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

Many sedimentary rock successions contain plan-view circular structures such as impacts, diapirs and carbonate buildups. When remotely sensed, it can be difficult to discriminate between their formation mechanisms. Here we examine this problem by assessing the origins of circular structures imaged in high-resolution multibeam bathymetric data from Weymouth Bay (UK). The imagery shows 30-150 m across, concave-down structures within the upper Purbeck Limestone Group on the southern limb of the Purbeck Anticline. Similar structures have not been identified in the extensive outcrops around the Bay.

The morphology and geological setting of the structures are consistent with three different interpretations; carbonate mounds, periclinal folds and evaporite diapirs. However, none of these structures have been previously recorded in the upper Purbeck Limestone Group outcrops of this internationally renowned geological region. We apply a scoring system to 25 features of the circular structures to discriminate between these three alternative interpretations. This analysis indicates that evaporite diapirs are the least likely and carbonate mounds the most likely origin of the structures. The presence of carbonate mounds revises the upper Purbeck palaeofacies distribution in its type area and provides an analogue for the exploration for hydrocarbon reservoirs in lacustrine mounds.

Supplementary material detailing the methods used in this paper are available at https://doi.org/10.6084/m9.figshare.c.4103840

Plan-view circular structures that are 10s to 100s of metres across such as impact structures, evaporite or mud diapirs, isolated carbonate buildups, dolines, periclinal folds, monadnocks (erosional remnants) and gas chimneys are common geological features. 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 this problem by assessing the possible origins of circular structures imaged on the sea-floor of Weymouth Bay in the west of the Wessex Basin and presents an objective method of analysis to assess the relative merits of different possible interpretations that can be applied to other remotely sensed data.

The structures are revealed in plan-view in high-quality, one metre resolution, multibeam echo sounding data (MBES) (Fig. 1; DORIS 2017). These previously unknown 30-150 m diameter circular structures are developed in Purbeck Limestone Group limestones and shales exposed on the seafloor of Weymouth Bay. Due to thin and patchy Quaternary sediment cover, the bedrock geology is exposed across the floor of Weymouth Bay similar to a time slice from 3-D seismic data (Fig. 1). The strata within the study area comprise a succession of marine mudstones (Kimmeridge Clay Fm) and limestones (Portland Gp), followed by non-marine limestones and shales (Purbeck Limestone Gp) and then fluvial siliciclastics of the Wealden Gp. The succession is deformed by the Cenozoic-aged, en échelon Purbeck, Lulworth Banks and Weymouth anticlines and by numerous N-S and NW-SE oriented faults. The circular features subcrop (i.e. as exposed bedrock on the present-day sea floor) in an arcuate band from the very well-known outcrops of the Purbeck Limestone Gp (Purbeck Lst Gp) from Durlston Bay in the east to the Isle of Portland in the southwest (Cope 2012; West 2012, 2013, 2014). Circular structures with a similar size and morphology have not been described from the onshore outcrops in the region despite well over a hundred years of intensive geological research and the inclusion of the outcrops around Weymouth Bay as a World Heritage Site. These coastal outcrops are regarded to include the most complete sections of Jurassic to Cretaceous rocks anywhere in the world (Cope 2012).

In this study we use the MBES data to map the occurrence of the circular structures, assess their diameters, the dips and strikes of their concentrically arranged beds and their stratigraphic architecture. A detailed stratigraphic correlation to the established lithostratigraphy of the Purbeck Lst

Gp is achieved by mapping the resistant intertidal ledges from the type area in Durlston Bay to prominent seafloor ridges in Weymouth Bay. New field studies and assessment of offshore seismic sections are undertaken to assess possible analogous structures within the Purbeck Lst Gp. Finally, we perform a semi-quantitative analysis of the characteristics of the circular structures to assess potential mechanisms for their formation and conclude that they are most likely to be *in situ* carbonate mounds but that periclinal folds and evaporite diapirs are also possible mechanisms for their formation. The presence of carbonate mounds in the upper Purbeck Lst Gp revises the palaeofacies distribution in these lacustrine deposits and provides an analogue for the exploration for hydrocarbon reservoirs in non-marine carbonate mounds.

Geological Setting

Stratigraphy

Previous studies have shown that the floor of Weymouth Bay is almost entirely bedrock (Donovan & Stride 1961; Sanderson *et al.* 2017). These subcropping rocks range in age from the Late Jurassic Oxford Clay to the Early Cretaceous Wealden Gp (Fig. 1).

Recent mapping by Sanderson *et al*. (2017) based on a subset of the MBES data used in this study, showed that the onshore and offshore geology could be integrated based on seafloor mapping of the different weathering characteristics of the Mesozoic units. Shale and shale-sand units (Kimmeridge Clay, Portland Sand Fm, and shales in the Lulworth Fm) and uncemented mudstones and sands of the Wealden Gp are preferentially eroded along the coastline and also form bathymetric lows in Weymouth and Durlston bays whilst cemented limestones of the Portland Stone Fm and Purbeck Lst Gp form ridges and broader highs on the seafloor. The present-day seafloor truncates both limbs of west – east trending anticlines (Weymouth, Lulworth Banks and Purbeck) together with a prominent set of approximately N-S faults (Sanderson *et al.* 2017). 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, in our offshore mapping we include the Portland Sand Fm with underlying Kimmeridge Clay Fm as the units do not display consistently different erosional characteristics on the seafloor. As is shown later in this paper the circular structures come from within the arcuate subcrop of Purbeck Lst Gp from Durlston Bay 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). These non-marine limestones, shales and some evaporites outcrop in their type locations in Lulworth and Durlston bays along the Purbeck coast and, in part, 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), comprise well-lithified, bedded, non-marine limestones, paleosols and microbial mounds (West 1975; Bosence 1987; Westhead & Mather 1996; Gallois *et al.* 2018). 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), containing the structures studied in this paper, comprises a lower Stair Hole Mbr (Shelly limestones interbedded with mudstones) including the Cinder Bed and Upper Building Stones (West 2013) and an upper Peveril Point Mbr (coarse grained shelly limestones and mudstones) including the Broken Shell Limestone and Purbeck Marble beds (West 2014). The Cinder Bed can be traced as a distinctive horizon from Durlston Bay to outcrops in the west.

Structure

Folds. The MBES data provide a plan-view of the Purbeck, Lulworth Banks and Weymouth anticlines (Fig.1) 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. These anticlines have shallow dipping southern limbs (consistent with 1-2^{o} dips on the Isle of Portland) and steeply dipping northern limbs that are well exposed, on the coast from Weymouth to Swanage (Fig. 1; Arkell 1947; House 1989; Sanderson *et al*. 2017).

These folds result from N-S directed Cenozoic shortening and inversion of the major, inverted Purbeck Fault (Fig. 1; Underhill & Patterson 1998). 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. The Purbeck units contain layering with high mechanical anisotropy and so readily form complex minor folds as 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 thrusted fold pair. The anticlinal core has radially outward dips that form a "bulge structure" so that individual beds (e.g. 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 that cut through all of the stratigraphic units in the area (Fig 1; Donovan & Stride 1961; Sanderson *et al*. 2017). 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 (Sanderson *et al*. 2017).

Harvey & Stewart (1998) also identified NW-SE and NE-SW conjugate strike-slip faults in nearby Lyme Bay that they also attributed to latest Cretaceous to Cenozoic compression. They 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 both 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 methods to investigate the circular structures. We combine an analysis of the offshore MBES data with previously unpublished commercial seismic data, and finally onshore fieldwork focused on resistant coastal ledge-forming limestones and plan-view and vertical cliff outcrops of folds in the Purbeck Lst Gp. Details of these methods are found in the Supplementary Pages to this article. Our research is 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).

Circular Structures

Morphology

In total some 27 circular structures have been identified within the NE-SW trending offshore subcrops of the Purbeck Lst Gp (Figs 4,5 and 6). Within this subcrop the structures are only seen on the southern, gently sloping, limb of the Purbeck Anticline in a band east of Kimmeridge Bay and west of Durlston Head (Fig. 4). Dip slopes interpreted from the slope raster vary from 2-22^{o} to the SE and SSE that 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 distances between them vary from 150 to

1065 m. Individual structures may be cut by the prominent N-S faults and the minor sets of NW-SE faults that are interpreted to be Cenozoic in age (Figs 4,5). 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; Supplementary Data table).

