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BATHYMETRIC MAPPING OF THE COASTAL AND OFFSHORE GEOLOGY AND STRUCTURE OF THE JURASSIC COAST, WEYMOUTH BAY, UK

David J. Sanderson[1*], Justin K. Dix[2], Keith R. Westhead[3], and Jenny S. Collier[4]

[1] School of Civil Engineering and the Environment, University of Southampton, Southampton, SO17 1BJ, UK.

[2] School of Ocean and Earth Science, National Oceanography Centre, University of Southampton, Southampton, SO14 3ZH, UK.

[3] British Geological Survey, The Lyell Centre, Edinburgh, EH14 4AP, UK.

[4] Department of Earth Science and Engineering, Imperial College, London, SW7 2BP, UK.

* Corresponding author (email d.j.sanderson@soton.ac.uk)

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ABSTRACT

Four hundred square kilometres of one metre binned, full coverage swath bathymetry data, integrated with similar resolution onshore topography, has been used to generate a seamless onshore to offshore bedrock map covering an extensive area adjacent to the “Jurassic Coast” World Heritage site. Analysis of these data provides new insights into the structural development of the Purbeck Monocline Cenozoic inversion structure, in particular, variations in the expression of strain between the hanging wall block and the fault inversion zone. The footwall to the basin-

bounding faults compartmentalized deformation and uplift, and acted as a buttress to compression. The data also show a lack of significant thickness changes within the major lithostratigraphical divisions, and a notable absence of basin-related extensional faulting in the offshore area that is in marked contrast to the more extensively studied onshore region. This indicates that prior to inversion, the basin evolved by intermittent activity on a few major extensional faults. This improved understanding of the development of the basin and inversion structures results from our ability to integrate and quantitatively manipulate these high resolution and spatially extensive offshore and onshore datasets.

Key words: Bathymetry, Jurassic Coast, structural geology, basin, extension, inversion, GIS

INTRODUCTION

The Jurassic Coast is a geological World Heritage site located on the south coast of England between Exmouth, South Devon, and Studland, Dorset. Here we present a new interpretation of the eastern part, focussing on the area surrounding Weymouth Bay (**Fig. 1**). The area has been of major significance in the world-wide development of much of the Jurassic stratigraphy since the classical work of Woodward (1893) and Arkell (1933) and it contains the type section for the Kimmeridge Clay – a major source rock for North Sea oil. The exposed geology is largely confined to an E-W trending coastal strip ~150 km long but generally less than 100 m wide. Poor inland exposure, difficulty of access to the coast in many places and gaps in the exposed sequences, have all limited the development of a 3-D perspective of the stratigraphy and structure of this important region. Petroleum exploration, both onshore and offshore, has added much in recent years (e.g. Underhill 1998) but this has been focussed to the north and east of our study area around Wytch Farm No 3D seismic data has been shot in Weymouth Bay, so interpretations are from 1-4 km spaced 2D sections. The interpretation of these data is further handicapped by a paucity of borehole data. Although the neighbouring onshore areas have many boreholes,

Weymouth Bay itself has just a single borehole - the famous “Lulworth Banks 1” that was drilled in 1961 and was the first offshore well ever drilled in UK continental shelf (Buchanan 1998). Previous interpretations of the 2D seismic data therefore required correlation from distant boreholes.

The Portland-Wight Fault Zone (PWFZ) forms the northern margin of the Channel Basin and plays a significant role in both basin development and as a locus of subsequent inversion. This structure comprises a complex series of en echelon fault and fold ‘disturbance zones’, associated in the current study area with the Abbotsbury-Ridgeway and Purbeck faults (**Fig. 1**). Most of the sea-bed beneath Weymouth Bay is in the hanging wall of the Purbeck Fault. The possibility of mapping the area using ship-borne equipment was first recognised by Stride (1960), who detected the folding and faulting on the Lulworth Banks using echo sounding. Donovan and Stride (1961) used an early side scan sonar system (asdic) to establish the presence of exposed bedrock across much of Weymouth Bay and augmented these observations with sea bed sampling obtained by diving and gravity coring. Although state-of-the-art for the period, the wide spacing of sounding lines (generally about 400 m) and errors in position fixing (Decca Navigation Equipment) limited the resolution and accuracy of this survey, but it was sufficient to map out the gross stratigraphical and structural components.

In this paper we present a geological analysis of some recently acquired high-resolution swath bathymetry (**Fig. 1A, B**). The almost complete exposure of bedrock on the seabed over large parts of Weymouth Bay, allows detailed mapping, at 1 m-scale resolution, of ~400 km^2 of outcrop, compared to ~5 km^2 available in the coastal strip. The geo-referenced nature of these data allows accurate integration with onshore and offshore geological and topographic datasets. We employ new techniques for the generation and visualisation of seamless digital elevation surfaces from onshore to offshore to provide the backdrop to the interpretation. This improved mapping

therefore provides a much better perspective of the stratigraphy and structure of this important region and, our understanding of basin development.

BATHYMETRIC DATA AND METHODS

The coastal and offshore geology of Weymouth Bay has been mapped using: a) IHO Order 1 swath bathymetry, collected as part of the collaborative Dorset Integrated Seabed Survey (Figure 1A and 2B); b) digital aerial photographs of the coastal strip, made available through the Channel Coastal Observatory (**Fig. 2A**); c) 1 m horizontal resolution Lidar data from the Environment Agency (**Fig. 2A**); d) the interpretation of rock samples recovered by divers and gravity coring (Donovan and Stride 1961) and published onshore borehole data (**Fig. 2A**); (e) the onshore geological mapping by the British Geological Survey (area covered by BGS 1:50 000 scale geological map sheets West Fleet & Weymouth, and Swanage (parts of sheets 341, 342, 342); see Barton et al., 2011 for full list of onshore published mapping); (f) borehole-correlated 2D seismic data from the UK Onshore Geophysical Library (**Fig. 2A**); and g) observations of faults in the coastal area (Putz-Perrier and Sanderson 2008; **Fig. 3**).

The bulk of the swath bathymetry, was collected by Fugro OSAE's vessels Meridian (for the offshore areas) fitted with a Reson Seabat 7125D and Jetstream (coastal sections) fitted with a Kongsberg EM 3002D; data from the north-western bay was collected by the Royal Navy vessel HMS Gleaner using a Kongsberg EM3002 swath system. These data were collected between summer 2008 and spring 2009. The raw bathymetry was reduced to Admiralty Chart Datum using the UKHO "Vertical Offshore Reference Frame" model. A final 1 m binned xyz data set was provided by the UKHO in UTM [Zone 30N] co-ordinates. The 2D seismic were acquired with conventional airgun and streamer arrays, and typically have a bandwidth of 12-60 Hz in the upper second, giving a vertical and horizontal resolution of around 10 m and 100 m respectively.

Fugro-BKS Limited, for the Environment Agency, acquired digital aerial photographs along the coastal strip from Portland Bill to Durlston Head, during May and June 2008. Flights were made during low-tide to optimise imaging of the coastal zone. Full overlapping coverage was acquired, from a Piper Aztec PA23 survey aircraft, using a large format, Intergraph Digital Mapping Camera, with a T-AS gyro stablilised mount and electronic forward motion compensation system. Positioning was provided by a combination of an Airborne Global Positioning System and Rinex data from the nearest OS active stations. The final ortho-rectified image data, in Ordnance Survey grid Co-ordinates, was supplied as 24-bit RGB compressed ECW 500 m tiles, with a ground sample distance of 0.09 m and a positional accuracy of $\pm$ 0.27 m.

Lidar data was collected using an ALTM 3100 LiDAR in a range of surveys between 2007 and 2009, with the most recent data taking precedence in overlapping areas. These data are delivered as ArcView ASCII GRID & XYZ Delimited Text files at 1 m resolution and a maximum vertical error $\pm$ 0.15 m when compared against terrestrial base stations and cross-sections. These datasets were combined in ESRI ArcGIS 10 and set to the UTM [Zone 30 N] co-ordinate system using the Petroleum seven-parameter transformation. The bathymetric data was integrated into a single raster surface that was used to generate four inter-related layers (all binned at 1 m): 1) Colour coded bathymetric raster (**Fig 1A**); 2) Hill-shade raster that was obtained by setting a position for a hypothetical light source and calculating the illumination values of each cell in relation to neighbouring cells (**Fig. 2B**); 3) Slope raster which presents the maximum rate of change of slope between each cell and its neighbours, and presented as an angle in degrees (**Fig. 2C**); and 4) Aspect raster that identifies the down-slope direction (relative to north) of the maximum rate of change in value from each cell to its neighbours, as calculated in the slope raster (**Fig. 2D**).

