmeridge Clay underlying the circular structures, mud diapirs are considered unlikely as they are not known to penetrate thick units of early lithified limestones such as the overlying Portland Stone and Purbeck Lst units. No such structures are seen in the seismic profiles examined in this study. Evaporites are known in the study area both within the Purbeck interval and also deeper within the Triassic. If the

diapirs are early evaporite-cored structures forming a positive feature on the sea-floor then marginal onlapping beds could be generated (Warren 1999). Onlap and outwardly radiating dips would be generated by diapir movement as seen in the active diapirs of Miocene salt in the southern Red Sea (Davison *et al.* 1996; Bosence *et al.* 1998). If tilted and eroded horizontally, syn-depositional diapirs could generate the distinctive omega morphology of the Weymouth Bay structures.

Salt diapirs have subcircular horizontal sections that are commonly kilometres in diameter. Trusheim (1960) gives diameters of salt stocks in Germany to range from 2 - 8 km and Stewart (1999) 1 – 5 km. Smaller, near surface diapirs of Miocene salt in the Red Sea range from 0.5 – 4 km (Davison *et al.* 1996; Orszag-Sperber *et al.* 1998). The latter authors describe and illustrate obliquely eroded horizontal sections at Wadi Iglat and Wadi Um Greifat through outwardly dipping “domes” that show plan-view circular structures (0.5 - 1 km diameter) with omega morphologies and laterally onlapping strata. The latter is developed in Pliocene shallow marine sands and limestones and is considered to be underlain by salt (Orszag-Sperber *et al.* 1998). Kilometre-scale, dome-shaped morphologies are also imaged in 3-D seismic reflection data (e.g. Stewart 1999; Al-Fahmi *et al.* 2014). Therefore syn-depositional or early post-depositional diapirs that were tilted and eroded horizontally in the Cenozoic could generate the distinctive omega morphology of the Weymouth Bay structures.

Evaporites are known to occur in this western area of the Wessex Basin at two stratigraphic levels; in the lower Purbeck Lst Gp (West 1975) and at greater depth, in the Triassic (Buchanan 1998). Triassic sourced diapirs are

considered unlikely as salt basins are thought to occur to the south and to the north of the study area, but not within it (Buchanan 1998) and none are seen penetrating through the Mesozoic stratigraphy of the study area in our grid of seismic data. Similarly, it is difficult to envisage why diapirs arising from Triassic levels would only penetrate the Durlston Fm and not other units. Similarly, no diapiric structures within, or arising from, the lower Purbeck evaporites are seen on the seismic profiles studied even though the extensional setting of the Purbecks would be conducive to halokinesis (Warren 1999).

Further arguments against the circular structures being evaporite diapirs (apart from their small size and apparent absence on seismic profiles) are that none are seen at outcrop and although it is known that the evaporites thicken into the basin to the east (West 1975) the circular structures disappear in this direction. The circular structures are restricted to a north-south band between Kimmeridge and Durlston bays within the arcuate Purbeck subcrop (Fig. 4). In addition, if the circular structures were diapirs then it would be a remarkable coincidence if they were all eroded to essentially the same level to reveal layers of concave-down stratified overburden but never a homogenous, or dissolved out evaporite core. Finally, it is well known that diapirs are most commonly formed of halite because of the buoyancy generated by its low density in relation to cover rocks, in this case cemented limestones and shales. The Purbeck evaporites comprise sulphate salts in places interbedded with limestone (West 1975; Abbot *et al.* 2016). Sulphate salt diapirs are known (e.g. de Ruig 1996; Hoyos *et al.* 1996) but are not considered to be suitable analogues for the Purbeck structures. Despite a similar tectonic setting the Triassic diapirs of the Prebetics of Spain with deposition in an extensional basin followed by Cenozoic

compression (de Ruig 1996) sulphate diapirs are closely related to existing folds and faults as penetrating decollement structures during Cenozoic inversion. As such, they are kilometre-scale lenses elongated parallel with the regional structural trend. Because of the high density of the original evaporite mineral (anhydrite) they do not owe their origin to buoyancy as in classic tear-drop shaped halite diapirs but to their low viscosity. Hydration diapirs formed from the hydration of anhydrite to gypsum are also inappropriate analogues as these are basin scale (10-30 km across) positive features relating to the former presence of playa lakes (Hoyos *et al.* 1996).

