Spatial variability of the Purbeck-Wight Fault Zone - a long-lived tectonic element in the southern UK.

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Abstract

New seamless onshore to offshore bedrock (1:10k scale) mapping for the Lyme Bay area is used to resolve the westward termination of the Purbeck-Wight Fault Zone (PWFZ) structure, comprising one of the most prominent, long-lived (Variscan-Cimmerian-Alpine) structural lineaments in the southern UK. The study area lies south of the Variscan Frontal Thrust and overlays the basement Variscide Rhenohercynian Zone, in a region of dominant E-W tectonic fabric and a secondary conjugate NW-SE/NE-SW fabric. The PWFZ comprises one of the E-W major structures, with a typical history including Permian to early Cretaceous growth movement (relating to basement Variscan Thrust reactivation) followed by significant Alpine (Helvetic) inversion. Previous interpretations of the PWFZ have been limited by the low resolution (1:250k scale) of the available offshore BGS mapping, and our study fills this gap. We describe a significant change in structural style of the fault zone from east to west. In the Weymouth Bay area, previous studies demonstrate the development of focussed strain associated with the PWFZ, accompanied by distributed strain, N-S fault development, and potential basement uplift in its hangingwall. In the Lyme Bay area to the west, faulting is dominantly E-W, with N-S faulting absent. Comparison of the newly mapped faulting networks to gravity data suggests a spatial relationship between this faulting variation and basement variability and uplift.

1. Introduction

Deformation in late Palaeozoic, Mesozoic and Cenozoic sequences in the southern UK is characterised by the development of major *en echelon* E-W orientated faults, which may be partially inherited from Variscan 'basement' structures, and which acted as growth faults controlling the deposition of Permian through to the late Cretaceous sequences, and furthermore provided the focus for Alpine inversion (Stoneley, 1982; Lake and Karner, 1987; Chadwick, 1986, 1993; Ziegler, 1987; Peacock and Sanderson, 1999; Smith and Hatton, 1998; Underhill and Stoneley, 1998; Underhill and Paterson, 1998; Blundell, 2002; Chadwick and Evans, 2005). The faults demonstrate significant structural variability along their length, relating for example to differing degrees of inversion in post-rift sequences and the development of overlapping major fault segments (e.g. Barton et al., 1998; Harvey and Stewart, 1998; Underhill and Paterson, 1998; Collier et al., 2006; Evans et al., 2011). Focussed inversion along these faults was accompanied by more distributed deformation and uplift of the intervening basins (Chadwick, 1993; Blundell, 2002; Sanderson et al., 2017).

The Purbeck-Wight Fault Zone (PWFZ) is one of the best-developed of these late Cretaceous-Cenozoic inversion lineaments, extending along strike for over 100 km from east of the Isle of Wight to Lyme Bay in the west (Fig. 1). It includes multiple overlapping fault segments, including, for instance, the Purbeck Fault extending across the south of the Isle of Purbeck, and the Abbotsbury-Ridgeway Fault extending westwards into Lyme Bay (Fig. 1; Fig. 2; Stoneley, 1982; Hamblin et al., 1992; Chadwick and Evans, 2005; Evans et al., 2011). The history of study of the spectacular exposures of this World Heritage site 'Jurassic Coast', accompanied by detailed onshore and offshore mapping, and subsurface seismic interpretation, also make it one of the best understood examples of a major structure affecting both the deposition and deformation of cover sequences in the southern UK (e.g. Arkell, 1936, 1947; Chadwick, 1993; Underhill and Paterson, 1998; Barton et al., 2011). The topographical and tectonostratigraphical position of the PWFZ, extending west towards the margins of the exposed Cornubian basement massif in SW England, and to lower exposed (Permo-Triassic) stratigraphical levels than many of the other inversion fault zones in the southern UK, make it of particular interest.

Our current knowledge of the structures in southern England comes mainly from the interpretation of geological and geophysical data collected in the 1980s-2000s (summarised, for example, in Chadwick and Evans, 2005). Much of this work was implemented by the BGS as part of its mapping programme of the British Islands, together with commercial organisations principally driven by exploration for conventional hydrocarbons (Underhill and Stoneley, 1998). More recently, the onshore area has been evaluated for shale oil and shale gas potential (Greenhalgh, 2016). This exploration has resulted in a wealth of information including outcrop observations, borehole logs, seismic reflection profiles and potential field grids. Whilst these traditional datasets are still being expanded with new acquisition campaigns it is the application of new technologies that arguably offer the biggest potential to significantly advance our understanding of the structure of this well-known area. Recent examples of these new approaches include DInSAR onshore (Aldiss, 2013), and swath bathymetry offshore (Collier et al., 2006; Sanderson et al., 2017), both of which provide high resolution imagery of previously unseen structures that complement traditional datasets and allow current interpretations to be tested.