Mapping was carried out by correlation of the fabric and texture of the bathymetric images (see Collier et al. 2006) with published stratigraphy from boreholes, BGS onshore mapping and other field observations. In coastal regions, one of the major challenges is bridging the gap between the shallowest waters accessible by boat and the land exposed at low-tide – the so-called "white ribbon". Here two survey methods were used to link the onshore to offshore geology: 1) Correlation of detailed air photo coverage with the bathymetry (**Fig. 3**); 2) Visualisation of the onshore Lidar and offshore bathymetric data as a seamless elevation surface in 2D GIS and also in the 3D BGS GeoVisionary virtual mapping software (Westhead et al., 2015). Completion of the digital geological map was carried out by importing the GeoVisionary surveying lines into the BGS System for Integrated Geological Mapping (SIGMA) Desktop toolkit extension (Jordan, 2010) within ESRI ArcGIS 10 and further interpretation over a hill-shaded version of the coastal elevation surface. The offshore lines were joined to the onshore 1:10 000 scale BGS bedrock mapping (DiGMapGB-10), completing the geological map through the 'White Ribbon' (Mason et al., 2006; Leon et al. 2013; **Fig. 1**). The resulting 1:10,000 map will be published under the auspices of MAREMAP (Westhead et al. in prep).

Offshore, the bathymetry allows tracing of many stratigraphic marker beds across large parts of Weymouth Bay (**Figs. 1A, 2D**). Dips were determined by locating bedding surfaces on the sea bed (**Fig. 4**) and using the slope raster (**Fig. 2C**) and also geometric tools in GeoVisionary to determine their dips. Dip direction was determined from the strike of the mapped features and from the aspect raster image. Outcrop widths on the sea-bed can then be used to determine thicknesses of stratigraphic intervals using the measured dips (**Fig. 4**). Faults were identified from offsets of marker beds and stratigraphic separations calculated (**Fig. 3**). These approximate the throw of the faults where dips are low and displacement is dip-slip (Putz-Perrier and Sanderson, 2008).

Finally, the bathymetric interpretation was integrated with the available seismic data (**Fig. 5**). The contrast in resolution between the existing seismic and the new bathymetric data can be seen in **Fig. 5**. The seismic data image the major faults, such as the Purbeck Fault, at depth and the large-scale structure, such as the Purbeck (or Lulworth Banks) Anticline, but otherwise are unable to clearly define the thicknesses of the Upper Jurassic units or detect finer scale structure such as secondary faulting and segmentation along anticline crests so clearly seen in the newly available bathymetry.

STRATIGRAPHY

Regionally, the Mesozoic and Tertiary strata form three megasequences (Underhill and Stoneley 1998; Underhill and Paterson 1998). 1) The Permian to Lower Cretaceous megasequence comprises Permian and Triassic continental sediments with a major marine transgression near the base of the Jurassic. The Jurassic and lowermost Cretaceous consist of repetitions of marine claystones, sandstones and limestones forming a series of six cycles (House, 1993). 2) The Upper Cretaceous megasequence (which also includes some uppermost Lower Cretaceous strata; Underhill & Paterson, 1998) lies above the important Albian-Aptian unconformity and comprises marine sandstones passing upward into a thick carbonate sequence – the Chalk. Around Weymouth Bay, this sequence has only local breaks, but to the west of Portland, the base of this megasequence progressively cuts down (oversteps) to the Lower Jurassic and Triassic. 3) Cenozoic (formerly termed 'Tertiary') near-shore and non-marine claystones and sandstones are only exposed onshore, to the north of the area, where they thicken into the Hampshire Basin.

Rocks of Middle Jurassic (Oxford Clay) to Upper Cretaceous (Chalk) age have been mapped from the swath bathymetry in Weymouth Bay (**Fig. 1B**), south of the main axis of the Purbeck Monocline. In the description that follows the character of the units and their thicknesses (discussed in more detail later) are derived from the integration of the rasters and field

observations. The lowest rocks mapped are ~100 m of ***Oxford Clay***, a claystone sequence that forms a flat, largely featureless sea-bed. The ***Corallian Group*** (60-70 m) is of Upper Oxfordian age and may be subdivided based on major textural changes and a few prominent marker horizons (Nothe Grit, Nothe Clay, Bencliff Grit, Osmington Oolites, Clavella Beds, Sandsfoot Grit and Clay). The resolution of the stratigraphy in the Corallian is illustrated in **Figs. 6** and **7**.

The ***Kimmeridge Clay*** is a thick (250-570 m south of the Purbeck Monocline) organic-rich claystone unit that contains prominent carbonate bands (known locally as “stone bands”). Only the upper part of the formation is exposed onshore, but the entire formation has been logged in detail from the Metherhills [SY 9112 7911] and Swanworth Quarry [SY 9675 7823] boreholes (Morgans-Bell et al. 2001; Gallois 2000; **Fig. 2A**). The stone bands generally form prominent ledges on the sea-bed (**Fig. 4**) and they can be easily correlated with coastal exposures (**Fig. 3**). A total of 19 stone bands have been identified individually and mapped across the area. The lower part of the Kimmeridge Clay contains five prominent stone bands not exposed in the cliffs, but revealed in the Metherhills-1 borehole (Morgans-Bell et al. 2001). The middle part of the formation, between the Flats and Basalt stone bands, includes a number of calcareous and bituminous claystones that also produce prominent ledges on the seabed. The uppermost part of the Kimmeridge Clay (top 60 m or so) lacks stone bands, and forms a characteristically featureless seabed that is 10-15m deeper across the southern part of Weymouth Bay.

The ***Portland Group*** (50-80 m) comprises a lower sand/clay dominated unit and an upper sequence of limestones with cherts, that includes the famous Portland stone. The overlying ***Purbeck Group*** (~50-110 m) comprises a series of limestones and claystones with evaporites. Textural variation of the bathymetry rasters allows subdivision into the following formations: Portland Sand and Portland Stone formations of the Portland Group, and Lulworth and Durlston formations in the Purbeck Group, and in places the component members of the Group. As has been known since the time of Arkell (1933) there is a good lithostratigraphic correlation in both

facies and thickness of the Portland Group between the Isle of Portland to the west and the Purbeck coast to the east. The ***Wealden Formation*** is a Lower Cretaceous, non-marine, fluvial sequence that mainly lies on the eastern edge of the study area. The formation shows a wide variation in thickness from just 65 m at Durdle Door to 435 m at Worbarrow Bay and as much as 1000 m in Swanage Bay (Barton et al., 2011). It has not been subdivided, but some of the course clastic horizons are recognisable from the bathymetry.

The 'Upper Cretaceous' megasequence lies above a regionally significant Albian-Aptian unconformity, which forms only a relatively minor break in sedimentation in the Weymouth Bay area. It consists of a relatively thin (~20–60 m) sequence of uppermost Lower Cretaceous marine sands and clays (the ***Lower Greensand***, ***Gault*** and ***Upper Greensand*** formations) that passes upward into more than 400 m of the Upper Cretaceous ***Chalk Group***. This sequence mainly crops out in the onshore area to the north but does extend into the nearshore near Durdle Door and White Nothe.

STRUCTURAL GEOLOGY

Basin extension in southern Britain began in the Permian and Triassic with episodic re-activation of E-W striking Variscan thrust faults and associated NW-SE trending, strike-slip faults (e.g. Ziegler 1987). A N-S extensional tectonic regime existed throughout the Jurassic and early Cretaceous, which culminated in the mid-Cretaceous and produced a series of asymmetric, N- and S-facing graben and half-graben structures. The Channel Basin, bounded to the north by the southerly-inclined Portland-Wight Fault Zone, is one such basin within which some 2,500m of predominantly marine Mesozoic sediments were deposited (Lake and Karner 1987, House 1993). During early extension, Jurassic carbonaceous shales were sufficiently buried to produce hydrocarbons (Selley and Stoneley 1987), currently exploited at Wytch Farm.