D'el-Rey Silva (2001) interprets domed features within the lower Caps and Cypris Freestones of the Lulworth Fm as being associated with evaporites and to be of diapiric origin. Extensive petrographic work on these dome-shaped structures indicates clearly that they are biogenic carbonate mounds (see above and Fig. 7) constructed by a microbial framework (West 1975; Bosence 1987; Gallois *et al.* 2017). In addition, these mounds occur below the evaporite horizons and not above them and so could not have been influenced by the overlying evaporites. The diapiric origin of these structures is also strongly discounted by West (2017).

Erosional remnants or monadnocks. Erosional remnants, termed monadnocks, inselbergs, or yardangs can form circular or omega-shaped positive relief outliers topographically above an eroded landscape (Fig 12C). Present day yardangs (Goudie, 2007) showing spectacular geometries similarity to the circular structures of Weymouth Bay are well developed in the Qaidam Basin, China, where they are spaced every few hundreds of metres and have

tens of metres of relief (Kapp et al. 2011). Pronounced bedding and gentle stratal dips in the Qaidam examples produce concentric sets of circles as observed in the north east of the studied area in Weymouth Bay.

However, the Weymouth Bay structures all show evidence indicating horizontally truncated domed strata (Fig. 10) with oldest strata in the centre (inliers) and, as such this is not an origin that can account for the circular structures described in this paper.

Discussion and Conclusions

Out of the four origins discussed above their formation as erosional remnants into gently tilted strata can be discounted but the other three mechanisms all have evidence both for and against as a viable mechanisms for their formation. To help resolve this issue a semi-quantitative analysis of the geological setting and morphological features of the circular structures is presented (Table 2) that assesses how likely any of the four possible origins are as a formative mechanism. This analysis derives from the semi-quantitative analysis of the different origins of “bumps” imaged in seismic sections by Burgess *et al.* (2013). For each of 25 geological and morphological features of the circular structures a numerical score from 0 to 4 is given on the basis of how good the evidence is that any of the three possible mechanisms could have formed the circular structures (with 0 being a very unlikely explanation for a feature and 4 being a very likely, or definite positive explanation, for details see Table 2). The 25 features of the circular structures that have been considered are assessed in 4 different ways based on 1) their basinal setting (e.g. stratigraphic and palaeo-environmental setting, spatial distribution and structural setting), 2) whether or

not they have analogues, either globally, or, within the Purbecks, and finally morphological features that can be seen in either 3) vertical sections or 4) in plan-oblique sections. By way of comparison their origin as erosional monadnocks is also tabulated together with the locally outcropping lower Purbeck carbonate mounds and periclinal folds of the Lulworth Crumple using the same semi-quantitative scoring (Table 2). This scoring assesses how well the outcrop data support the published views as to the origin of these mounds and periclinal folds based on the same chosen 25 criteria used for assessing the circular structures.

As there are 25 assessed features and the highest score for each feature is 4 the possible total score is 100 (*i.e.* a percentage) if all the criteria were seen and scored a definite positive explanation for the origin of the circular structure. This score is never reached, even for the known outcropping examples because even the outcropping examples do not allow all features to be assessed. However their scores are relatively high at 90% for the Mupe Member mounds and 93% for the Lulworth crumple periclinal folds.

For the circular structures of this paper, diapirs are the least likely mechanism (68%), then periclinal folds (79%) and finally, carbonate mounds, are considered, from this analysis, to be the most likely mechanism (94%) that could lead to the formation of the circular structures. Monadnocks score the lowest (45%) as a mechanism that would account for the origin of the circular structures thus supporting the qualitative assessment above.

Further, detailed analysis that is beyond the scope of this paper may result in the removal of one or more of the three hypotheses for their origin. Diver collected samples along transects across the structures have been

considered, as samples from central areas could indicate an evaporitic core or a carbonate mound core. However, this has been rejected because of the water depth, strong tidal currents (short diving times) and poor visibility in the area (and a recent diver fatality on one of the preferred sites). Seabed photographs from the area (DORIS 2017) over circular structures indicate that meaningful geological observations would be difficult as they show rich eipilithic communities and a shallow covering of sand, gravel and pebbles. In addition, the samples retrieved may not resolve the origin if they come from overburden strata and not the defining lithologies from the core of the structure of either evaporite diapirs or carbonate mounds. Periclinal folds would have no defining lithologies but may have visible minor structures. Shallow drilling is considered to be more likely to resolve the issue as it would differentiate between an evaporite or a carbonate mound core, or neither of these two lithologies that would support a periclinal fold. However, it could also mean that the core had been missed by drilling. Position fixing over such small structures in an area of strong tidal currents would be challenging as would permission to drill as the area is a Marine Special Area of Conservation and we view this solution as beyond the scope of the current paper.