The majority (17 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, sea-floor sections (Figs 1D, 5). These structures are underlain by SE-dipping strata with a uniform NE-SW strike producing bedding-parallel ridges on the sea floor. 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 onlap and 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 either isolated or stacked one on top of another, and at one place, stacked within three successive stratigraphic levels within the within the Purbeck Lst Gp (CS 13-15, Fig. 4). 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 1D) so the plan-view morphology of these structures is not controlled by differential erosion of gently dipping strata.

A smaller number (9 out of 27) have a subcircular to 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 - 27, Figs 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 (Fig. 6).

Lithostratigraphic correlation and palaeoenvironmental context

A prominent eastward plunging anticline is seen in the MBES data between Durlston Head and Peveril Point (Figs 1, 4). Mapping of seismic data and sea-floor bedding traces indicates that this anticline is continuous with the Purbeck Anticline to the west. The northern limb of the anticline is cut by a prominent W-E fault (Figs 3, 4) that has seafloor expression and projects onshore to the two adjacent normal faults near the Zig Zag path that repeat the Purbeck succession within Durlston Bay (Arkell 1947). The cliff and foreshore outcrops strike offshore as a series of ledges in Durlston Bay (Fig. 3) and are used to map four of the most prominent limestones in the Purbeck Lst Gp, 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 Fm and, all bar one of the structures occur between the Cinder Bed and the Broken Shell Limestone (Fig. 2). This places them within units of alternating limestones and mudstones in the upper part of the Stair Hole Mbr and the lower part of the

Peveril Point Mbr (Fig. 2).

There are no known stratigraphic features that might form plan-view circular structures within the outcrops of the Durlston Fm. This 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 deposition in a marginal marine to brackish lagoonal environment (El Shahat & West 1983). However, in the Mupe Mbr of the Purbeck Gp carbonate mounds are present that are variably developed in all outcrops from the Isle of Portland through to Durlston Head (Gallois 2016; Gallois *et al.* 2018). They form structures that are concave down, dome-shaped and with sub-circular plan-views and measure metres to 10s of metres across and decimetres to metres in height (Fig. 7; Gallois 2016). 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.* 2018). Smaller-scale laminated microbialites (stromatolites) have been observed higher in the succession in the Lulworth Fm on Portland and locally in the Durlston Formation in Lulworth and Mupe Bay outcrops but are not mound forming.

Possible analogues

Outcropping structural analogues

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

The folds are defined by resistant limestone beds interbedded with recessive shales and are planed horizontally at about modern mean sea level. The stratigraphy generally dips north at about 40°- 50°, except where the fold pair causes gentle to moderate southerly dips (Fig. 9). The syncline is concave-up, and pinches out abruptly in the west, forming semi-circular bed outcrops. The narrower anticline also tips out where the syncline terminates, passing into uniformly north-dipping strata to the west (Figs 8A, 9). The syncline is upright, whilst the anticline is broadly north-vergent. The folds are parallel (i.e. layer thickness is preserved), and this may be accomplished by flexural slip along the shale interbeds. Similarly, the abrupt termination of the fold along a thick recessive layer in the north may result from bedding-parallel shearing in shales. The curvature of the exposed beds around the western tip of the syncline demonstrably indicates an easterly plunge, while sixty-nine bedding measurements taken along four profiles across the fold indicate a statistically 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 western Mupe Bay (Fig. 1; Cope 2012). The former have wavelengths of a few hundred metres and limbs dipping to the north and south at between 5º to 12º. 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 the variable quality of the seismic data (see Supplementary material; Methods- *Subsurface Data*) stratigraphic and structural features can be identified within the Purbeck Lst Gp. The Purbeck Gp is seen to conform to the the regional SE dip and thicken towards the east and the southeast in agreement with outcrop and borehole data (West 1975; Westhead & Mather 1996). One example of an isolated convex-down structure is observed in an east-west line within the upper part of the Purbeck Gp (Fig. 10A). This is underlain by, and passes laterally into, essentially horizontal concordant reflectors and the structure climbs through the upper Purbeck stratigraphy. Although the plan-view morphology of this feature is unknown it is consistent in size and morphology with a vertical-section through a concave-down, or dome-shaped circular structure, and comes from an area where they are imaged on the sea floor.

Associated with the faults in the area are numerous minor folds (Figs 6, 10) that have wavelengths that overlap and exceed the size of the circular structures. These occur most commonly adjacent to the steeply dipping N-S and NW-SE faults within the area. The folds are interpreted as compressional, buttress folds related to Cenozoic inversion in the area (*cf*. Sanderson *et al.* 2017). Less commonly, more open buckle folds are seen away from faults that are also considered to be formed by 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 Lst Gp interval as well as to the deeper post-Triassic sections.

Interpretation of circular structures

Physical models

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

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

a) Parallel layered gently dipping strata overlain by a hemispheric body with its flat lower surface parallel to regional dip. Both features overlain by further layered strata, firstly abutting, and then draping the hemisphere. 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 surface is carved through the tilted model, leaving an erosional remnant, or monadnock, circular stratal geometries are formed (Fig. 12C). In this case, the youngest strata form the raised circular core to the structure. 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 structure No. 27 a dome-shaped core of older strata is imaged and not an outlier.

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, tilted and eroded stratigraphy. Erosional monadnocks, although forming circular structures, are outliers and not dome-shaped inliers.

Hypotheses for origin

A large number of plan-view circular structures have been described from sedimentary successions (Stewart 1999; Burgess *et al.* 2013). The size, geometry and setting 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 to the Weymouth Bay features, generate concave-up and not concave-down geometries in their cores. Carbonate buildups/mounds, periclinal folds, diapirs (evaporite or shale) and monadnocks are all possible interpretations based on their size, and circular plan-view geometry and these interpretations are discussed in detail below.

Carbonate Mounds. Mounds or carbonate buildups possess many of the morphological features of these circular structures. 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. 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 the compilations of 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 Kieslling *et al.* (2002) gives Phanerozoic reef (including mounds) thicknesses as 20 – 140 m. Non-marine carbonate buildups (Mesozoic to Quaternary) vary in size from 1-130 m wide (av. 63m) to 4-25 m high (av. 15 m) (Bosence *et al.*, 2015 and references therein). At 27-147 m across the Weymouth Bay 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 and Peveril Point Mbrs 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. Lacustrine carbonate mounds commonly occur in depth-restricted zones. From regional palaeogeography and sedimentology it is known that facies belts are orientated SW – NE within the study area, a palaeo-shoreline lay to west, and basinal environments occurred to the east (Casey 1963; West 1975). If the mounds were only forming in intermediate water depths (e.g. 20-40 m, Lake Tanganyika, Cohen & Thouin 1987) this could explain their absence in subcrops to the east (too deep) and to the west (too shallow).

Arguments against a mound origin for the circular structures are that there are no known mounds in the outcrops of the Durlston Fm. However, microbialite mounds are known, albeit of smaller size, in the underlying basal parts of the Purbeck Lst Gp (Gallois 2016; Gallois *et al*. 2018) and these are within the global size field for non-marine carbonate mounds. Microbialites with centimetre to decametre-scale morphology occur in outcrops of the Purbeck Lst Gp (see above) but they are not mound forming.

Periclinal Folds. Folds are seen at outcrops in inverted northern limbs to east-west folds and are imaged in 2-D seismic sections through the area. Periclinal geometries are seen in plan-view as, for example, in the Poxwell and Chalbury folds near the inverted Ridgeway Fault (Fig. 1; Arkell 1947; House 1974, 1989). However, they are 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 contains the circular structures in Weymouth Bay. These outcropping folds are best known from the Lulworth area and the plan-view outcrop in eastern Lulworth Cove indicates that these folds are non-cylindrical with softer shale layers facilitating flexural shearing between competent limestone layers as well as ductile flow from fold limbs to hinges (Fig. 9). Half of an omega morphology is developed in plan-view and the fold terminates northwards 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). 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 (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 fold pairs, 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). 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 Fm 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.