The Albian-Aptian unconformity separates the early extensional events and later compressional events, with no evidence for significant post-Aptian N-S extension along the Dorset coast (Arkell, 1933). During the late Cretaceous and early Cenozoic the Channel Basin underwent inversion as a result of N-S compression (Lake and Karner, 1987; Chadwick, 1993). Reverse movement occurred on pre-existing E-W striking, normal faults at depth, which at higher tectonic levels produced monoclinal and periclinal folds along the Portland-Wight Fault Zone, represented in the Weymouth Bay region by the Abbotsbury-Ridgeway and Purbeck lineaments (**Fig. 1**). It is widely agreed that inversion events in southern England occurred during the Oligocene-Miocene (Lake and Karner 1987; Bray et al. 1998).

Following the onset of basin inversion, continued N-S compression produced N-S striking normal faults observed in South Wales, Lyme Bay (Harvey and Stewart 1998) and Weymouth Bay (Donovan and Stride 1961; Hunsdale and Sanderson 1998). These structures, and the inverted E-W faults, formed under a similarly oriented stress field, with N-S maximum and E-W minimum horizontal stresses. The E-W trending PWFZ dominates the structure of the region, although other E-W faults are widely distributed through the Wessex basin (Stoneley 1982; Underhill and Stoneley 1998; Underhill and Paterson 1998).

Structural observations

Our mapping demonstrates a clear structural division of the region into two ‘domains’ based on fault orientations and folding:

1. In the hanging wall to the south of the PWFZ deformation is distributed. Faulting is predominantly N-S to NNE-SSW striking, cross-cutting more open W-E orientated folds, most notably on Lulworth Banks where Corallian Group units are offset by the faults and in the continuation of the anticlinal structure in the Portland and Purbeck groups east of Swanage.

2. Within the PWFZ, deformation is more intense and localized. Faulting is predominantly E-W striking and parallel to tighter E-W folds and related bedding strikes. E-W faulting is also developed to the north of the PWFZ, as in the vicinity of the Wytch Farm oilfield (e.g. Kattenhorn and Pollard 2001).

Much of the area of Weymouth Bay lies in the hanging wall domain, where detailed mapping of the stratigraphy and faulting using the bathymetry is made possible by the fact that bedrock is exposed at the seabed across much of the bay, with only limited cover of younger Holocene seabed sediments (**Fig. 1A**). The development of N-S to NNE-SSW orientated faults dominates the structural style in Weymouth Bay and further east to offshore Swanage, evident by their displacement of bedrock features within the Kimmeridge Clay Formation, and Corallian, Purbeck and Portland groups. These faults are predominantly spaced 300-500 m apart and range from 100's m to over 10 km in length. Individual faults can be traced into the coastal region (**Fig. 3**) where they form a conjugate set of normal faults with dips of 60-80º whose geometry and displacement have been described in detail by Hunsdale and Sanderson (1998) and Putz-Perrier and Sanderson (2008). In the offshore, the majority of the faults (about 70%) downthrow to the east – as evident, for example, in the 'saw-tooth' outcrop pattern of the seabed escarpment formed by Portland and Purbeck group running between the Isle of Portland and St Alban's Head (**Fig. 1B**). However, significant individual or groups of westerly downthrowing faults also occur. Offsets in the stratigraphy allow calculations of fault throws: most are in the order of 10-20 m with a number ranging up to 50 or 70 m. On the north flank of the Purbeck Anticline, these faults appear mostly to die out as the dips increase towards the Purbeck Fault.

The apparent lateral 'offset' of the crest of the Purbeck Anticline and associated Corallian strata on Lulworth Banks (**Fig. 7**) can be attributed to variations in throw on these later N-S faults and is not evidence of any strike-slip component. Individual faults show similar stratigraphic separations and downthrow directions when traced through the crest despite changes in their

lateral separations. These are characteristics of faults with a dominant dip-slip component. Occasional NW-SE trending faults (e.g. south of St Alban's Head; **Fig. 1**) have been identified in the bathymetry and may represent reactivation of basement structures or the manifestation of strike-slip faults seen elsewhere in the Wessex Basin (Peacock and Sanderson 1998).

The widespread development of the N-S faults throughout Weymouth Bay is consistent with observations in the coastal exposures between Worbarrow Bay and Durlston Head. However in the onshore regions to the north of the PWFZ, such faults are rare and, where identified, appear minor and secondary to E-W faults. For example, the absence of such faults in the interpretation of the 3-D seismic data at Wytch Farm is striking. This may, in part, be attributed to the small throws on these faults, which would make their detection difficult in commercial seismic data and in poorly exposed areas.

Within the PWFZ domain itself, the structural character is dominated by E-W-aligned faulting and folding. The new seamless onshore-offshore mapping enables detail within these structures to be discerned. For example, in the vicinity of Osmington Mills, a complex faulted, periclinal anticline is revealed in the nearshore platform (extending to 13 m water depth), affecting the formations within the Corrallian Group (**Fig. 6**). A series of 100 to 300 m spaced, E-W faults, running parallel to the fold axis, show throws in the order of 10 to 20 m down to the north and south, on the north and south-dipping flanks of the anticline respectively. The dip direction of these faults is unclear, but they are interpreted as a having developed coevally with the folding, possibly as a flower structure. The temporal relationship between folding and faulting is therefore strongly contrasting to that seen in the hanging wall zone. The structure lies with the overlap zone between the Abbotsbury-Ridgeway and Purbeck Fault disturbance zones (**Fig, 1**), which together form part of the PWFZ. The structure is interpreted as having developed where displacement is being transferred between these two fault systems through a relay ramp (**Fig 1**; Harvey and Stewart,

1998) with the faults forming synthetically and antithetically to the principal south-dipping faults of the PWFZ.

Thickness observations

The new mapping also enables the thickness of some key Upper Jurassic sequences to be determined in relation to the regional structure. This is done by identifying exposed bedding planes on the seabed and using the slope raster to determine the dip. This works especially well for the limestones ledges in the Kimmeridge Clay where the dip-slopes can be accurately determined on the seabed (**Fig. 3**) and the slope map (as **Fig. 2C**) used to determine their dips. These dips, combined with the outcrop widths mapped on the seabed allow estimates of thickness within the Kimmeridge Clay beneath Weymouth Bay. The accuracy of the dip determinations varies with the dip of the beds, but generally thickness estimates are considered accurate to about ±15%, and, locally, these thicknesses correlate well with those determined in the boreholes.

To the west of the Isle of Portland, where the Corallian and Kimmeridge Clay are well exposed on the sea-bed and dip at ~2.5º to the SE, the Kimmeridge Clay is only ~250 m thick; an estimate that is compatible with the ~300 m thickness reported in the Portland No1/1A Borehole (Gallois 2010). This thickness is about two-thirds to half the ~450-550 m total logged in the cliffs around Kimmeridge Bay and in the Metherhills and Swanworth Quarry boreholes (Morgans-Bell et al. 2001). The Encombe Borehole [SY 9712 7831] and Southard Quarry [SY 0234 7775] boreholes, onshore between St Alban's Head and Swanage in the East, proved at least 541 m and 444m respectively of Kimmeridge Clay (Barton et al. 2011).

Our measurements demonstrate that in Weymouth Bay, the Kimmeridge Clay is around 380 ±30 m thick on both the north and south limbs of the Lulworth anticline, with more detailed studies demonstrating possible North-South thickness changes at certain stratigraphical levels. For example, the interval between the Grey Ledge and Basalt stone bands (**Fig. 4**) varies from around

20 m thick near Portland, based on evidence from outcrop width and shallow boreholes at the Upper Osprey site on Portland (Gallois 2010), to 47 m in the Swanworth Quarry No. 2 borehole [SY 9678 7824] and 43 m thick just south of Worbarrow Bay as calculated from outcrop width. Clearly this could be part of the general West to East thickening of the Kimmeridge Clay, but our mapping suggests a South to North doubling of the thickness of this interval to the south of Kimmeridge Bay. A similar study carried out on the Portland Limestone shows no significant thickening.