Implications

If the structures are mounds, as is suggested by the evidence presented in this paper, then these are previously unrecorded from the Stair Hole Mbr and the Durlston Fm of the Purbeck Limestone Group. As mentioned above, microbialite facies are found within the Durlston Fm but these have not been observed to be mound forming. However the occurrence of mounds within the

746 interpreted palaeoenvironment of this member would not be remarkable. If this
747 interpretation is correct then they would be the largest mounds, by an order of
748 magnitude, known within the Purbeck Gp and would explain the mounded
749 seismic geometries seen in this unit an east to west seismic section from the
750 study area (Fig. 10B). Because of the economic significance of carbonate
751 mounds within non-marine carbonates in extensional basins of this age in the
752 South Atlantic (Bosence *et al.* 2015) the discovery of large-scale mounds in the
753 Wessex basin may be significant. Their occurrence in intermediate water
754 depths would have implications for establishing facies models or mound spacing
755 in subsurface exploration for hydrocarbons in the south Atlantic, or in the
756 Wessex Basin.

757 If the structures are folds they must be considered either syn-depositional
758 structures or tectonically driven, either related to the Late Jurassic-Early
759 Cretaceous extension or to Late Cretaceous-Cenozoic inversion. Given the
760 lagoonal depositional environment and likely early diagenesis, gravity-driven
761 syn-depositional folding is unlikely. Nor do the structures propagate vertically
762 into surrounding strata, making extensional fault propagation folding an unlikely
763 scenario. If they are inversion-related folds, their NW-SE orientation is at odds
764 with the regional trend of major Alpine-related structures in the southern UK,
765 which formed in response to N-S compression. While Atlantic and Tethyan
766 opening have also been considered as driving factors for inversion in NW
767 Europe (e.g. Underhill & Patterson, 1998; Vandyke 2002), it would be surprising
768 if these processes formed strata-bound minor folds of the kind documented
769 here. They also occur on the southern, gently sloping limb of the Weymouth,
770 Purbeck and Durlston anticlines, where such folds have not previously been

771 recognised. The occurrence of tight, non-cylindrical buckle folds on the steeply
772 dipping northern limb has been related to footwall buttressing and antithetic
773 reverse faults related to inversion on the Purbeck fault (Sanderson *et al.* 2017).
774 However, if similar, highly non-cylindrical folds are found in gently dipping strata
775 many kilometres away from the Purbeck fault then décollement along
776 interbedded shales and shale deformation in the long limbs of the folds needs to
777 be a significant process in the generation of these folds (*cf.* Sanderson *et al.*
778 2017).

779 If the circular structures are interpreted as diapirs arising from the lower
780 Purbeck evaporites, then these would be the first diapiric structures to be
781 recognised in this unit. Although thick sulphate salts are known deeper within
782 the basin in the central Weald (West, 1975, Abbot *et al.* 2016) there are no
783 reported diapiric structures in this area. Similarly, diapiric structures in the
784 literature generated by sulphate evaporites form structures that are of a different
785 scale and morphology to classic cylindrical halite diapirs. Anhydrite, the primary
786 evaporite mineral within the Purbeck strata would be denser than the overlying
787 cemented carbonates and therefore the mechanism for diapir formation could
788 not be buoyancy. Formation of diapiric structures through low viscosity, fault
789 related injection, or volume increase through hydration to gypsum by Early
790 Cretaceous meteoric waters are possible mechanisms but are not known to
791 form simple cylindrical diapirs that would generate circular structures in plan-
792 view. Migration of halite from Triassic evaporites remains a possibility but
793 evidence for this has not been seen in the studied seismic sections from the
794 study area. For these reasons an origin for the circular structures as evaporite
795 diapirs is the least likely interpretation.

Conclusions

From an analysis of MBES data it is clear that the circular structures on the floor of Weymouth Bay are essentially truncated domes, with concentric layers of outwardly dipping strata giving an overall concave-down, morphology. The structures only occur within the Stair Hole Member of the Purbeck Limestone Gp, a unit of alternating limestones and shales with minor evaporites. Strata overlying the domes show thinning over their crests and thickening on their flanks. Their size and geometry can be used to discount some hypotheses for their origin; impact structures are generally too large at kilometres to 10s of km across, whereas gas chimneys and dolines, although circular in plan, are concave-up structures and do not preserve a layered stratigraphy in their cores. Carbonate build-ups/mounds, periclinal folds, evaporite diapirs or erosional remnants (monadnocks) are all possible interpretations and are explored in this paper.