Salt diapirs have subcircular horizontal sections and 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). Evaporites are known in the study area both within the Purbeck interval and also deeper within the Triassic. No diapirs are seen penetrating through the Mesozoic stratigraphy from the Triassic 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 so this origin is unlikely. If the diapirs are early evaporite-cored structures arising from the Purbeck evaporites then these could have formed positive features on the sea-floor and marginal onlapping beds could be generated. 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.

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, or reported from the subsurface, and although it is known that the evaporites thicken into the basin to the east (West 1975) the circular structures disappear in this direction (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 strata but never a homogenous, or dissolved out evaporite core. Finally, 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 interbedded with limestones and shales (West 1975). Sulphate salt diapirs are known but are not considered to be suitable analogues for the Purbeck structures because of their large size and tectonic setting.

D'el-Rey Silva (2001) interprets domed features within the Mupe Mbr of the Lulworth Fm as being associated with evaporites and to be of diapiric origin. This interpretation is discounted by petrographic work that indicates these are microbial carbonate mounds (see above and Fig. 7) (West 1975, 2017; Bosence 1987; Gallois *et al.* 2018).

Erosional remnants or monadnocks. Isolated, positive erosional features are variously termed monadnocks, inselbergs, or yardangs and can form circular or omega-shaped positive relief outliers on an eroded surface (Fig 12C). Present-day examples (Goudie 2007) showing spectacular geometries similar to the circular structures of Weymouth Bay are well developed in the landscape of 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 circular structures as observed in the north-east of the studied area in Weymouth Bay.

However, the Weymouth Bay structures all show evidence indicating horizontally truncated, concave-down, 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.

Semi-quantitative analysis

Out of the four origins discussed above their formation as erosional remnants into gently tilted strata can be discounted but the other three all have qualitative evidence both for and against as viable mechanisms. To attempt to resolve this issue a semi-quantitative analysis of the geological setting and morphological features of the circular structures is presented (Table 1) that objectively assesses how likely any of the three possible origins are as a formative mechanism (*cf*. Burgess *et al*. 2013). Twenty-five features of the circular structures of Weymouth Bay were identified within four different categories 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. For each of these 25 geological and morphological features of the circular structures a numerical score from 0 to 4 is given on the basis of how consistent it is with any given formation mechanism (with 0 being a very unlikely explanation for a feature to 4 being a very likely, or definite positive explanation (for details see Table 1). By way of comparison, their origin as erosional monadnocks is also tabulated. The onshore outcropping lower Purbeck carbonate mounds and periclinal folds of the Lulworth Crumple which are well known from published literature are also scored for comparison (Table 1). Including these two known outcropping examples shows that a perfect score of 100% is never reached because even outcrops do not allow all features to be fully assessed.. However, their high scores (90% for the lower Purbeck (Mupe Member) mounds and 93% for the Lulworth Crumple periclinal folds) attest to the robustness of this method.

For the circular structures of his 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 their formation. As expected, monadnocks score the lowest (45%) as a mechanism that would account for the origin of the circular structures thus supporting the qualitative assessment above.

Discussion

If the structures are mounds, as is suggested by the evidence presented in this paper, then these are previously unrecorded from the Durlston Fm of the Purbeck Lst Gp. However the occurrence of mounds within the interpreted palaeoenvironment of this formation would not be remarkable and need to be considered in palaeofacies maps for this unit. If this interpretation is correct then they would be the largest mounds, by an order of magnitude, known within the Purbeck Gp and would explain the mounded seismic geometries seen in this unit an east to west seismic section from the study area (Fig. 10B). Because of the economic significance of carbonate mounds within non-marine carbonates in extensional basins of this age in the South Atlantic (Bosence *et al*. 2015) the discovery of large-scale mounds in the Wessex Basin is economically significant. Their depth-restricted occurrence has implications for establishing facies models and for mound spacing in subsurface exploration for hydrocarbons such as in the South Atlantic (Saller *et al*. 2016) and the Wessex Basin.

If the structures are folds they must be considered either syn-depositional structures or tectonically driven, either related to the Late Jurassic-Early Cretaceous extension or to Late Cretaceous-Cenozoic inversion. Given the lagoonal depositional environment and likely early diagenesis, gravity-driven syn-depositional folding is unlikely. Because the structures do not propagate vertically into surrounding strata, extensional fault propagation folding is also an unlikely scenario. If they are inversion-related folds, their NW-SE orientation is at odds with the regional trend of major Cenozoic aged structures in the southern UK, which formed in response to N-S compression. While Atlantic and Tethyan opening have also been considered as driving factors for inversion in NW Europe (e.g. Underhill & Patterson 1998; Vandyke 2002), it would be surprising if these processes formed strata-bound minor folds of the kind documented here. They also occur on the southern, gently sloping limb of the Weymouth, Purbeck and Durlston anticlines, where such folds have not previously been recognised. The occurrence of tight, non-cylindrical buckle folds on the steeply dipping northern limb has been related to footwall buttressing and antithetic reverse faults related to inversion on the Purbeck Fault (Sanderson *et al.* 2017). However, if similar, highly non-cylindrical folds are found in gently dipping strata many kilometres away from the Purbeck Fault then décollement along interbedded shales and shale deformation in the long limbs of the folds needs to be a significant process in the generation of these folds (*cf.* Sanderson *et al.* 2017).

If the circular structures are interpreted as diapirs arising from the lower Purbeck evaporites, then these would be the first diapiric structures to be recognised in this unit. Although thick sulphate salts are known deeper within the basin in the central Weald (West 1975; Abbot *et al.* 2016) there are no reported diapiric structures in this area. Similarly, diapiric structures in the literature generated by sulphate evaporites form structures that are of a different scale and morphology to classic cylindrical halite diapirs. Migration of halite from Triassic evaporites remains a possibility but evidence for this has not been seen in the seismic sections from the study area. An origin for the circular structures as evaporite diapirs is proposed to be the least likely interpretation.

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 epilithic 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 during drilling. Position fixing over such small structures in an area of strong tidal currents would be challenging and we view this solution as beyond the scope of the current paper.

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 non-marine limestones and shales with minor evaporites of the Stair Hole and Peveril Point Mbrs of the Purbeck Limestone Gp. 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 buildups/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 buildups, folds, diapirs or monadnocks. 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 score the lowest and 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 despite over 200 years of published geological research. 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; Saller 2016). If they are periclinal folds related to Cenozoic 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.

This study emphasises the value of remotely sensed data for geological mapping on Earth and for other planets. In an area that is extremely well known from surface and subsurface data remotely sensed images have revealed previously unknown structures that contribute to our understanding of a geological World Heritage Site.

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Figure Headings

Fig. 1. Locality map, geological setting and data used in this study. A) Bathymetry (MBES) image of Weymouth Bay with interpreted sea floor geology constrained by coastal outcrops, 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, and grab samples (from Donovan and Stride 1961). C) Rose diagram with 70 fault orientations (from 1A) binned at 10^{o} intervals. D) Examples of two circular structures imaged from MBES data from centre of study area (Nos. 5 and 6). Location indicated with star in A) and in figure 4.

Fig. 2. Lithostratigraphy of Jurassic to Cretaceous units of the 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 viewed to east to Peveril Point indicating resistant limestone ledges striking offshore in the Durlston Formation of the Purbeck Limestone Group (CB=Cinder Bed, UBS= Upper Building Stones, BSL= Broken Shell Limestone, PM=Purbeck Marble). 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 (3 B and C). Also note the seafloor trace of the normal fault striking offshore from Zig-zag path fault. Area of A, B and C shown in box in figure 4.

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

Fig. 5. Circular structures with concave-down dome, or omega, morphology. A-D) circular structure (No. 10) in centre of study area showing A) grey scale bathymetry; B) coloured slope raster in degrees; C) aspect raster showing compass direction of maximum slope direction; D) geological interpretation. E) Circular structures (Nos. 3 and 4) viewed with bathymetry raster (water depths in metres) with cross section (X-X'). Note saw-tooth nature of profile with gentler SE

dipping slopes interpreted as dips of strata and erosion of circular structure 4 creating a 1-2 m deep hollow. All depths in metres.