The Portland Group is measured from the bathymetry to be about 69 m thick across the seabed escarpment south of the Purbeck Anticline, and at 61 m and 62 m on its northern side, just offshore of Durdle Door and Worbarrow Tout respectively. The Group is known to be 52 m thick on the Isle of Portland (Coe, 1996), but thicker in the East towards Swanage at 75-80 m (Barton et al., 2011). However, existing onshore evidence demonstrates that the Portland and Purbeck groups do show significant thinning within and along the Abbotsbury-Ridgeway and Purbeck Fault structures (within the PWFZ). For instance, the Portland Group, showing its full stratigraphical sequence, is recorded as only 27 m thick at Ringstead Bay (just to NE of Osmington Mills; Barton et al., 2011). The Purbeck Group, again in full stratigraphical sequence, thins from 60 m at Upwey just to the North of Weymouth, to 45-47 m at Stair Hole and Lulworth, and then thickens again to over 110 m at Durlston Bay near Swanage (Westhead and Mather 1996). This thinning of the Portland and Purbeck groups is attributable partly to sedimentological thinning effects in proximity to the major PWFZ, possibly in relation to syn-sedimentary movement, but is also likely to be in part due to structural thinning in association with shearing effects.

These results demonstrate the potential of using the offshore geology to help elucidate the stratigraphy and tectonics of the area. They suggest that any thickening (rollover) in the hanging wall of the Purbeck Fault is restricted to specific stratigraphic intervals and that there is a thinning

of most strata within its footwall. Thus, movement on the Purbeck Fault would have been limited and intermittent during the Jurassic and lowermost Cretaceous.

DISCUSSION

Extensional faulting and basin development

Extensive E-W extensional faulting in the onshore area, as exemplified by the detailed sub-surface exploration at Wytch Farm (Kattenhorn and Pollard 2001), is only seen along parts of the northern edge of Weymouth Bay (as at Osmington, **Fig. 6**). Throughout most of the Weymouth Bay area covered by the bathymetric survey, and despite the abundance of well-exposed marker beds on the sea floor, only a few short (<200 m) E-W fault traces with small (<5 m) throws have been mapped. This suggests that the upper Jurassic strata within the hanging wall of the PWFZ behaved as a relatively undeformed slab during much of the basin formation, with only limited tilting into the Purbeck Fault, and that internal deformation was largely confined to the footwall.

A complex of WNW-ESE-trending faults are mapped in the extreme SW of the surveyed area, beyond Weymouth Bay and to the West of the Isle of Portland, in an area not affected by N-S faulting. These faults affect the lower part of the Kimmeridge Clay, and the underling Corallian Group and Oxford Clay (**Fig. 1B**), downthrowing to the south by up to 10's metres, although their dip directions are unclear from the bathymetry alone. They are provisionally interpreted as forming under the same N-S extensional-compressional strain regime as the PWFZ, but occurring beyond its hanging wall. Only limited changes in the overall thickness of the sequences (in particular, Kimmeridge Clay Formation, and Portland and Purbeck groups) are mapped both across Weymouth Bay and northward into the coast. Detecting whether individual units thicken into the hanging wall of the Purbeck Fault, is important for understanding the pre- and post-inversion development of this structure. As discussed above, local thickness changes close to the Purbeck faults have been detected from our offshore mapping, supporting a model of limited roll-over and

supporting the model proposed by Underhill and Paterson (1998). This contrasts with significant thickness changes across the PWFZ and within major relays in the fault zone itself (e.g. Newell, 2000). Thus, taken together with a regional Eastwards thickening of many units, this suggests regional subsidence during the uppermost Jurassic (Oxfordian to Portlandian) with only limited and intermittent roll-over and thickening into the PWFZ.

Inversion Folding

Reactivation of the PWFZ during lower Tertiary inversion produced a major N-facing monocline, with the associated deformation zone being characterised by steep dips and tectonic thinning through omission of parts of the stratigraphy. The main manifestation of this inversion in Weymouth Bay is the northward steepening of dips, which become sub-vertical in the area around Durdle Door. This produces a narrowing of the outcrop of the strata, which can be clearly seen in the outcrop pattern of the Kimmeridge Clay (**Fig. 1**) where dips of over 30º to the north occur. To the south, the strata generally dip gently (2-5º) to the south. This produces an open rounded anticline whose crestal trace is seen offshore in the broad inlier of Corallian strata forming Lulworth Banks (**Fig. 7**). Donovan and Stride (1961) called this the “Purbeck Anticline”, which is misleading as it represents the crest, not the axial trace, of the main structure. Thus the axial trace of the anticline occurs farther to the north, where the dips change rapidly from gently to steeply inclined. To the east this structure becomes the asymmetric Kimmeridge Anticline (**Figs. 2B-D**).

Strain Partitioning

Our new mapping clarifies the structural framework of the area, demonstrating a broad division into a southerly domain of N-S faulting and open E-W folding, and a northerly, higher strain domain characterised by E-W faulting and tighter folding associated with the major inversion structures of the Abbotsbury-Ridgeway and Purbeck faults (together part of the major PWFZ lineament).

In the southerly domain, the geometry of the folds and faults indicates a general N-S principal shortening direction and sub-horizontal E-W extension. We propose that this indicates a distributed strain regime strain affecting the thicker sediments in the hanging wall to the PWFZ. This is consistent with the known style of Cenozoic inversion and the development of structural highs above the thicker fills in former Permian-Cretaceous basins (Evans et al. 2011).

In the northerly domain, we propose that the N-S shortening was accompanied by significant shear, with top-to-north movement associated with the PWFZ. In addition, important antithetic south-directed, 'conjugate' reverse faulting is interpreted as being responsible for the development of complex folding structures within the PWFZ, such as at Osmington (**Fig. 6**) and Lulworth (e.g. the 'Lulworth Crumple', Underhill & Paterson 1998). The intensity of deformation indicates that levels of strain are also higher in this domain, which would be consistent with focussed inversion movement on and above the PWFZ. The development of reverse, antithetic fault structures associated with the principal south-dipping inversion faults is also recognised on the Isle of Wight in the eastern continuation of the PWFZ (Evans et al. 2011). In that case, these reverse structures are largely seen affecting the Chalk, whereas in the current study they affect the underlying (Wealden, Portland and Purbeck) strata in the hanging wall of the Purbeck Fault.

An interesting additional observation is that the N-S faulting appears to largely die out to the west of the Isle of Portland, suggesting a relationship between N-S fault development and the intensity of deformation within the northern structural domain associated with the PWFZ. The steeper dips and more tightly constrained E-W structures of the Purbeck Monocline open out into the broader E-W trending and E-W faulted Weymouth anticline (**Fig. 1**). In the proposed partitioned strain model, this suggests a link between the distribution and intensity of shortening in the hanging wall domain with the level and focus of strain developed in association with the inversion fault zone. Thus, one might expect more intense strain in inverted basins south of the most intensely developed inversion lineaments and related monoforms.

Existing onshore BGS mapping shows that North of the PWFZ in Dorset, faulting and folding becomes less prominent, indicating generally lower levels of strain in the footwall, which may have acted as a rigid 'buttress' against which the above domains deformed. Such a rigid buttress could be responsible for focussing strain into the northern domain immediately above and within the PWFZ.

CONCLUSIONS

A hundred years of onshore geological investigation has provided an extensive data base of observations within a well-constrained stratigraphic framework that has allowed us to deduce the geological history of the area. The recently acquired offshore bathymetry has high resolution (1 m bin) and, when combined with aerial photographs and Lidar imaging of the coastal tract, provides new insights into the spatial arrangement of the structures over a much wider area. Several very important new insights into the sedimentary and tectonic inversion history of the Purbeck-Wight Fault Zone in Dorset and its adjacent depositional basin have emerged.

1) The upper Jurassic strata within the hanging wall of the PWFZ behaved as a fairly coherent slab, with only limited tilting into the Purbeck Fault, and that internal deformation was largely confined to the footwall. At least during the uppermost Jurassic (Oxfordian to Portlandian), there was only limited roll-over into the PWFZ, with only intermittent activity on it at this time.