The geological setting and morphological features of the circular structures, as imaged in MBES and commercial seismic data, are tabulated and scored to assess their similarity to carbonate build-ups, folds, diapirs or monadnocks (i.e. erosional remnants). This provides semi-quantitative data to discriminate structures formed by these four, very different, geological processes. From this, it is interpreted that the circular structures are most likely to be carbonate mounds, then periclinal folds, and least likely to be diapirs. Monadnocks are discounted on the basis of their internal structure. No structures formed by the three remaining mechanisms have been previously reported from this stratigraphic interval or from this area. If the structures are carbonate mounds then this work improves current models for the spatial and stratigraphic distribution of mounds within lacustrine deposits that are used in

subsurface exploration in the south Atlantic (Bosence *et al.* 2015). If they are periclinal folds related to Cenozoic Alpine shortening in the area this demonstrates a far wider occurrence of inversion folding that is currently only recorded adjacent to major inverted, south-dipping faults (Sanderson *et al.* 2017). Should they prove to be formed by salt diapirism then this indicates a far wider occurrence of Triassic and/or Purbeck evaporites than is currently understood.

Confirmation of these interpretations could only come from extensive and precisely located shallow drilling that is beyond the scope of the current study.

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Figure Headings

Fig. 1. Locality map, geological setting and data used in this study. A) MBES image of Weymouth Bay with interpreted sea floor geology constrained by coastal outcrops, seafloor bathymetry, seismic sections and grab samples. B) Map indicating locations of seismic sections studied (those illustrated in this paper indicated Fig. 10A etc), wells within area (those used for tying stratigraphy to seismic reflectors are numbered), and grab samples (from Donovan and Stride 1961). C) Rose diagram with 70 fault orientations (from 1A) binned at 10° intervals. D) Examples of three circular structures (Nos. 5 and 6) imaged from MBES data from centre of study area (Location indicated with star in 1A, central circle of structure bottom centre about 150 m across, depths in metres).

Fig. 2. Lithostratigraphy of study area with stratigraphic position of mapped units and marker beds. Stratigraphic occurrence of circular structures shaded in grey. Lithostratigraphy after Westhead and Mather (1996).

Fig. 3. Tying coastal outcrops to MBES data in Durlston Bay. A) Photograph view east to Peveril Point indicating resistant limestone ledges in the Durlston Formation of the Purbeck Limestone Group striking offshore (CB=Cinder Bed, UBS= Upper Building Stones, BSL= Broken Shell Limestone, PM= Purbeck Marble). B) and C) Un-interpreted B) and interpreted C) images of merged aerial photograph and MBES data to indicate match between coastal outcrops (3A) and prominent seafloor ridges. Also seafloor trace of normal fault striking offshore from zig-zag path fault.

1042

1043 **Fig. 4.** Seafloor bathymetry from MBES data for the study area (for location see
1044 Fig 1) with locations of studied circular structures (numbered as per Table 1).
1045 Marker beds within Durlston Fm of the Purbeck Limestone Gp have been mapped
1046 from Durlston Bay, around Purbeck Anticline and into area of circular structures
1047 (cf. Fig. 3). Dips and strikes measured at coastal outcrops. Inset shows detail of
1048 cluster of circular structures Nos. 5-9 and seafloor bathymetry in metres. CB-
1049 Cinder Bed, UBS- Upper Building Stones, BSL- Broken Shell Limestone, and PM-
1050 Purbeck Marble.

1051

1052 **Fig. 5.** Circular structures with concave-down dome, or omega, morphology. A-
1053 D) circular structure (No. 10) in centre of study area showing A) grey scale
1054 bathymetry; B) coloured slope raster in degrees; C) aspect raster showing
1055 compass direction of maximum slope direction; D) Interpretation. E) Circular
1056 structures (Nos. 3, on the left and 4, on the right) viewed with bathymetry raster
1057 (water depths in metres) with cross section (X-X') as viewed in Fleidermaus
1058 software indicating bathymetric profile. Note saw tooth nature of profile with
1059 gentler SE dipping slopes interpreted as dips of strata and negative erosion of
1060 circular structure 4 creating a 1-2 m deep hollow.