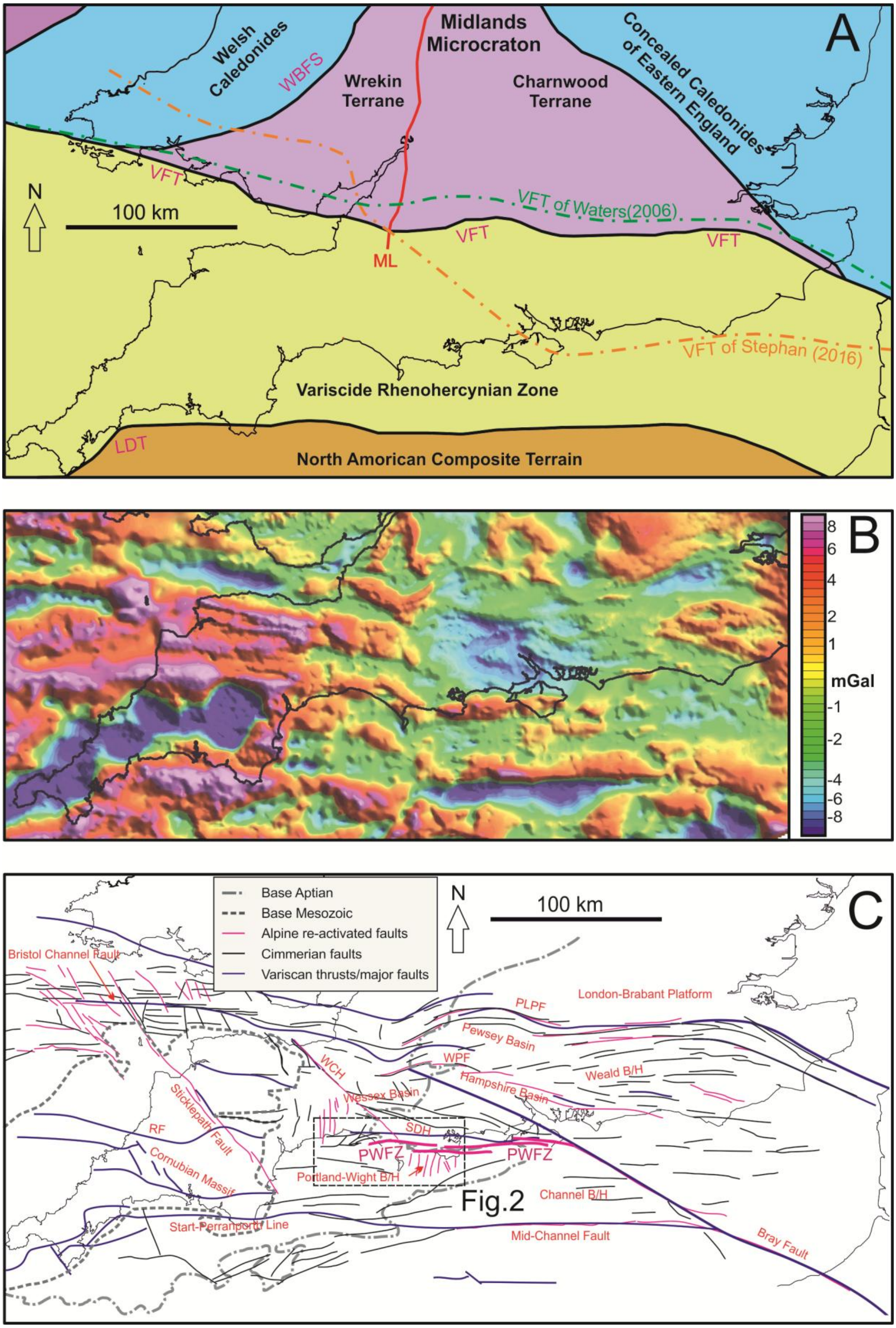

A
Midlands Microcraton
Welsh Caledonides
WBFS
Wrekin Terrane
Charnwood Terrane
Concealed Caledonides of Eastern England
N
100 km
VFT
VFT of Waters(2006)
ML
VFT
VFT
VFT of Stephan (2016)
Variscide Rhenohercynian Zone
LDT
North Amorican Composite Terrain
B
8
6
4
2
1
mGal
-1
-2
-4
-6
-8
C
Base Aptian
Base Mesozoic
Alpine re-activated faults
Cimmerian faults
Variscan thrusts/major faults
N
100 km
Bristol Channel Fault
PLPF
London-Brabant Platform
Pewsey Basin
WPF
WCH
Hampshire Basin
Weald B/H
Wessex Basin
Sticklepath Fault
RF
SDH
PWFZ
PWFZ
Cornubian Massif
Portland-Wight B/H
Fig.2
Channel B/H
Start-Perranporth Line
Mid-Channel Fault
Bray Fault

Figure 1. Regional tectonic setting. **A.** Basement terranes of Southern Britain, after Chadwick and Evans (2005), including their proposed position of the Variscan Frontal Thrust (labelled VFT); differing positions proposed by other authors for the VFT are also shown; WBFS = Welsh Borderland Fault System; ML = Malverns Lineament.; **B.** BGS regional gravity compilation, with scale as shown (Bouguer onshore and free-air offshore; residual after subtraction of an upward-continued field); **C.** Compilation map of major fault lineaments in southern Britain, both concealed and cropping out. WCH = Watchet-Cothelstone-Hatch Fault; SDH = South Dorset High; WPF = Wardour-Portsdown Fault Zone; PLPF = Pewsey-London Platform Fault Zone; B/H = Basin/High; RF = Rusey Fault Zone. Base of Mesozoic cover and Base Aptian (Lower Cretaceous) shown. Compiled principally from Chadwick and Evans (2005), with additional information from the literature (including Stephan et al., 2016; Warr, 2012; Holdsworth, 2012; Waters and Davies, 2006; Leveridge and Hartley, 2006; Chadwick and Evans, 2005; Stoneley, 1982), plus additional lines from BGS digital mapping. Principal faults within the PWFZ emphasised in bold purple. Offshore faults in the study area (Fig. 2) taken from Sanderson et al. (2017) for Weymouth Bay, and from the present mapping in Lyme Bay.

We aim to improve our understanding of the PWFZ, by building on the work Sanderson et al. (2017), and extending the seamless onshore-offshore bedrock mapping westwards from Weymouth Bay to include a further 800 km^2 of the offshore area of Lyme Bay (Fig. 2). This area is key to understanding the lateral variation in structural style along this major structure, and has previously been covered only by 1:250 k mapping (BGS DigRock250). We also extend previous subsurface understanding, such as that of Harvey and Stewart (1998) for Lyme Bay, by linking seismic interpretation to the surface mapping. The new surface mapping, in particular the fault network distribution, is compared to existing BGS onshore and UKCS regional gravity compilations in order to understand any potential link between higher and deeper level (potentially Variscan) structure. This contribution considers the PWFZ in a regional context, and provides new details on the tectonic regime in this pivotal location, as well as adding to the wider understanding of inversion tectonics in southern Britain.