2) The main effect of later N-S inversion-related compression was to produce an asymmetric, N-facing monoform in association with the PWFZ, whose upper anticlinal hinge is mapped through the northward steepening of dips. Within the hanging wall to the structure, strain is postulated to have been partitioned between distributed deformation in a broad southern domain and more intense shortening and shearing in a narrower northern domain associated with the immediate hanging wall of the PWFZ.

The latter coincides with the development of the steepest dips, extensive shearing (Bevan, 1985), thinning and omission of strata. This style of inversion deformation continues eastward to the Isle of Wight, where it is known from both surface mapping and offshore interpretation of seismic and bathymetric data (Collier et al. 2006).

3) Well-developed N-S extensional faulting is seen all across Weymouth Bay, in the southern hanging wall domain described above, and is known from coastal exposures (Putz-Perrier and Sanderson 2008). This faulting is postulated to be coeval with or late-stage in relation to broad E-W folding. This faulting was first detected by Donovan and Stride (1961), but can now be mapped in much greater accuracy and detail. These faults generally die out to the north as they approach the steeper zones in the Purbeck Monoform. This structural pattern is taken to reflect a distributed strain domain with N-S shortening and E-W extension. In contrast, N-S faulting is only occasionally described from the onshore (footwall) area, for example at Wytch Farm it appears to be almost entirely unrecognised.

What do these new observations tell us about the evolution of this and other basins? Firstly, it appears that the basin evolved by intermittent activity on a few major extensional faults, with large blocks of continuously subsiding sea-bed. Tilting producing limited thickness change but little facies variation, thus, most of the extension on these basin-bounding faults took place in the lower Cretaceous, i.e. at the end, not the start, of the ‘rift phase’ and led to widespread erosion of the uplifted footwall.

Secondly, inversion in the Cenozoic produced both reactivation of the basin-bounding PWFZ, and development of the Purbeck Monoform in the post-rift sequence (i.e. above the Albian Aptian unconformity) and in the pre- and syn-rift sequence to the south of the PWFZ, where it produces a broad open fold associated with distributed N-S shortening. Laterally variable reactivation of

the major faults along the PWFZ lead to the development of a high strain zone in its immediate hanging wall, characterised by combined shortening and shearing, with consequent synthetic and antithetic thrusting, structural thinning and localised fold development. Hence, the inversion-related deformation was not restricted to slip on the earlier faults, but distributed more broadly in the hanging wall block, with the widespread development of the N-S faulting. Thus the basin-bounding faults appear to have compartmentalized deformation and uplift, with the footwall block acting more as a buttress to compression.

ACKNOWLEDGMENTS

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563

564 **FIGURE CAPTIONS**

565 **Fig. 1.** Offshore mapping of the Weymouth Bay area. A) bathymetry image, with OS Panorama
566 topography for onshore areas. B) Geological map produced from the new digital imagery ARF
567 and PF stand for Abbotsbury-Ridgeway and Purbeck Fault respectively.

568 **Fig. 2** (**A**) Shows ancillary datasets: OS Panorama topographic data, CCO Lidar (coastal strip),
569 boreholes, cores of Donovan & Stride and 2D seismic data. The locations of other figures are also
570 shown. (**B**) Detail of the hill-shade image showing location of small faults. (**C**) Slope raster image
571 together with dips of bedding determined from this. (**D**) Aspect raster with details of mapping of
572 thin carbonate layers referred to locally as carbonate “stone bands”.

573 **Fig. 3.** (**A**) Detail of area to the east of Kimmeridge Bay (location in Fig. 2) showing the
574 integration of Lidar (inland – grey scale), air photographs (coastal strip) and bathymetry (offshore
575 – colour scale) . (**B**) shows the mapping of a series of thin (~0.5 m) carbonate “stone beds” in the
576 Kimmeridge Clay Formation: WL - Washingstone Ledge, ML - Maple Ledge, YL - Yellow Ledge,
577 CL - Cattle Ledge, GL - Grey Ledge, RL - Rope Lake, B - Basalt, W - Whitestone, FS - Freshwater
578 Steps; together with location of faults examined in the cliffs (red symbols).

579 **Fig. 4.** Image and profile of the sea-bed produced by combining bathymetry (colours) with hill-
580 shade images showing “stone bands” in part of the Kimmeridge Clay. Location shown in Fig. 2;
581 note North is orientated to left in this image. Stone band ledges correlated with those established
582 from borehole logging (Gallois 2000, Morgans-Bell et al. 2001): sB, sC, sD – Swanworth B, C, D;

H - Hobarrow; F – Flats; W – Washing stone, M - Maple Ledge, Y - Yellow, C - Cattle, G - Grey, RL - Rope Lake, B - Basalt, W - Whitestone, FS - Freshwater Steps.

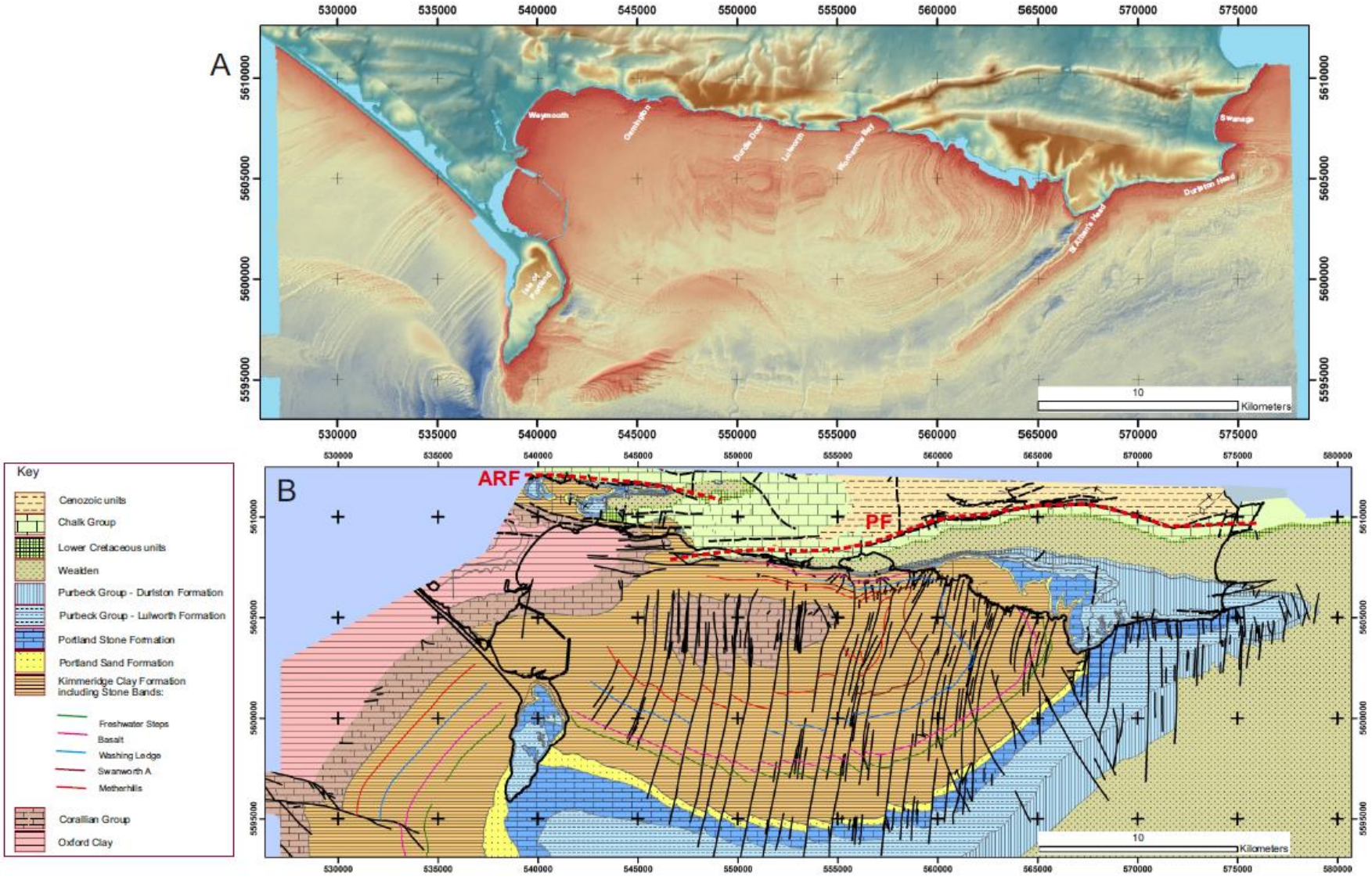
Fig. 5. Perspective view of 2D seismic and bathymetry (colour scale) and lidar (grey scale) showing the Lulworth Banks anticline and Purbeck Fault. The seismic data (line AUK-94-AJ056) was acquired by Amoco UK Exp. Ltd in 1994 using a conventional airgun array. The section has a post-stack time migration applied.