1061

1062 **Fig. 6.** Circular features (Nos. 23, 25, 26-centre left to right, 24-lower left, 27-
1063 lower right) with more irregular morphologies, but all with concave-down, dome-
1064 shaped cores, eroding as positive features on the sea floor. Note folding
1065 associated with N-S fault on left of image. Shallow, elongate structure in centre of
1066 image is the wreck of the SS Kyarra (126 m long) that was sunk in May 1918.

1067

1068 **Fig. 7.** Photograph of exhumed plan-view of carbonate mounds within the Mupe
1069 Member of the Purbeck Limestone Group. Bedding plane dipping northwards
1070 towards viewer on top of Hard Cap in Lulworth Fm. East Point, Lulworth Cove.

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1072 **Fig. 8.** A) Photograph of northerly verging buckle folds (Lulworth Crumple) in
1073 Purbeck Limestone Gp at Stair Hole (looking east) with location of Fig. 9 (boxed)
1074 on east side of Lulworth Cove (CB=Cinder Bed). B) Open, upright, east to west
1075 trending (080-088°) minor folds in Durlston Fm, Durlston Bay (person near fold
1076 axis for scale).

1077

1078 **Fig. 9.** Structural data for fold pair exposed in intertidal wave-cut platform on east
1079 side of Lulworth Bay (located in Fig. 8 A with box). Cross sections based on
1080 measurements of dip and strike along 4 profiles (A – D) and poles to bedding
1081 stereonet of dip and strike readings (see text for details).

1082

1083 **Fig. 10.** Seismic profiles showing stratigraphic and tectonic features of Portland
1084 and Purbeck groups within study area (location of lines see Fig 1). A) N to S
1085 profile within eastern Weymouth Bay showing onlap of the Purbeck Limestone
1086 Gp. on the Portland Gp. B) E to W profile showing erosional truncation below
1087 upper surface to the Portland Gp and onlap at the base of Purbeck Limestone
1088 Gp. Note possible circular structure in Purbeck Gp 1 km from eastern margin of
1089 profile and minor folds associated with steeply dipping NW to SE (Group 2) fault.
1090 C) N to S profile showing thickening of the Purbeck Limestone Gp. in hanging-

1091 wall fault blocks indicating extensional syn-rift setting. Buttress folds adjacent to
1092 fault indicate inversion of faults during the Alpine compression event.

1093

1094 **Fig. 11.** Graphical cross sections of circular structures and plan views of stratal
1095 geometries. With increased erosion of a dome tilted by 10° towards the SE
1096 (similar to the overall regional dip in the DORIS survey) the eroded plan-view of
1097 the dome is firstly circular and then semi-circular. The surface area of the dome in
1098 eroded map view also decreases and once erosion passes the centre of the circle
1099 on the base of the dome (e.g. d-d') no internal concentric rings of strata can be
1100 preserved and the distinctive omega shaped geometry is seen.

1101 **Fig. 12.** Sketches drawn from plasticine models of layered strata tilted 12 degrees
1102 to right and truncated horizontally. A) basal parallel thickness layers (green to
1103 orange with hemisphere (light and dark brown), overlapped by parallel thickness
1104 layer (red) and draped over by final 3 parallel thickness layers (pink to blue). The
1105 structure develops the omega geometry with a circular core and overlapping strata.
1106 B) Original parallel layered stratigraphy (green to blue) deformed into a down-dip
1107 plunging fold generating omega structure but no circular core. C) Parallel layered
1108 stratigraphy (green to blue) sculpted to leave a central circular outlier of younger
1109 strata surrounded by older.