2. Tectonic setting

The depositional and tectonic framework of the southern UK to the south of the Variscan Frontal Thrust (VFT) relates to the characteristics of both 'basement' rocks (generally Carboniferous or older in age) and 'cover' rocks (generally Permian or younger). The basement is defined tectonostratigraphically as the Variscide Rhenohercynian Zone (Chadwick and Evans, 2005; Leveridge and Hartley, 2006; Fig. 1A), bounded to the north by the Variscan Frontal Thrust, the origin and position of which has been the subject of debate (e.g. Chadwick and Evans, 2005; Waters and Davies, 2006; Stephan et al., 2016; Fig. 1). This thrust is interpreted as the northern limit of major Variscan orogenic deformation, typified by northward-propagating thrusting (with E-W striking thrusts developed under broadly N-S shortening), and pervasive cleavage development of the basement rocks, such as evident in the Devonian and Carboniferous sequences exposed in SW England (Leveridge and Hartley, 2006; Holdsworth et al., 2012; Warr, 2012; Woodcock and Strachan, 2012). The cover sequences range from Late Palaeozoic (Permian), through Mesozoic, to Cenozoic in age, and are affected by several generations of less pervasive deformation.

The dominant 'tectonic fabric' of the southern UK is formed by major, 10's km-spaced E-W striking faults, and secondary fabric of similar spatial scale formed by mainly NW-SE but also NE-SW striking fault lineaments, each with associated, often sub-parallel, open to locally intense folding. These deformation lineaments in the cover are commonly but not always linked to Variscan structures in the basement (e.g. Chadwick et al., 1983; Hawkes et al., 1998; Underhill and Stoneley, 1998; Blundell, 2002). The Variscan Orogeny extended from the Devonian, through the Carboniferous, to the early Permian (Chadwick and Evans, 2005; Holdsworth et al., 2012; Warr, 2012). In its later stages in NW Europe and the UK the development of E-W orientated thrust structures was accompanied by the development of NW-SE striking right-lateral strike slip faults developed under oblique NNW-SSE shortening (transpression) across the E-W to WNW-ESE trending Variscan deformation belt (Lake and Karner, 1987; Stephan et al., 2016). Such NW-SE striking faults occur widely across the Variscan belt and include the Watchet-Cothelstone-Hatch and the Sticklepath Fault (Holloway and Chadwick, 1986; Chadwick and Evans, 2005; Leveridge and Hartley, 2006; Fig. 1C). Right-lateral strike-slip offset is also inferred to have occurred, principally during the Carboniferous, along the NW-SE Bristol Channel-Bray Fault, a notable crustal structure, which was responsible for north-westwards transport for some 400 km of the Cornubian terrane against the Avalon terrane (Holder and Leveridge, 1986; Holdsworth et al., 2012; Warr, 2012; Woodcock, 2012).

The E-W tectonic fabric is apparent beneath cover rocks in SE England as curvilinear and en echelon lineaments on gravity and magnetic data (Lee et al., 1990; Blundell, 2002; Fig. 1B). The basement structures are thought to have exerted a spatially variable and episodic influence on deposition and subsequence inversion of overlying Mesozoic sequences (Chadwick, 1993; Blundell, 2002; Chadwick and Evans, 2005). Although the degree of this basement influence is debatable, there is evidence for interaction between newly formed Mesozoic extensional faults and selective re-activation of favourably orientated Variscan structures (Holdsworth et al., 2012).

Orogenic collapse and thermal uplift following the Variscan Orogeny led to the development of the Variscan unconformity, above which the cover sequences of Permian and younger cover rocks were deposited (Hounslow et al., 2012; base Mesozoic on Fig. 1C). These cover sequences are affected by the late Palaeozoic (Permian) to Cenozoic Cimmerian-Alpine tectonic cycle, subdivided by the regional Cimmerian, or Albian-Aptian unconformity into the Permian to Lower Cretaceous, and Upper Cretaceous (and younger) megasequences (Underhill and Paterson, 1998; Underhill and Stoneley, 1998; Chadwick and Evans, 2005; Sanderson et al., 2017; Fig. 1C). Permian and Triassic deposits in the southern UK were deposited in a series of fault controlled basins (with evaporites common in thicker basinal settings), which were influenced by re-activation of existing Variscan contractional structures (e.g. Chadwick, 1986). East-west trending extensional basins were also compartmentalised by NW-SE trending faults possibly inherited from Variscan structures (Lake and Karner, 1987; Barton et al., 1998; Blundell, 2002; Chadwick and Evans, 2005). The relationship between the Variscan and higher level structures is in places complicated by the development of 'short-cut' faulting structures extending upwards from the shallower basement thrusts (Blundell, 2002; Chadwick and Evans, 2005). Regional uplift formed a persistent high in SW England (the Cornubian massif) during Permian and later times, acting as a source of sediment to basins to the east and south (Gale, 2012; Hesselbo, 2012; Hounslow et al., 2012;). Thermal doming and regional uplift, which formed the Albian-Aptian unconformity, was followed by passive margin subsidence and deposition of the late Cretaceous megasequence, including the Chalk (Lake and Karner, 1987; Underhill and Stoneley, 1998).

The Alpine deformational phase includes earlier 'Laramide' (Cretaceous) and later 'Helvetic' (Neogene) phases (Chadwick and Evans, 2005). The later phase was responsible for reversed movements (inversion) on many of the basin-bounding growth faults inherited from the Variscan template, accompanied by more distributed uplift of the basinal areas; this produced vertically and laterally variable, and often significant, erosion of the Chalk (Chadwick, 1993). One of the best examples of this is the PWFZ, with around 1000 m of distributed hangingwall uplift and erosion south of the main fault zone, and up to 2000 m within the fault zone (Chadwick, 1993; Law, 1998).