Fig. 6. (**A**) Bathymetry and aerial photography of an area between between Osmington Mills and Ringstead (location in Fig. 2). (**B**) Interpretation of the stratigraphy and E-W-trending normal faults affecting the Corallian sequence. These are developed in a large relay ramp between the Purbeck and Abbotsbury-Ridgeway faults.

Fig. 7. (**A**) Hill-shaded bathymetry of Lulworth Banks (location in Fig. 2). (**B**) Interpretation of the stratigraphy and N-S-trending normal faults affecting the Corallian and lower part of the Kimmeridge Clay sequence.

Figure

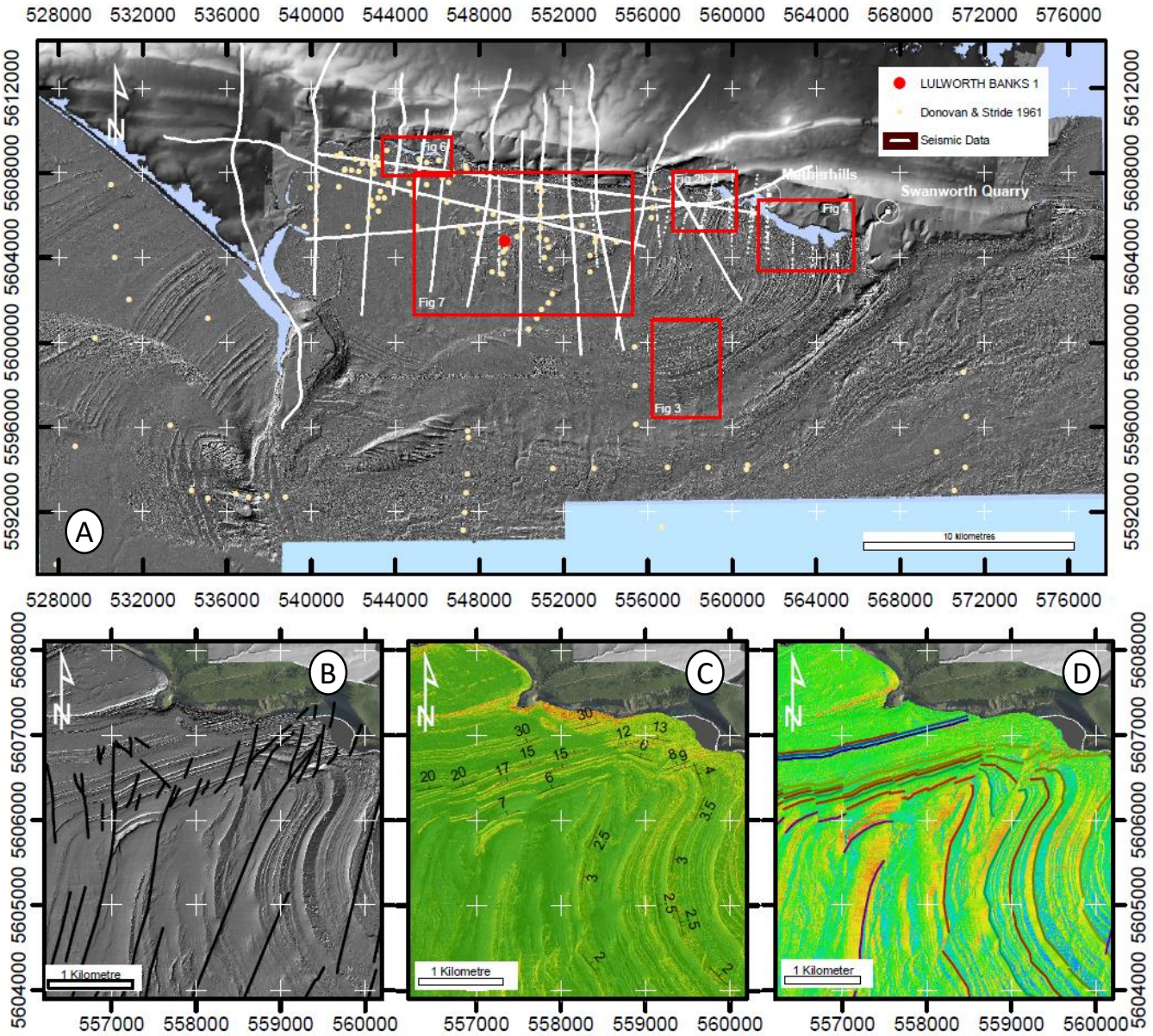
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Sanderson, Dix, Westhead, Collier Fig. 1

Figure

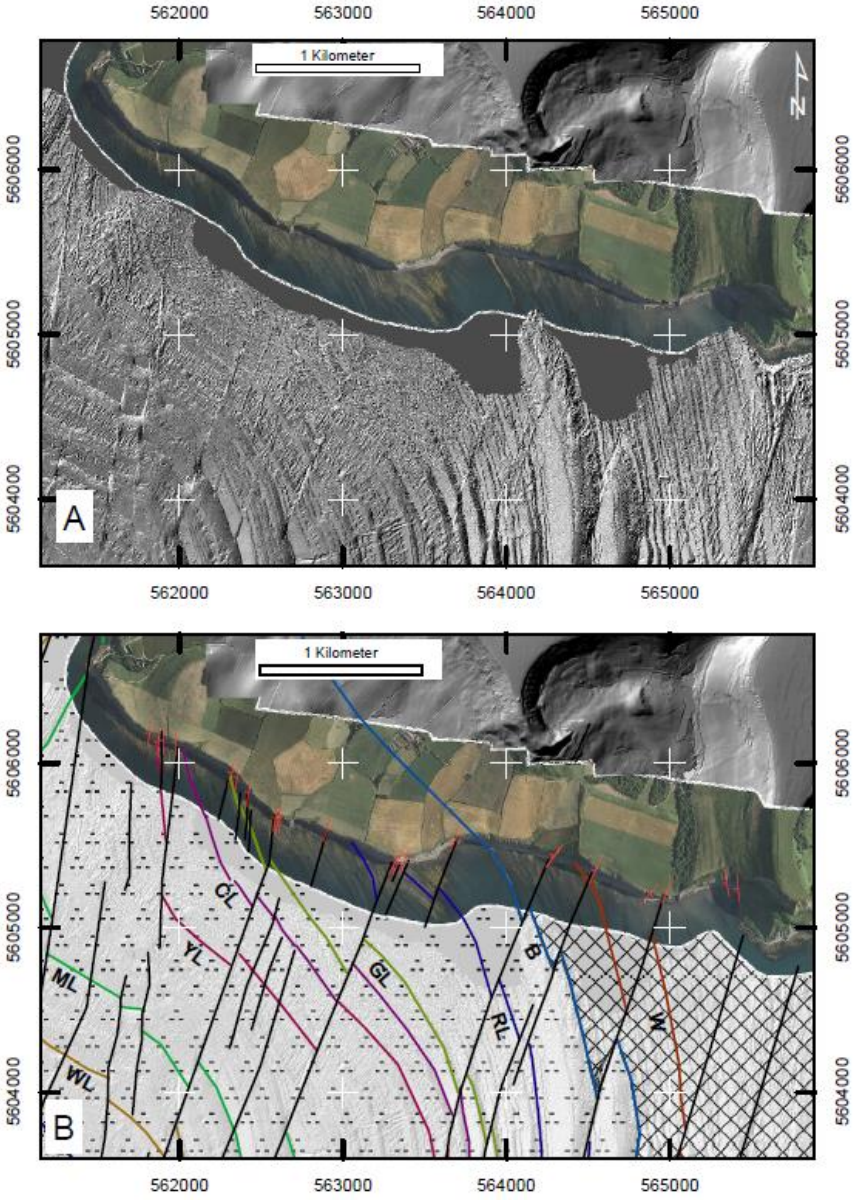
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Sanderson, Dix, Westhead, Collier Fig. 2