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Tables

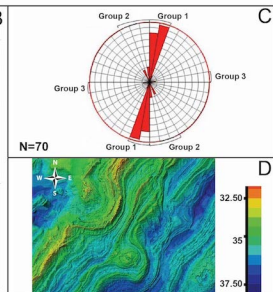
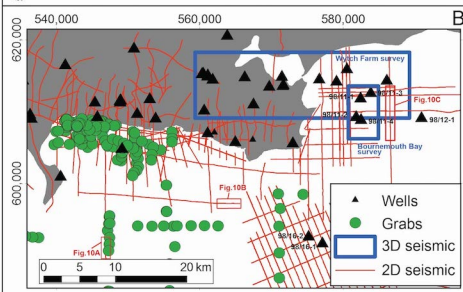
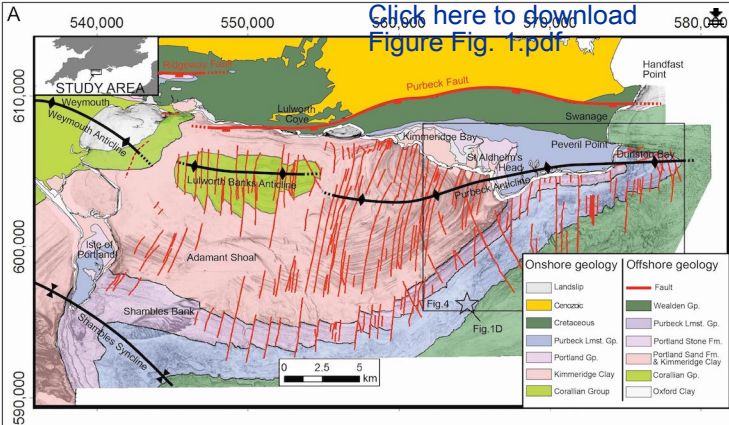
Number	UTM_E	UTM_N	Diameter (m)	Nearest Neighbour (m)
1	562290	594437	57	360
2	562331	594058	95	382
3	562644	594517	117	360
4	563042	594386	134	420
5	564824	596056	118	450
6	564589	596426	147	450
7	565317	597169	76	150
8	565463	597133	120	150
9	565766	597601	61	560
10	566471	598371	133	370
11	566829	598090	81	450
12	566800	598529	55	370
13	568755	599735	120	350
14	568899	600224	63	515
15	568939	599442	101	350
16	570042	601132	93	330
17	570192	601428	95	330
18	572040	603054	52	1065
19	572066	602656	95	420
20	573096	603246	99	264
21	573363	603238	110	264
22	573430	602832	86	422
23	574377	603818	30	169
24	574471	603503	34	327
25	574545	603814	33	169
26	574819	603819	27	236
27	574894	603600	128	236

Table 1. Locations, sizes (measured as diameter of largest circle that can be fit within imaged structure) and distance to nearest neighbouring circular structure.

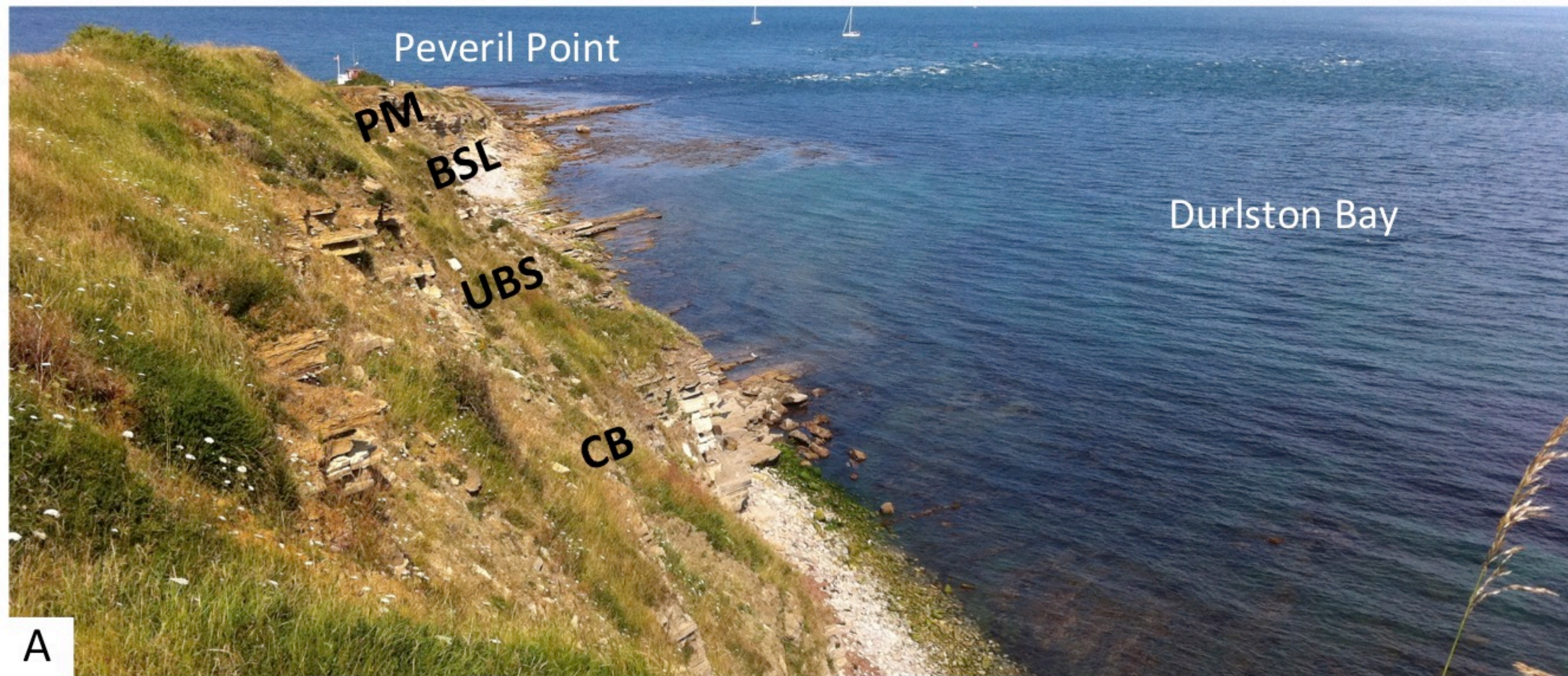
Table 2. Semi-quantitative scoring of basinal setting and morphological features of circular structures as indicative of carbonate mounds, folds or diapirs, or monadnocks (0=Definite negative, 1=Weak negative, 2=Criterion cannot be assessed, 3=weak positive, 4=Definite positive. (i.e. a score of 4 in the mound column for a particular feature indicates that this is a definite positive feature for a carbonate mound). The last two columns use the same scoring system for well-studied, outcropping examples of lower Purbeck carbonate mounds and for folds within the Lulworth Crumple. For more detail see text.