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

Fig. 7. Photograph of exhumed plan-view of carbonate mounds within the Mupe Member of the Purbeck Limestone Group. Upper surface of three mounds outlined on bedding plane dipping northwards towards viewer in Lulworth Fm, East Point, Lulworth Cove (50^{o} 36’ 58.37” N, 2^{o} 14’ 36.07” W, also see Fig. 1).

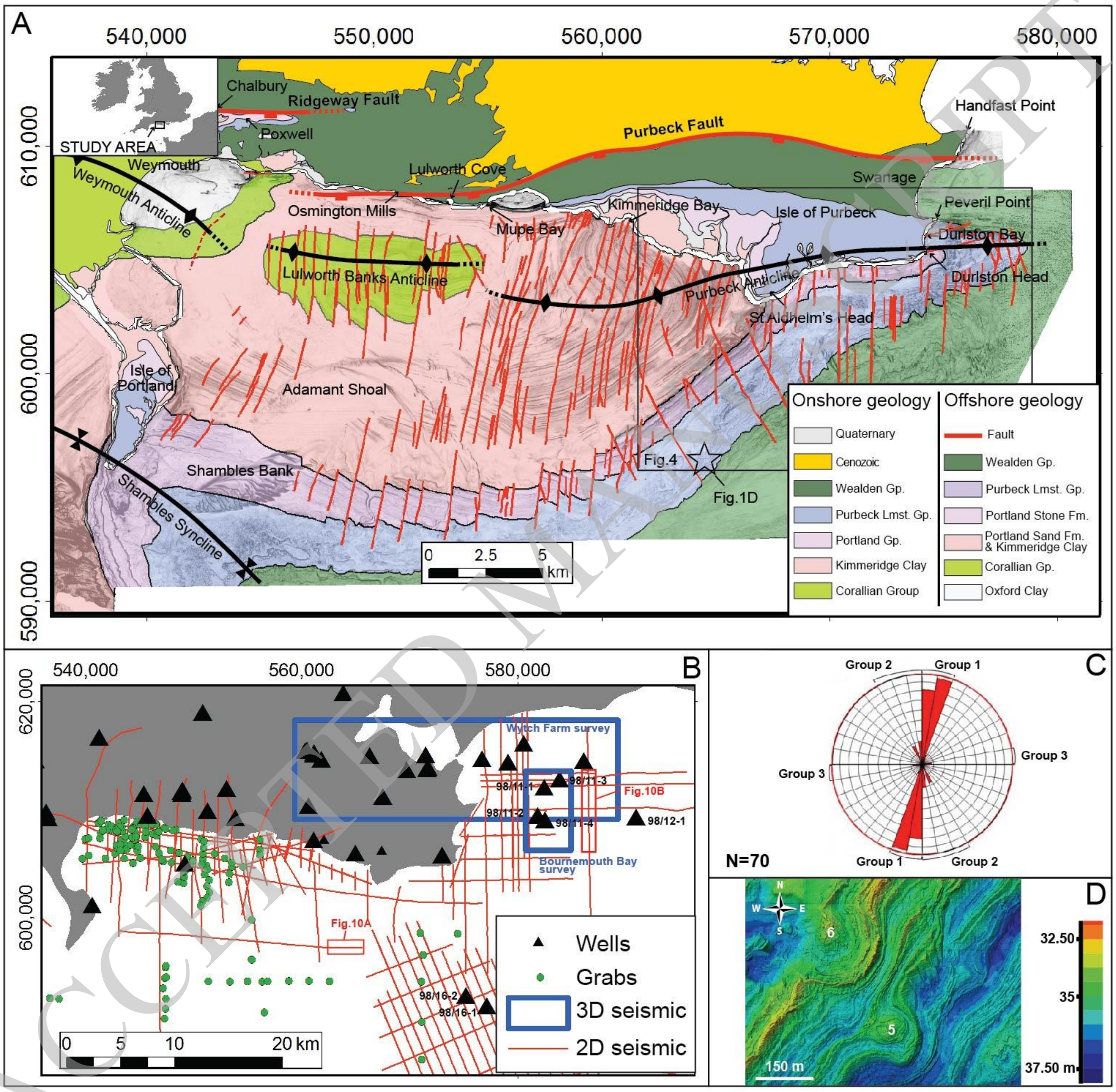
Fig. 8. A) Photograph (viewed to east) of northerly verging buckle folds (Lulworth Crumple) in Purbeck Limestone Gp at Stair Hole (cliff in foreground) with location of Fig. 9 boxed in black on east side of Lulworth Cove (bay and cliff in background), (CB=Cinder Bed). B) Open, upright, east to west trending (080-088^{o}) minor folds in Durlston Fm, Durlston Bay (person, centre of picture, base of cliff near anticlinal fold axis for scale).

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

Fig. 10. Seismic profiles showing stratigraphic and tectonic features of Portland and Purbeck groups within study area (location of lines see Fig 1). A) W to E profile showing regional dip to SE of the Portland and Purbeck Limestone Groups. Note possible circular structure in Purbeck Gp and minor folds associated with steeply dipping NW to SE (Group 2) reverse fault. B) N to S profile showing thickening of the Purbeck Limestone Gp. in hanging-wall fault blocks indicating extensional syn-rift setting. Buttress folds adjacent to fault indicate inversion of faults during the Cenozoic compression event.