3. Faulting history in the southern UK

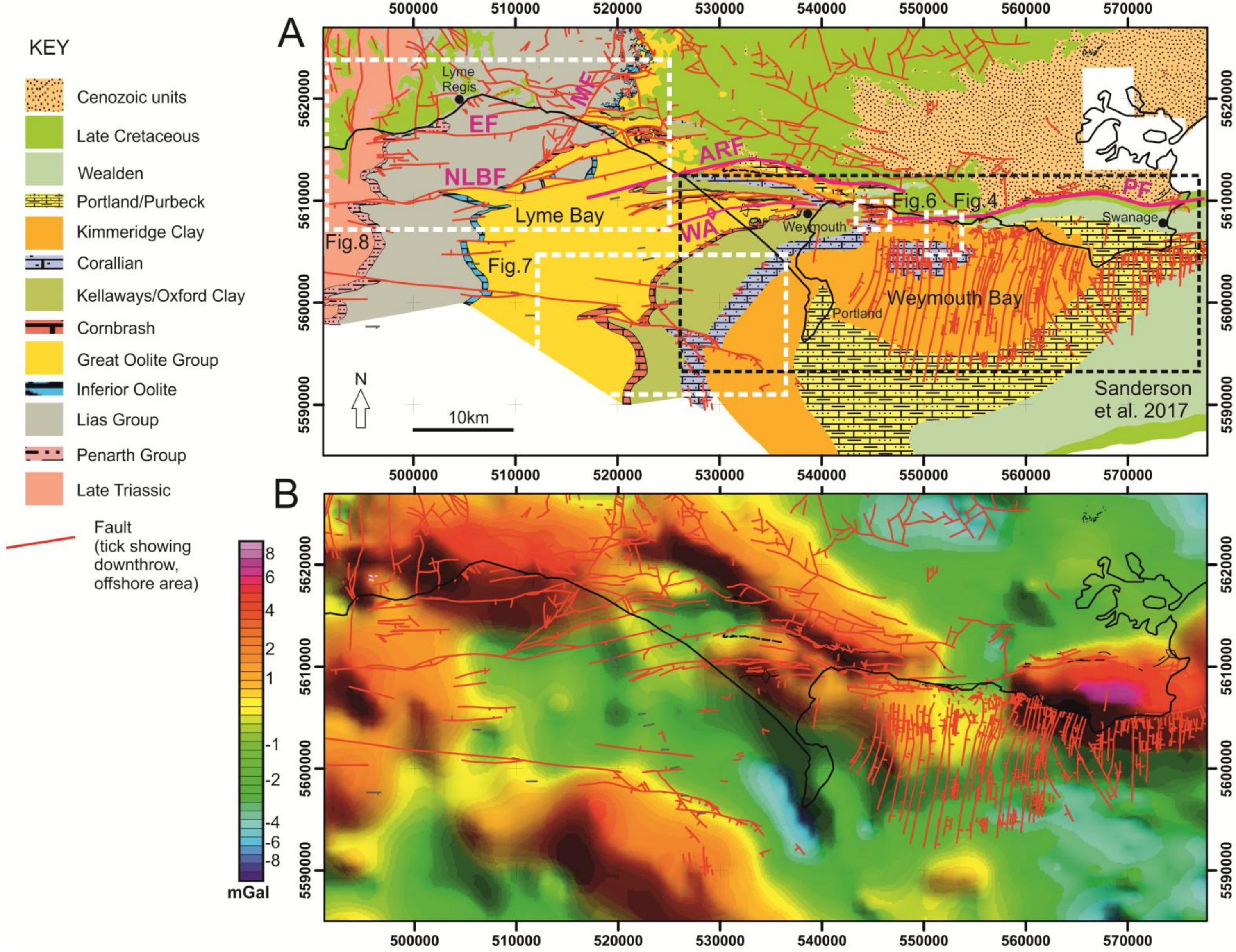
We have compiled information from the literature regarding the principal (most laterally and vertically persistent) faults in the southern UK. This compilation elucidates the broad picture that this region is characterised by E-W and NW-SE structural fabrics, picked out by major fault zones at depth and at outcrop (Fig. 1C). Two broad domains are apparent, separated by the projected trend of the Bray Fault: a region to the east, characterised by the dominantly E-W orientated en echelon faults, and; an apparently more complex region to the west, where the E-W fault traces are often accompanied by NW-SE, and subsidiary NE-SW and N-S traces. Our study area occupies a central location in the western region, lying on the northern margin of the Channel Basin, which is bounded by the Bray Fault to the east and Sticklepath Fault to the west (Harvey and Stewart, 1998; Fig. 1C). The north-westwards projection of the Bray Fault to link up with the Bristol Channel fault zone is, however, contentious. A number of authors project the lineament north-westwards across central southern England to link up with the Bristol Channel fault system, in order to define broad tectonic terranes (e.g. Holdsworth et al., 2012, on which the projected line in Fig. 1 is based), whilst others prefer to show the Bray Fault merging with the PWFZ (e.g. Lake and Karner, 1987; Mortimore and Pomerol, 1997; Harvey and Stewart, 1998). We would support the latter interpretation given that the gravity data (Fig. 1B) does not show any features supporting the north-westwards projection.

In the southern UK, the direction of principal extension during Permian to late Cretaceous basin development was approximately N-S (Stoneley, 1982; Chadwick, 1993). Key examples of basin-controlling E-W striking faults are the PWFZ (including the Purbeck-Wight and en echelon Abbotsbury-Ridgeway elements) and the Wardour-Portsdown Fault further to the north (Fig. 1C). The PWFZ is linked to deeper Variscan structures and was periodically active as a growth fault from Triassic to early Cretaceous times with significant downthrow to the south, for example, by at least 1700 m on the Isle of Wight (Chadwick and Evans, 2005). The fault zone is taken broadly to define the northern margin of the Channel Basin (also termed Portland-Wight Basin), itself bounded to the south by the E-W Mid-Channel Fault lineament (e.g. Lake and Karner, 1987; Harvey and Stewart, 1998; Underhill and Stoneley, 1998; Chadwick and Evans, 2005).