Table 2

Stratigraphic and Morphological features			Mounds	Periclinal Folds	Diapirs	Monadnocks	L Purbeck mounds	Lulworth crumple folds
Basinal Setting	1	Stratigraphic occurrence consistent	3	2	3	2	4	4
	2	Palaeo-environmental setting	4	2	3	2	4	4
	3	Spatial distribution consistent with r	4	3	3	3	4	4
	4	Structural setting	3	3	3	3	4	4
Outcrop/subsurface	5	In Purbecks	3	3	0	0	4	4
	6	Global	4	3	3	4	4	4
Features imaged in vertical section	7	Domes over horizontal strata	4	3	3	2	4	4
	8	Strata thicken into dome	4	3	1	2	4	4
	9	Apparent onlap on margins of dome	4	3	4	2	4	1
	10	Strata with radial dips off the dome	4	4	4	0	4	4
	11	Overburden thinning over dome	4	3	4	2	4	4
	12	Concentric, parallel, concave-down s	4	4	1	0	4	4
	13	Related to faults	3	4	3	0	0	4
	14	Size in VS	4	4	3	4	4	4
	15	Shape in VS	4	3	1	4	4	4
Features imaged in plan - oblique view	16	Size in HS	4	4	3	4	4	4
	17	Shape in HS	4	1	3	4	4	1
	18	Omega stratigraphic geometry	4	3	3	3	3	4
	19	Domes built on horizontal strata	4	3	3	0	4	4
	20	Strata thicken into dome	4	3	1	0	4	4
	21	Apparent onlap on margins of dome	4	3	4	0	4	3
	22	Strata with radial dips off the dome	4	4	4	0	4	4
	23	Overburden thinning over dome	4	3	4	0	4	4
	24	Related to faults	3	4	3	0	0	4
	25	Layering within dome	3	4	1	4	3	4
Scores (max points 100 or 100%)			94	79	68	45	90	93



Lithostratigraphic units			Prominent surfaces mapped on sea-floor
Groups	Formations	Members	
Wealden Gp (65-1000m)			Base Wealden Gp
Purbeck Limestone Gp (46-119m)	Durlston Fm	Peveril Point	Purbeck Marble beds (PM) Broken Shell Lst (BSL)
		Stair Hole	Top Corbula Bed (TCB) Upper Building Stones (UBS) Cinder Bed (CB)
	Lulworth Fm	Worbarrow Tout	
		Ridgeway Mupe	Caps and Cypris Freestones (CCF)
Portland Gp (55-75m)	Portland Stone Fm		Top Portland Stone Fm



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