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

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



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Lulworth Cove
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Swanage
Kimmeridge Bay
Isle of Purbeck
Peveril Point
Mupe Bay
Durlston Bay
Lulworth Banks Anticline
Purbeck Anticline
Durlston Head
St Aldhelm's Head
Isle of Portland
Adamant Shoal
Shambles Bank
Shambles Syncline
Fig.4
Fig.1D
0 2.5 5 km
Onshore geology
Quaternary
Cenozoic
Wealden Gp.
Purbeck Lmst. Gp.
Portland Gp.
Kimmeridge Clay
Corallian Group
Offshore geology
Fault
Wealden Gp.
Purbeck Lmst. Gp.
Portland Stone Fm.
Portland Sand Fm. & Kimmeridge Clay
Corallian Gp.
Oxford Clay
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Wytch Farm survey
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98/11-3
Fig.10B
98/11-2
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98/12-1
Bournemouth Bay survey
Fig.10A
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2D seismic
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Group 2
Group 1
Group 3
Group 3
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Group 1
Group 2
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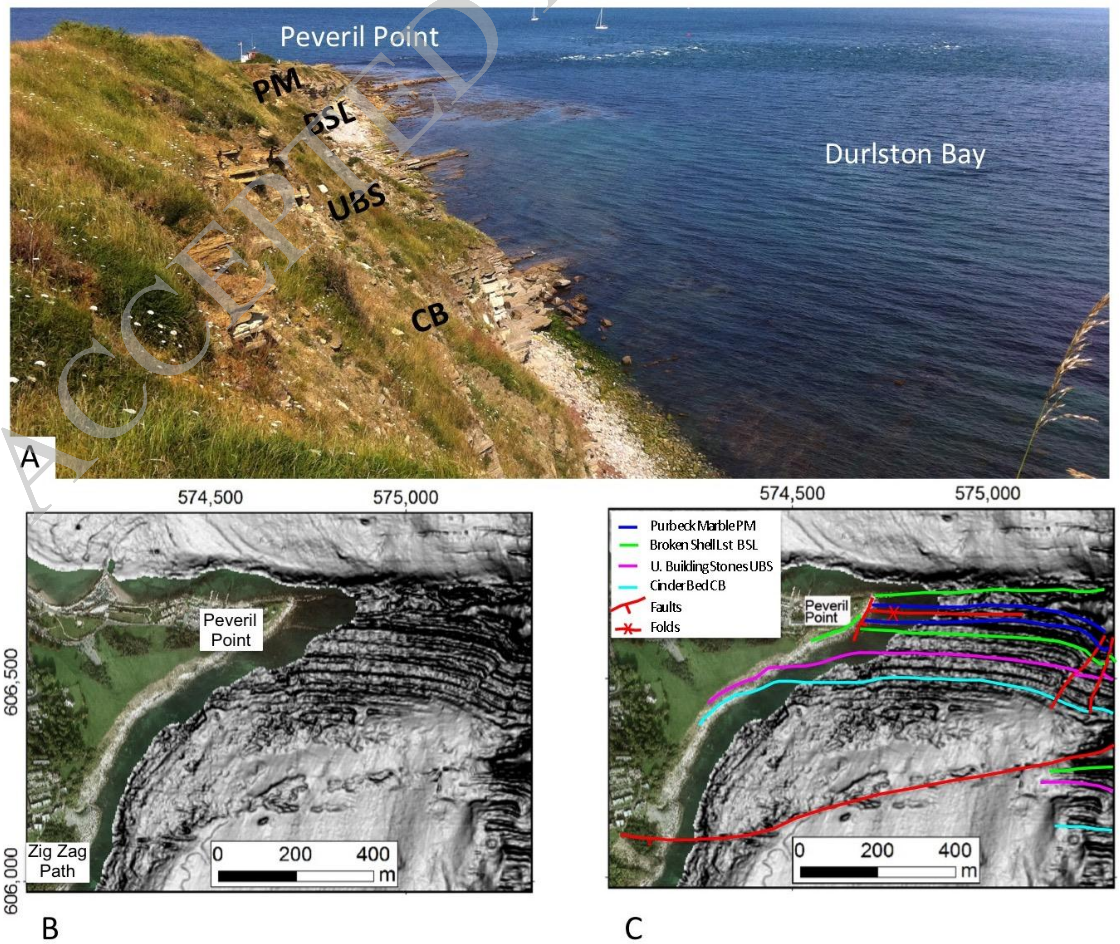
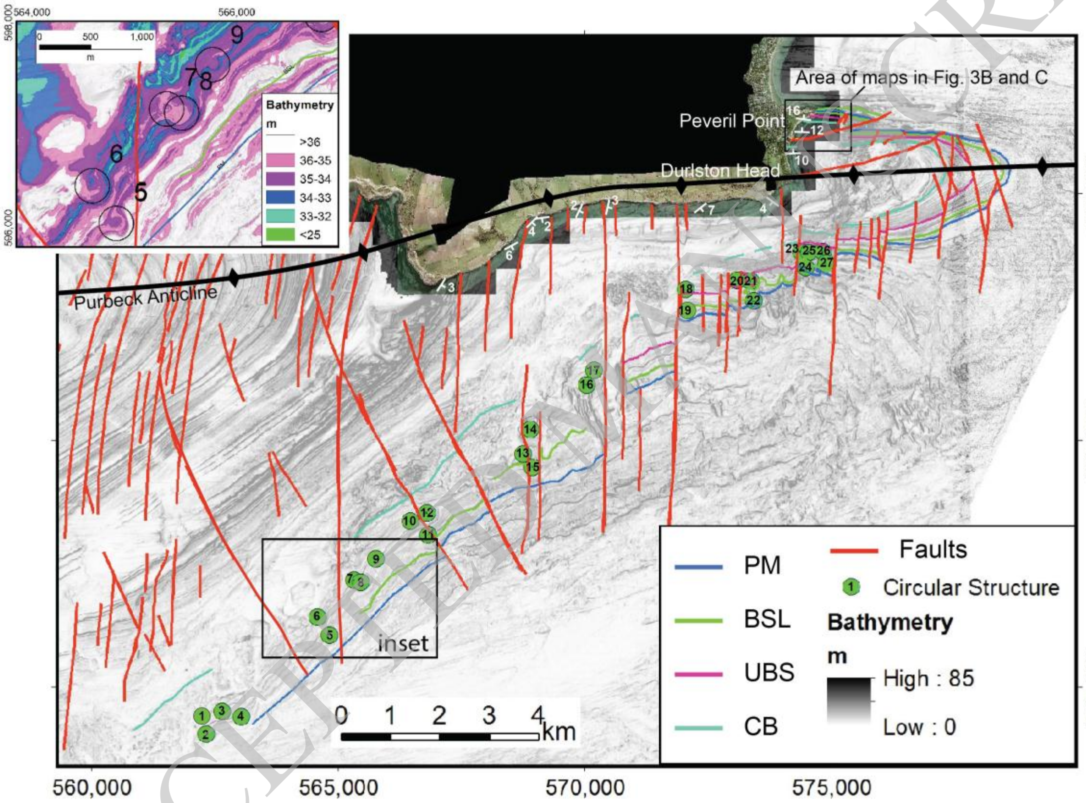
37.50 m

Lithostratigraphy: Groups	Formations	Members	Prominent surfaces mapped on sea floor
Wealden Gp (65-1000m)			Base Wealden Gp
Purbeck Limestone Gp (46-119m)	Durlston Fm	Peveril Point	Purbeck Marble (PM)
			Broken Shell Lst (BSL)
		Stair Hole	Upper Building Stones (UBS)
			Cinder Bed (CB
	Lulworth Fm	Worbarrow Tout	
		Ridgeway	
		Mupe	
Portland Gp (55-75m)	Portland Stone Fm		Top Portland Stone Fm
	Portland Sand Fm		Top Portland Sand and Kimmeridge Clay Fms
	Kimmeridge Clay Fm		