Figure

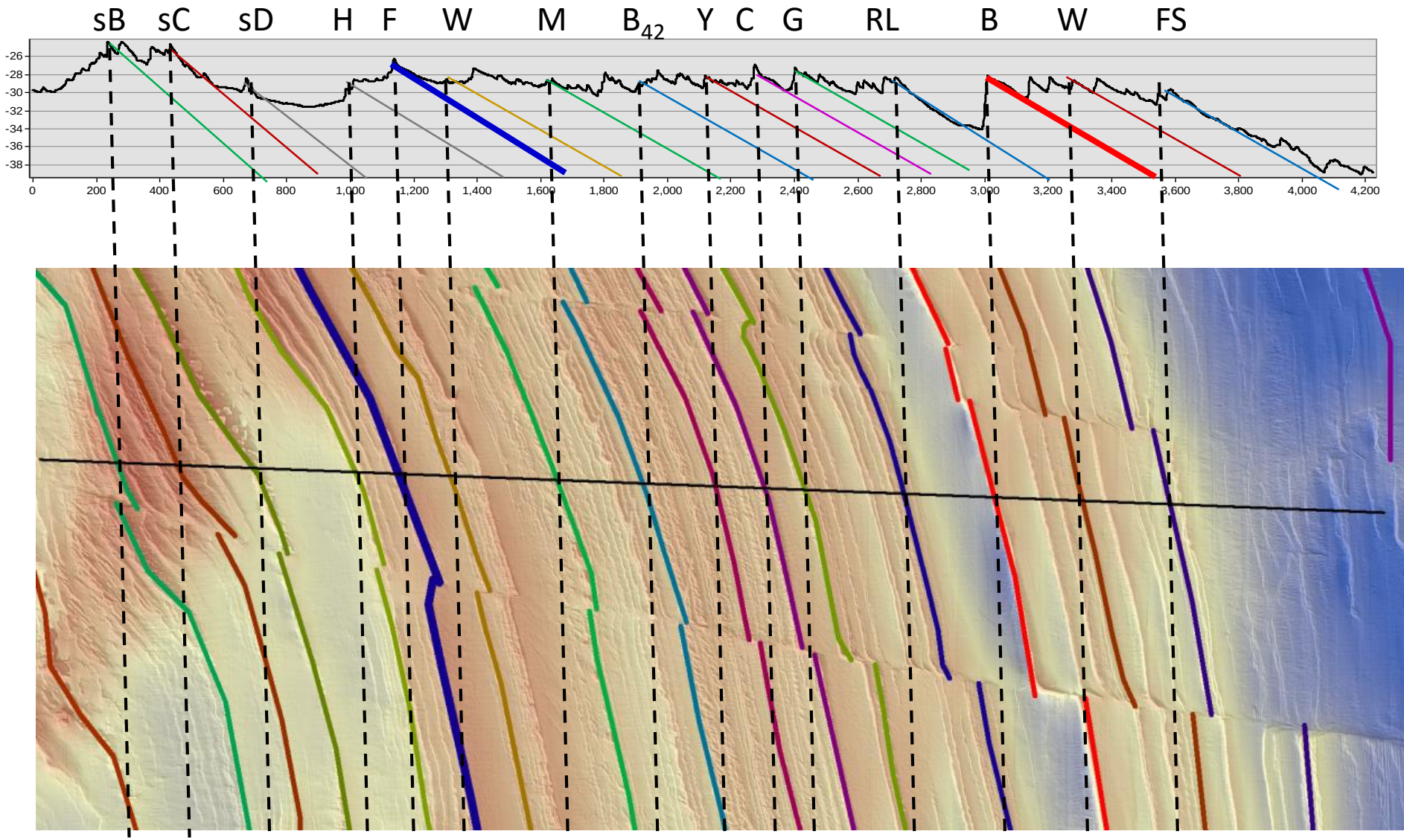
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Sanderson, Dix, Westhead, Collier Fig. 3

Figure

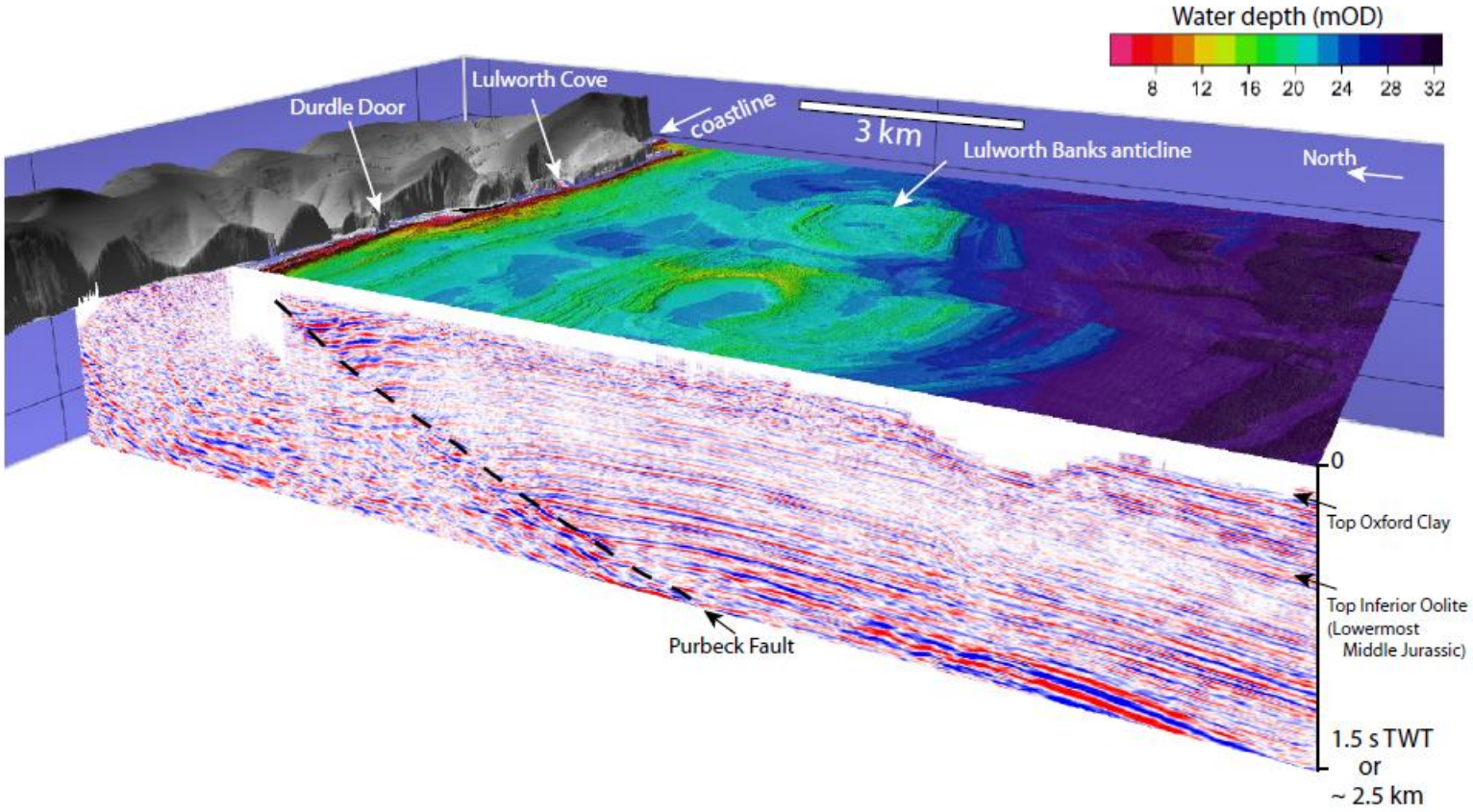
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Sanderson, Dix, Westhead, Collier Fig. 4