The PWFZ is also one of the best examples in the southern UK of late Cretaceous-Cenozoic inversion (relating to N-S shortening) on an earlier E-W striking extensional fault. This is seen in the development of the Purbeck monoclinal structure in the (post-rift) late Cretaceous Chalk (e.g. Stoneley, 1982; Chadwick, 1993; Blundell, 2002). Other similar examples in the southern UK are the Wardour and Hog's Back monoclines (Lake and Shepherd-Thorn, 1985; Barton et al., 1998). The degree of evident inversion on these major structures is dependent on both the observed stratigraphical level and the amount of pre-inversion extensional displacement (Stoneley, 1982, Chadwick, 1993, Underhill and Stoneley, 1998, Blundell, 2002, Chadwick and Evans, 2005). The Abbotsbury-Ridgeway Fault component of the PWFZ, for example, shows an apparent reversed sense of movement in its eastern (largely onshore) segment, with Jurassic sequences upthrown to the south against Chalk, but apparent normal displacement in its western segment (as it tracks offshore) with downthrow to the south of late Jurassic against early Jurassic sequences (Chadwick and Evans, 2005; Fig. 2).

Across the southern UK, away from such major fault zones, deformation of the intervening basins during the inversion phase was characterised by open folding and domal uplift (Blundell, 2002). Collier et al. (2006) demonstrate how deformation of the Channel Basin graben, between the inverted Purbeck-Wight fault to the north, and the Mid-Channel Fault to the south, is characterised by broad folding in the centre and more intense folding near the rift margins. The form of the rift-margin deformation varies along strike, however, indicating that it is partly controlled by variation in the properties of the basin fill. Where incompetent rocks are present they focussed uplift, or mechanical 'extrusion', by up to 1500 m (Collier et al., 2006). This behaviour is in contrast to the neighbouring Weald Basin, which has a symmetric outcrop and inversion structure. The Weald Basin did not initiate until the Early Jurassic and the lower syn-rift fill of this (Lias) age is a more competent succession of limestone and sandstone with occasional mudstone than that deposited in the Channel Basin (Hawkes et al., 1998). The Weymouth Anticline, which is in the hangingwall of the PWFZ, is thought to have developed in response to inversion, or to represent an uplifted earlier roll-over fold (Fig. 2; Underhill and Paterson, 1998; Chadwick and Evans, 2005). The footwalls to the major inversion faults also acted as rigid 'buttresses' during the inversion phase. For example, Chadwick and Evans (2005) suggest the footwall of the Abbotsbury-Ridgeway fault acted as a buttress, which encouraged short-cut reverse faulting in the hangingwall during inversion. Sanderson et al. (2017) similarly propose that the footwall to the Purbeck Fault acted as a rigid buttress, encouraging the development of extensive N-S striking normal faulting (exposed beneath Weymouth Bay; Fig. 2) in response to distributed stress in the hangingwall.

The NW-SE striking Sticklepath and Watchet-Cothelstone-Hatch faults, which bracket the Lyme Bay area to its west and north-east, have long-lived movement history (dominated by strike-slip), extending from the Variscan through to the Alpine phases, with a number of reversals in the sense of strike-slip movement. Holloway and Chadwick (1986), for example, imply a 10 km right-lateral offset on the Sticklepath Fault during the late Variscan. This is demonstrable through offset of an earlier thrust structure (implied itself to be later re-activated as a basin-bounding fault to the Permian deposit-filled Crediton trough), and Leveridge and Hartley (2006) indicate that the structure had a basin-constraining role during deposition of Carboniferous sequences. Holloway and Chadwick (1986) suggest a reversal of this offset (by up to 6 km) through left-lateral strike-slip during the early Cenozoic (Eocene-Oligocene; forming the 'pull-apart' Bovey Tracey and Petrockstowe basins), followed by a return to right-lateral strike slip during the later Cenozoic (relating to variations in the Cenozoic stress field). Chadwick and Evans (2005) propose a similar history for the NW-SE orientated, steeply SW-dipping Watchet-Cothelstone-Hatch Fault, culminating in late Cenozoic (Alpine Helvetic) transpression (in response to N-S shortening), driving right-lateral strike slip and the development of the Compton Valence Dome as a 'pop-up' structure along the fault.



KEY
Cenozoic units
Late Cretaceous
Wealden
Portland/Purbeck
Kimmeridge Clay
Corallian
Kellaways/Oxford Clay
Cornbrash
Great Oolite Group
Inferior Oolite
Lias Group
Penarth Group
Late Triassic
Fault (tick showing downthrow, offshore area)
mGal
A
B
Lyme Regis
EF
MF
NLBF
ARF
WA
PF
Lyme Bay
Weymouth
Weymouth Bay
Portland
Swanage
Fig.4
Fig.6
Fig.7
Fig.8
Sanderson et al. 2017
N
10km

Figure. 2. Onshore-offshore bedrock mapping of the Lyme Bay- Weymouth Bay region (location shown in Fig. 1). The area of Weymouth Bay previously mapped by Sanderson et al (2017) is shown outlined with a black dotted line; the rest of the offshore area, including Lyme Bay, is that mapped in the present study. **A.** Geological bedrock map, showing locations of figures later in the paper, outlined with white dotted lines. The Abbotsbury-Ridgeway Fault (ARF) and Purbeck Fault (PF) in the PWFZ are emphasised in bold purple; other principal faults are labelled: comprising: MF = Mangerton Fault; EF = Eypemouth Fault; NLBF = North Lyme Bay Fault. The Weymouth Anticline (WA) trace is also shown. **B.** Residual gravity grids taken from the BGS regional gravity compilations (see methods), with scale shown. Overlain with the surface-mapped faults shown in A.

4. Lyme Bay to Weymouth Bay study area

We focus on the east Devon-west Dorset area, extending the work of Sanderson et al. (2017) in Weymouth Bay westward into the offshore area of Lyme Bay (Fig. 1C; Fig. 2). One key aim was to understand if the structures detected in Weymouth Bay, in particular, the intense development of N-S striking extensional faulting in the PWFZ hangingwall extended further westwards.