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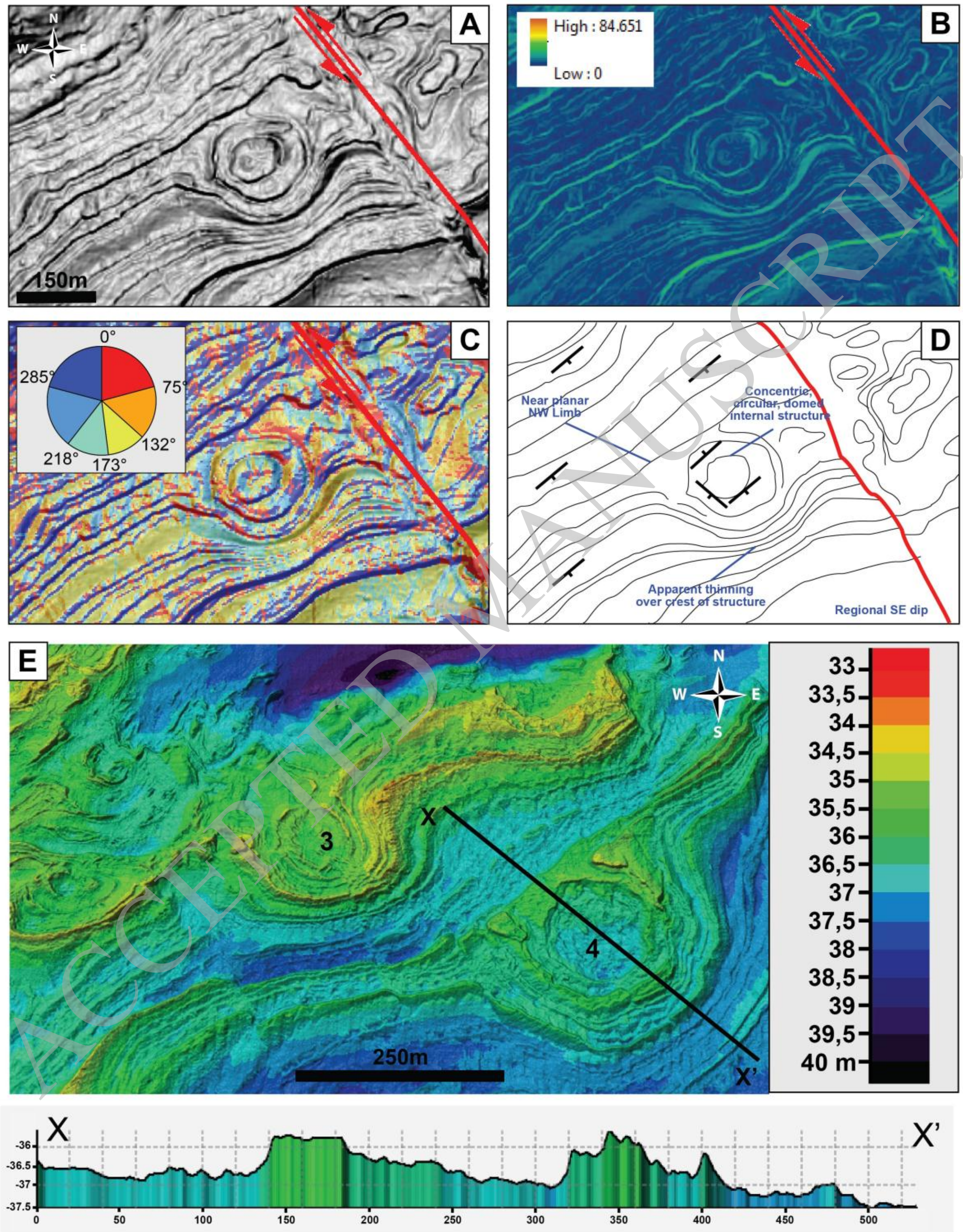
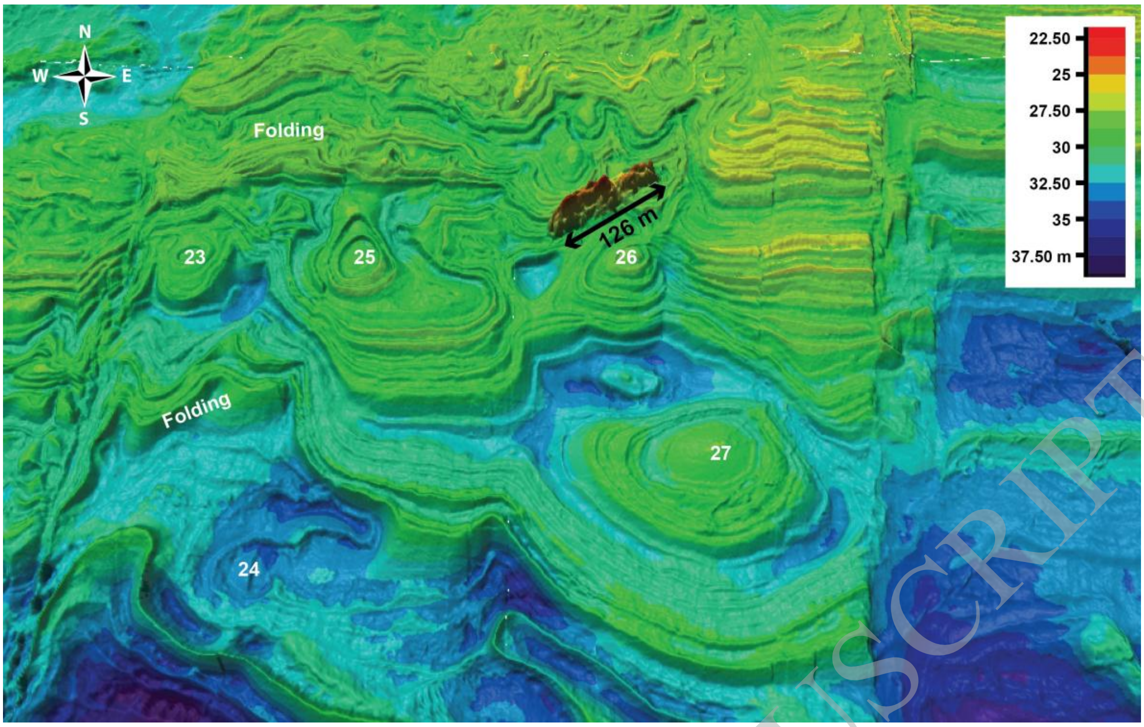
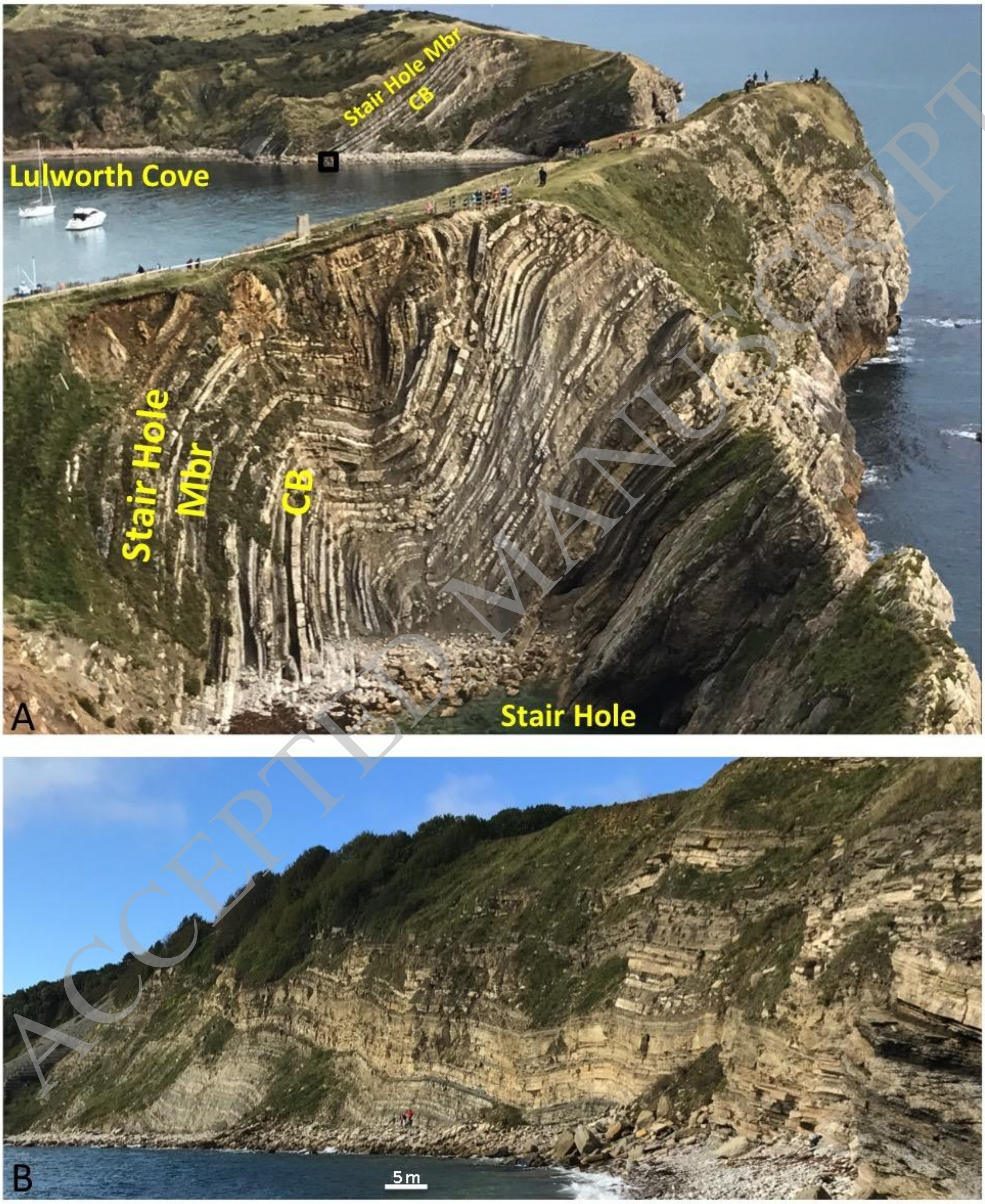
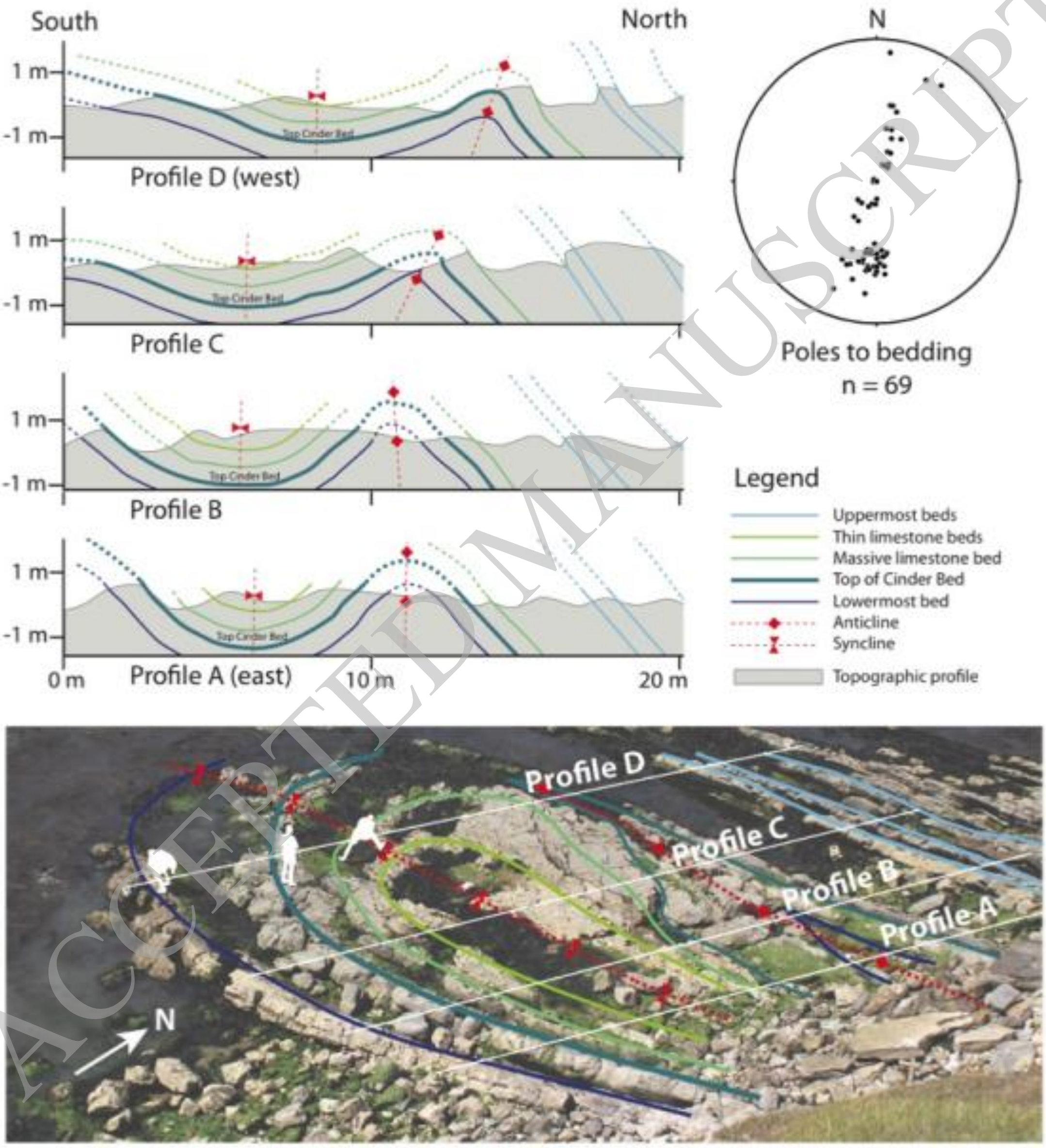
0 500 1,000
m
Bathymetry
m
>36
36-35
35-34
34-33
33-32
<25
Area of maps in Fig. 3B and C
Peveril Point
Durlston Head
Purbeck Anticline
inset
0 1 2 3 4 km
PM
BSL
UBS
CB
Faults
Circular Structure
Bathymetry
m
High : 85
Low : 0
560,000
565,000
570,000
575,000
595,000
600,000
605,000