Figure

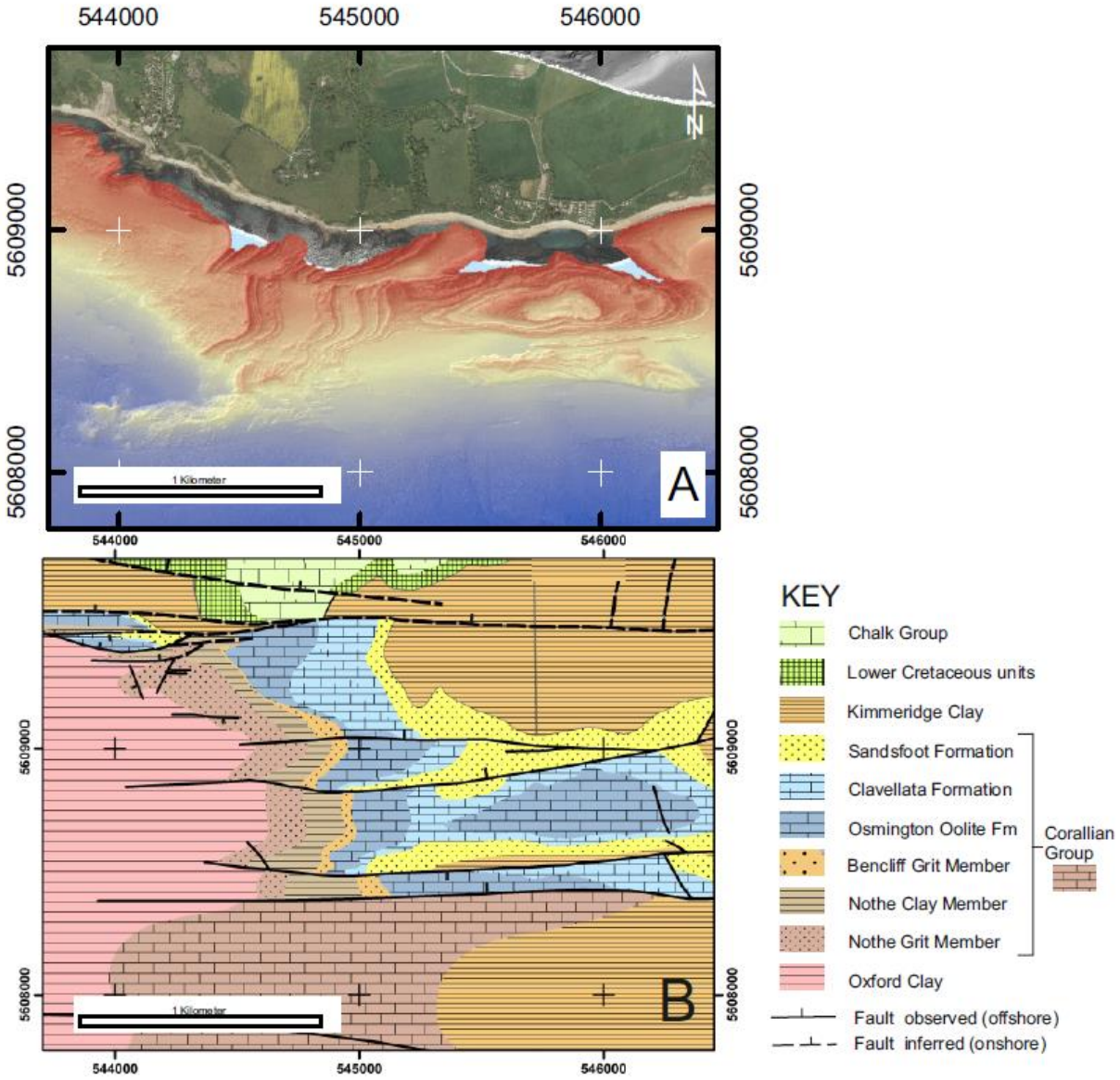
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Sanderson, Dix, Westhead, Collier Fig. 5

Figure

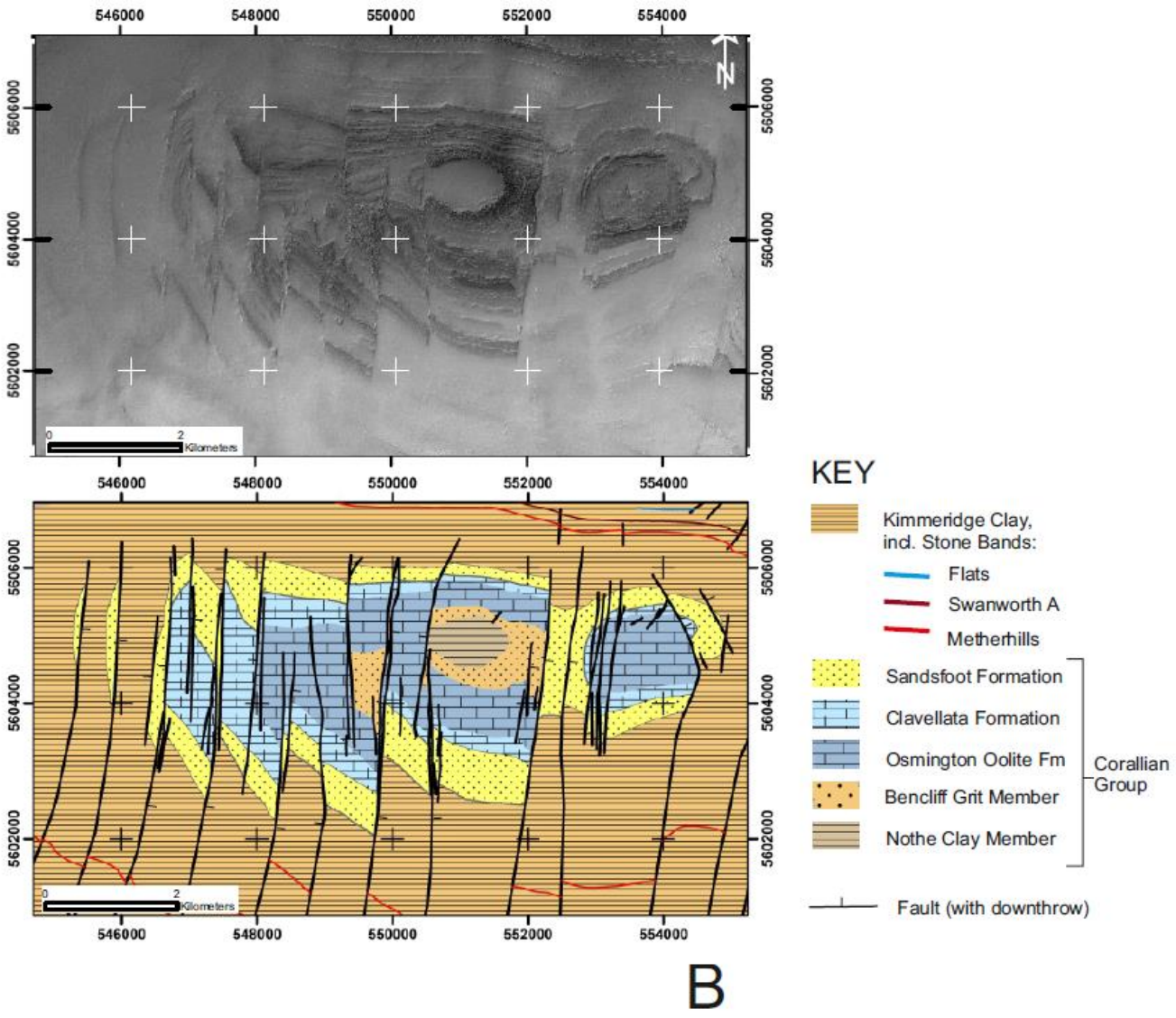
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Sanderson, Dix, Westhead, Collier Fig. 6

Figure

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Sanderson, Dix, Westhead, Collier Fig. 7