4.1. Methods and data

We have undertaken a new bedrock mapping interpretation across ~800 km^2 of the seabed and coastal area of Lyme Bay at a detailed 1:10 000 scale using compiled bathymetric and coastal Lidar data, and joined it to the existing onshore BGS mapping. Figure 2 shows the extent of the mapping of Sanderson et al. (2017) and the remaining offshore area shown is our new interpretation. Additionally we have re-interpreted a number of key seismic sections to discern the surface and subsurface structure, both in Lyme Bay and along the Weymouth Bay coast. We have also used the detailed coastal and seabed mapping based on side-scan sonar of Darton et al. (1981) for the area of northern Lyme Bay south of Lyme Regis to contribute to the interpretation.

The geological mapping and seismic interpretations are based on identification of key marker formations in the Triassic, Jurassic and Cretaceous sequences occurring across the area, which form identifiable geomorphological featuring (onshore and offshore) and principal reflectors on seismic profiles. The bedrock mapping is based primarily on geomorphological feature mapping against swath bathymetry data for the offshore areas, supported by aerial Lidar data for the coastal sections. The key markers used in the mapping are generally the thinner, limestone-dominated shallower-water originating formations, including the Penarth Group, Inferior Oolite Formation, Cornbrash Formation, Corallian Group, and Portland and Purbeck groups (undivided) (Fig. 3). These lie between the thicker, mudstone-dominated, generally deeper-water sequences, including Triassic mudstones, Lias Group, Great Oolite Group, Kellaways and Oxford Clay formations (undivided) and Kimmeridge Clay Formation. Figure 3 provides summary lithologies but for detailed descriptions see Barton et al. (2011) and Sanderson et al. (2017).

The interpretations were carried out using modern digital mapping techniques described in detail in Sanderson et al. (2017), in particular use of the 3D BGS-Virtalis GeoVisionary virtual mapping software (Westhead et al., 2015) in conjunction with the BGS System for Integrated Geological Mapping (SIGMA) Desktop toolkit extension (Jordan, 2010). These enabled production of BGS digital map-standard (DiGMapGB-compatible) outputs, which have been used to derive the figures in this paper, although re-projected in UTM [Zone 30N] co-ordinates.

We have produced new structural interpretations of key coastal sections in the north of Weymouth Bay (St. Oswald's Bay-Stair Hole and Ringstead), based partly on the mapping of Westhead et al. (2017; as described in Sanderson et al., 2017), which used the following public-domain, contiguous Lidar and bathymetry datasets (depicted in figs. 4 and 6):

- Maritime and Coastguard Agency (MCA) swath bathymetry data collected under the UK Civil Hydrography Programme, HI_1154 (2008/9), as part of the Dorset Integrated Seabed

(DORIS) Survey for the Weymouth Bay area (and extending around the south and west of the Isle of Portland), gridded at a 1 m horizontal resolution.

- 1 m horizontal resolution coastal Lidar data from the Environment Agency, sourced from Channel Coastal Observatory, for the 1 km onshore strip around the north of Weymouth Bay.

	Lithostratigraphy	Thick-ness (m)	Summary lithology
	Cenozoic units	200+	Clay & sand
Cretaceous	Cretaceous units (post-Aptian)	500+	Sandstone & mudstone in lower part (Greensand & Gault). Chalk in upper 400m
Cretaceous	Wealden Formation	65-435	Sandstone & mudstone
Cretaceous	Portland & Purbeck groups (undivided)	100-190	Limestone, sandstone & mudstone
Jurassic	Kimmeridge Clay Formation	250-570	Mudstone with thin limestones ('Ledges')
Jurassic	Corallian Group	60-70	Limestone, sandstone & mudstone
Jurassic	Kellaways & Oxford Clay formations (undivided)	c. 150	Mudstone, sandy in lower part
Jurassic	Cornbrash Formation	10-20	Limestone
Jurassic	Great Oolite Group	c. 350	Dominantly mudstone with variable thin limestones
Jurassic	Inferior Oolite Formation	c.10	Limestone
Jurassic	Lias Group	c.600	Dominantly mudstone, with thin limestones (locally dominant), sandy towards upper part
Triassic	Penarth Group	20-40	Limestone & mudstone
Triassic	Late Triassic	200+	Reddish-brown mudstone

Figure 3: Summary lithostratigraphy for the study area, with thicknesses and summary lithologies for the key units, from Sanderson et al. (2017), Barton et al. (2011), and present interpretation. Colours as used for figures 2 and 9.

The mapping of Lyme Bay is our new interpretation, based primarily on extending the geological mapping using the same technique of geomorphological feature mapping against an elevation surface generated from the bathymetric and coastal Lidar datasets, as described below and depicted in figures 7 and 8 (supported by analysis of additional information such as seabed samples):

- Maritime and Coastguard Agency (MCA) swath bathymetry data collected under the UK Civil Hydrography Programme, for both survey areas: HI_1453 (2016) covering the west and south parts of Lyme Bay at a 1 m horizontal resolution, and; HI_1343 (2010) covering the central Lyme Bay, and nearshore coastal area (re-gridded at a 2 m horizontal resolution). These data are depicted in part in figures 7 and 8.
- 1 m horizontal resolution Lidar from the Environment Agency, sourced from Channel Coastal Observatory, for the 1 km onshore strip around the north of Lyme Bay (Fig. 8).

The coastal join for the bedrock mapping is implemented against the existing onshore British Geological Survey 1:10k digital bedrock mapping (DiGMapGB-10), for the coastal area of map sheets Sidmouth, Bridport, West Fleet and Weymouth, and Swanage (parts of sheets 326, 327, 340, 341, 342, 343). The method involves overlapping the offshore mapping onto the existing onshore mapping for a strip of up to several hundred metres, ensuring a seamless coastal join. We have also used the seabed mapping of Darton et al. (1981) for the northern part of Lyme Bay to support our interpretation. This onshore overlap in our mapping was all carried out within the 1 km wide strip of Lidar data specified above. For completeness, however, the inshore area of the hill-shaded elevation surface shown in Figure 8B is generated from NEXTMap Britain elevation data from Intermap Technologies, a high resolution Digital Elevation Model dataset generated from airborne IFSAR (Interfereometric Synthetic Aperture Radar).