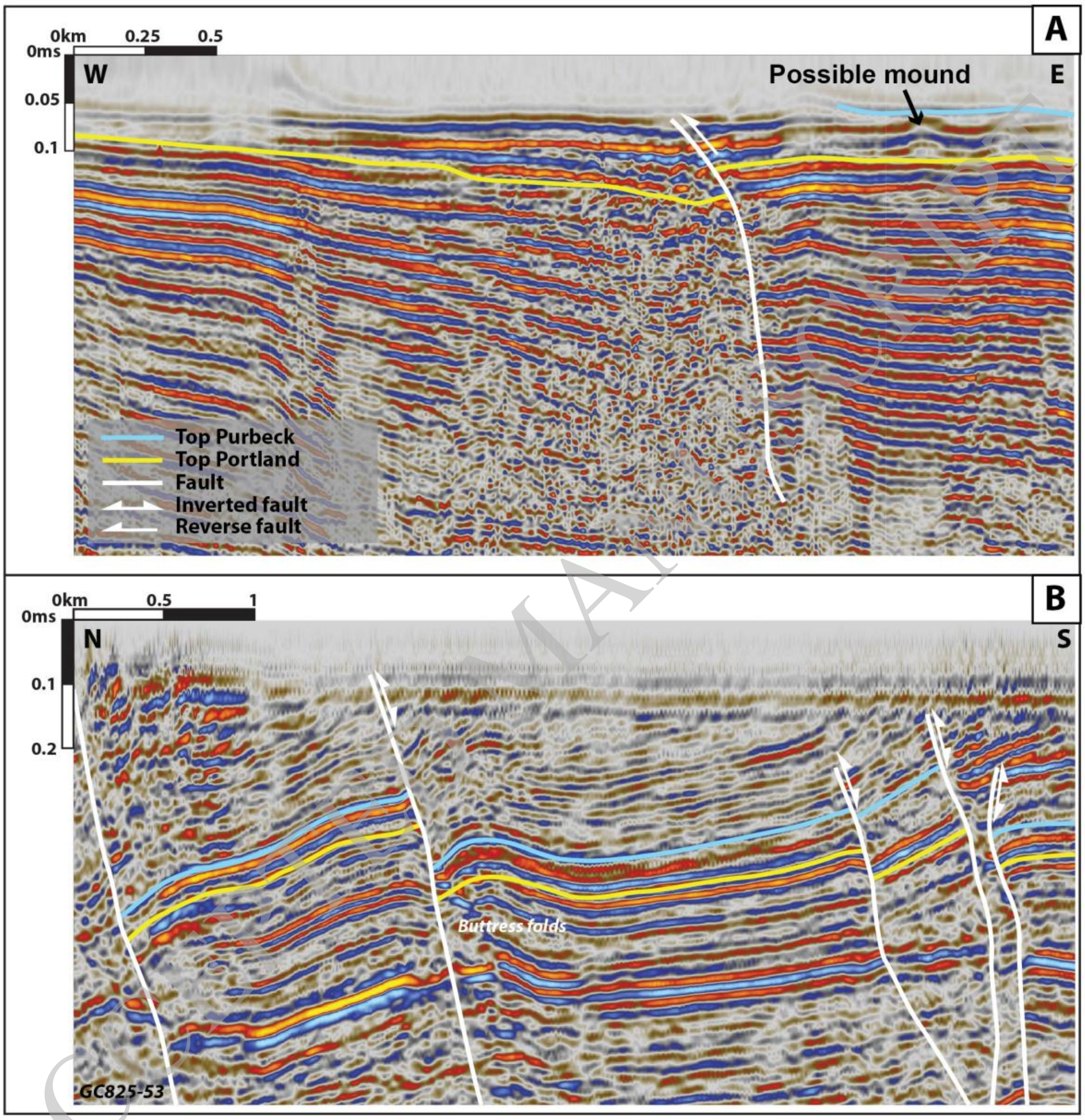

A
N
W
E
S
150m
B
High : 84.651
Low : 0
C
0°
75°
132°
173°
218°
285°
D
Near planar NW Limb
Concentric, circular, domed internal structure
Apparent thinning over crest of structure
Regional SE dip
E
N
W
E
S
X
3
4
X'
250m
33
33,5
34
34,5
35
35,5
36
36,5
37
37,5
38
38,5
39
39,5
40 m
X
X'
-36
-36.5
-37
-37.5
0
50
100
150
200
250
300
350
400
450
500

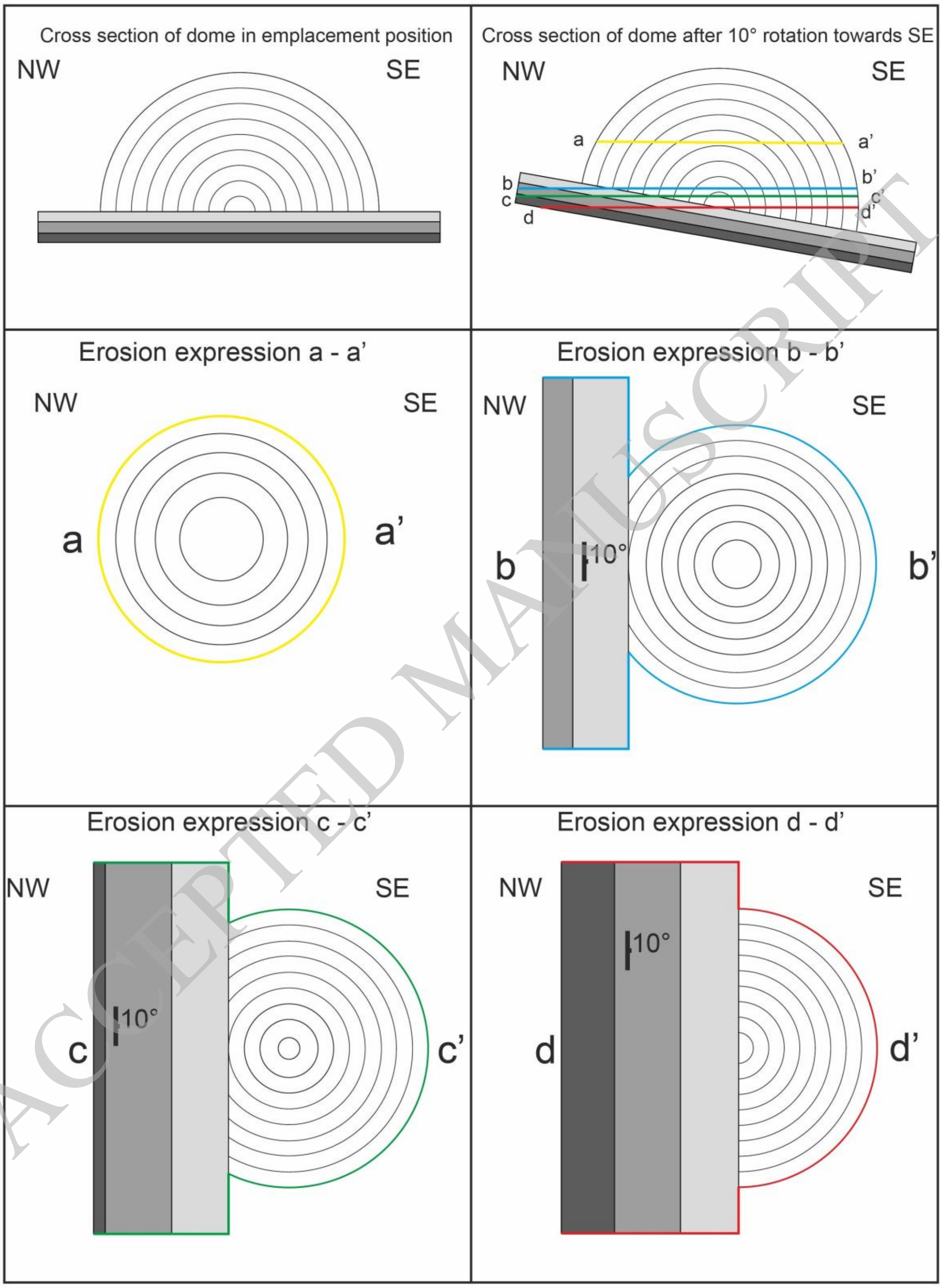

N
W
E
S
Folding
126 m
23
25
26
Folding
27
24
22.50
25
27.50
30
32.50
35
37.50 m


5 m


Stair Hole Mbr
CB
Lulworth Cove
Stair Hole
Mbr
CB
Stair Hole
A
B
5 m


South
North
1 m
-1 m
Top Cinder Bed
Profile D (west)
Profile C
Profile B
Profile A (east)
0 m
10 m
20 m
N
Poles to bedding
n = 69
Legend
Uppermost beds
Thin limestone beds
Massive limestone bed
Top of Cinder Bed
Lowermost bed
Anticline
Syncline
Topographic profile
Profile D
Profile C
Profile B
Profile A
N


A
0km
0.25
0.5
0ms
0.05
0.1
W
Possible mound
E
Top Purbeck
Top Portland
Fault
Inverted fault
Reverse fault
B
0km
0.5
1
0ms
0.1
0.2
N
S
Buttress folds
GC825-53



Cross section of dome in emplacement position
NW
SE
Cross section of dome after 10° rotation towards SE
NW
SE
a
a’
b
b’
c
c’
d
d’
Erosion expression a - a’
NW
SE
a
a’
Erosion expression b - b’
NW
SE
b
10°
b’
Erosion expression c - c’
NW
SE
c
10°
c’
Erosion expression d - d’
NW
SE
d
10°
d’

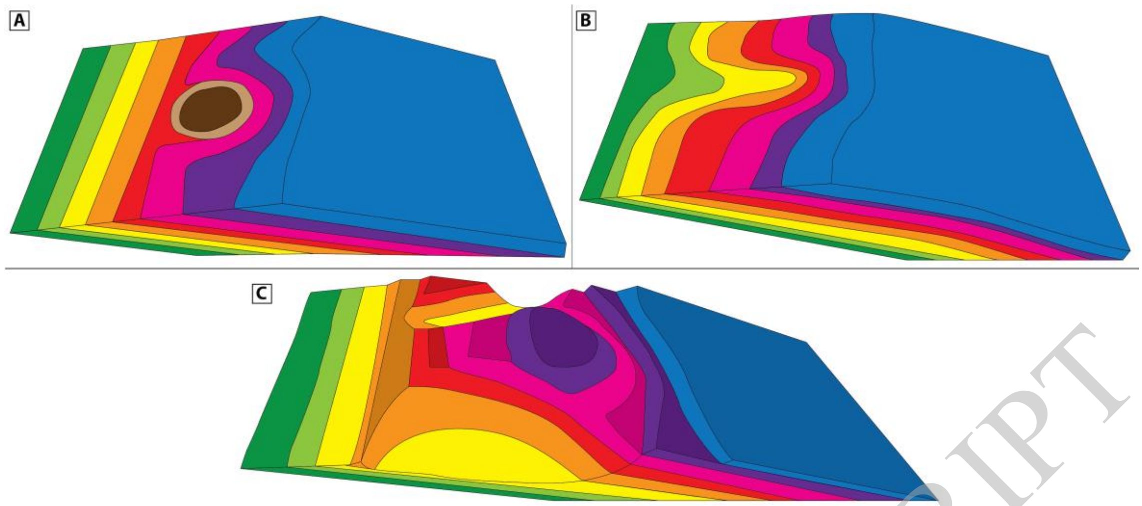


Table 1. Semi-quantitative scoring of basinal setting, analogues and morphological features of circular structures as indicative of carbonate mounds, folds or diapirs, or monadnocks (0=Definite negative, 1=Weak negative, 2=Criterion cannot be assessed, 3=Weak positive, 4=Definite positive. (i.e. a score 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.

Stratigraphic and Morphological features			Mounds	Periclinal Folds	Diapirs	Monadnocks	L Purbeck mounds	Lulworth crumple folds
Basinal Setting	1	Stratigraphic occurrence consistent with mechanism	3	2	3	2	4	4
	2	Palaeo-environmental setting	4	2	3	2	4	4
	3	Spatial distribution consistent with mechanism	4	3	3	3	4	4
	4	Structural setting	3	3	3	3	4	4
Outcrop/subsurface analogues	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 strata	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 (HS)	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**