The geological mapping and structural interpretations are also supported by selected interpretation of key seismic sections (shown in figures 4, 6 and 9) and boreholes (although no deep boreholes occur in Lyme Bay). This seismic reflection data used are freely available and were sourced from the UK Onshore Geophysical Library and the BGS GeoIndex. Correlation of surface data with available subsurface sections is carried out in 2D Move and 3D Move software (Midland Valley Exploration Ltd). Where possible fault traces are linked to the bathymetry data and extrapolated between sections using surface expressions. The main reflectors mapped on seismic are: Corallian; Cornbrash; Inferior Oolite; Top Green Ammonite Beds (within the Lias Group); Top Triassic/Penarth Group; Top Triassic Salt; Top Sherwood Sandstone. As many of the sections used in this study are scans of original paper records, a depth conversion has not been attempted.

The results from the mapping are also compared to regional gravity data presented in figures 1 and 2 as a set of 1km grids of residual gravity taken from BGS regional gravity compilations. The onshore gravity data for the UK are freely available to download from the BGS website. The offshore data for the UK continental shelf are not available to download. Residual gravity was calculated by subtraction of an upward-continued field. The gravity data for onshore was processed using the Bouguer method, whilst the offshore data is free-air gravity.

4.2. Structural observations

A. St Oswald's Bay-Stair Hole

This coastal segment includes the geomorphological features of Durdle Door, Stair Hole and Lulworth Cove (Fig. 4). The onshore-offshore mapping (Westhead et al., 2017) allows us to map and fully reveal the geological structures in the coastal section, which are only partly seen in the cliff exposures. This includes a set of c. 500 m long WNW-ESE to E-W striking faults with intervening N-S to SW-NE striking faults (Fig. 4A). The latter appear to truncate or bend into the E-W striking faults, demonstrating a likely coeval relationship. The limestone units of the Purbeck and Portland groups form a topographical feature in the bathymetry beneath St Oswald's Bay, and are offset perpendicularly to strike by 300 m by an E-W fault, into which they curve in open folds on both sides (Fig. 4A, B). The Wealden Formation, which forms a less featured seabed, is repeated by this fault and is apparently downthrown on the south side against Portland Sand Formation. The coastal bedrock mapping in this area also confirms significant thinning of the succession, particularly of the Wealden Formation to the north of Durdle Door, where it is only 65 m thick compared to 425 m in Worbarrow Bay only 4 km to the east (Barton et al., 2011). The Purbeck Group is also known to be at its thinnest in this area (Westhead and Mather, 1996). Given the contractional nature of the deformation in the PWFZ, the most feasible explanation for the structure beneath St Oswald's Bay is a north-inclined thrust, with south-directed overthrusting and repetition of the Wealden Formation and Portland and Purbeck groups; the oblique, cross-cutting geometry of the thrust in relation to bedding implies a lateral ramp structure. The northward inclination would imply an antithetic relationship to the principal southerly inclined Purbeck Fault structure, as shown diagrammatically in Figure 5. A seismic section crossing the structure (AUK-94-AJ054) shows the main southerly inclined Purbeck Fault, which projects to just south (around shot point 1250) of the outcropping synclinal monocline hinge mapped in the Chalk onshore to the north of the bay (Fig. 4A, C), but the resolution of the seismic section across the coastal section does not allow discernment of the possible antithetic fault proposed above. This mapping and structural interpretation is significantly different to earlier interpretations of this area (e.g. Nowell, 1997, and previous BGS mapping e.g. as published on the Swanage 1:50k map sheet), made before the bathymetric data were available, in which the northward deflection in the outcrop is related principally to NNW-SSE or NW-SE striking, E-downthrowing fault structures.

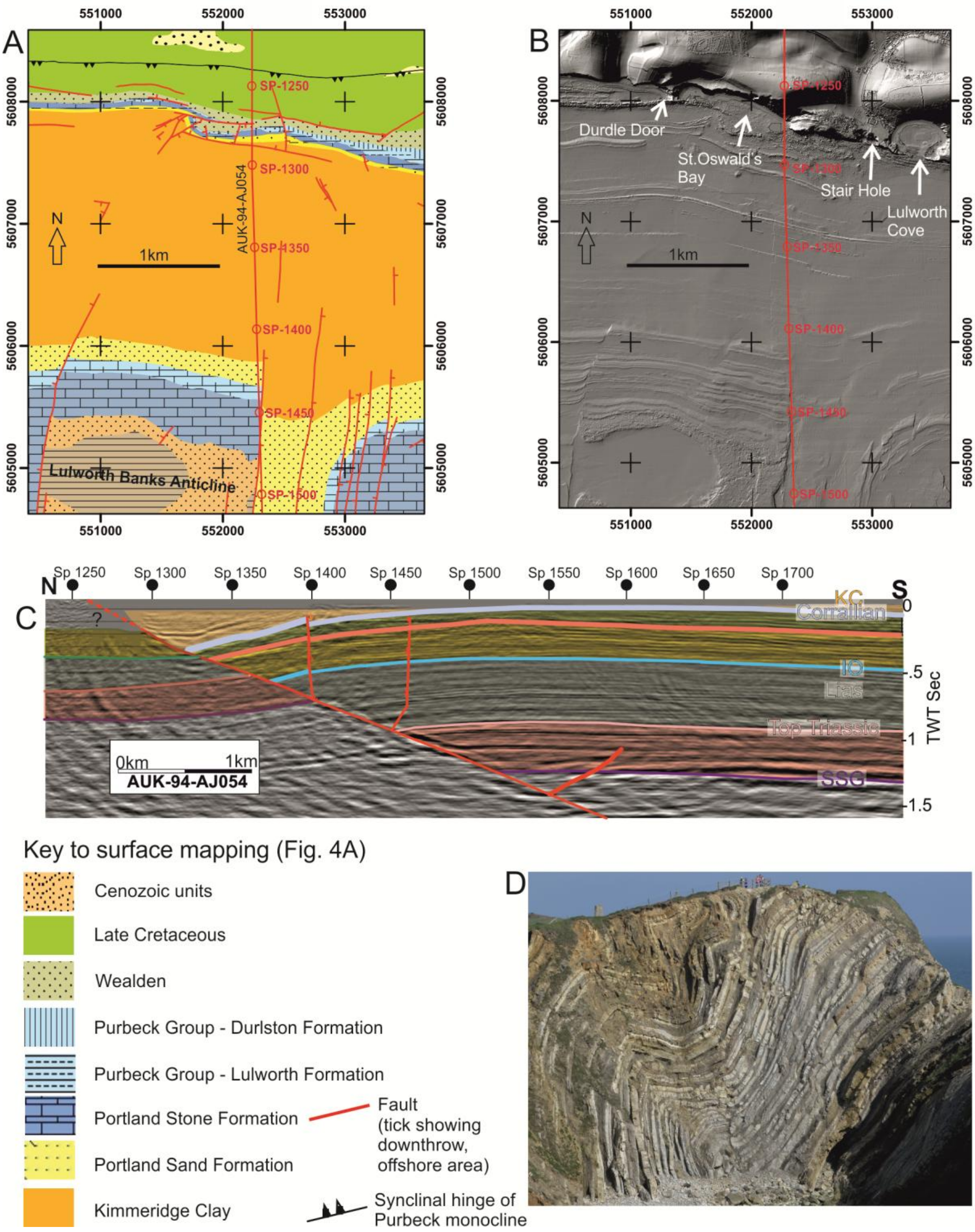


Figure 4: St Oswald's Bay-Stair Hole geological interpretation. **A.** Bedrock mapping from Westhead et al. (2017), with key as shown. The map area is shown in Figure 2. The position and shot points for seismic line AUK-94-AJ054 (displayed in C) are shown. The synclinal hinge of the Purbeck monocline is depicted within Late Cretaceous outcrop. **B.** Hill-shaded elevation surface for the same area as A, generated from bathymetric and Lidar data as described in the text **C.** An interpretation of seismic line AUK-94-AJ054 (faults shown in red). The colours match key in Figure 2, with units shown for clarity. **D.** A photograph of the 'Lulworth Crumple' fold at Stair Hole, viewed looking east; the cliff height is approximately 33 m (photo: Keith Westhead).

The new structural mapping at St Oswald's Bay has implications for the interpretation of the 'Lulworth Crumple' fold structure at Stair Hole, less than a kilometre along strike to the east (Fig. 4B, D). The Lulworth Crumple itself is a south-verging fold with longer north-inclined limbs and a short south-inclined intervening limb (Fig. 4D), with additional parasitic folds (Underhill and Paterson, 1998). Interpretations of this structure vary from 'gravity collapse' (Phillips, 1964) to 'upwards drag' Arkell (1938). West (1964) similarly argues for 'upwards movement' and accompanying shortening of the Purbeck Group to form the fold. Our mapping indicates this structure is along strike from and at the same structural and stratigraphical level as the implied south-directed, antithetic thrust beneath St Oswald's Bay. This supports an interpretation of south-directed shear for the formation of the Lulworth Crumple. Figure 5 shows this diagrammatically, indicating the enclosure of the Stair Hole structure in a south-directed shear envelope. Therefore, the Lulworth Crumple could be a lateral equivalent of the St Oswald's Bay thrust structure, with the reverse movement expressed as a fold structure. This interpretation supports the previous hypotheses of Arkell (1938) and West (1964), in which they imply south-directed shear. It is also consistent with that of Underhill and Paterson (1998) who interpret the Lulworth Crumple as formed under intraformational, flexural slip in the hangingwall to the main, southerly inclined Purbeck Fault structure but refines this by proposing the antithetic movement in the immediate hangingwall of the principal Purbeck Fault. Additionally, the observed stratigraphical thinning of the Purbeck Group and Wealden Formation in this area at Stair Hole and Lulworth could in part be due to structural thinning through shearing out of the mudstone layers.

The structural picture to the south across Weymouth Bay contrasts to that along the St Oswald's Bay-Stair Hole coastline, instead characterised by evenly 300-500 m spaced, N-S to NNE-SSW striking faults (Fig. 2; Fig. 4A; Sanderson et al., 2017). These faults vary from 100's m to 10's km in length, and affect gently dipping (generally less than 5^{o}), openly folded strata with normal throws of 10's m. They are evident in the bathymetric data, displacing Corallian Group strata in the Lulworth Banks anticline (Fig. 4B), and also affecting Kimmeridge Clay Formation, Portland and Purbeck groups and Wealden Formation strata across Weymouth Bay (Fig. 2; Sanderson et al. 2017). Where these faults can be traced onshore, in the coastline from Kimmeridge Bay and to the east towards Swanage, they are observed to form a conjugate set of normal faults with dips of $60\text{-}80^{o}$ (Hunsdale and Sanderson, 1998; Putz-Perrier and Sanderson, 2008). Sanderson et al. (2017) propose that these N-S striking faults indicate a distributed strain regime affecting sediments in the hangingwall of to the PWFZ during its Cenozoic inversion phase, with a N-S principal shortening direction and sub-horizontal, E-W extension. These authors contrast this to more focussed strain along the PWFZ itself, with the N-S shortening is accompanied by top-to-the-north shear, with related movement on the E-W striking faulting described. We provide a model for this structural contrast in Figure 5, showing how the St Oswald's Bay-Stair Hole structures occur within the PWFZ 'shear zone', and the N-S striking faults lie in the hangingwall block to the south.

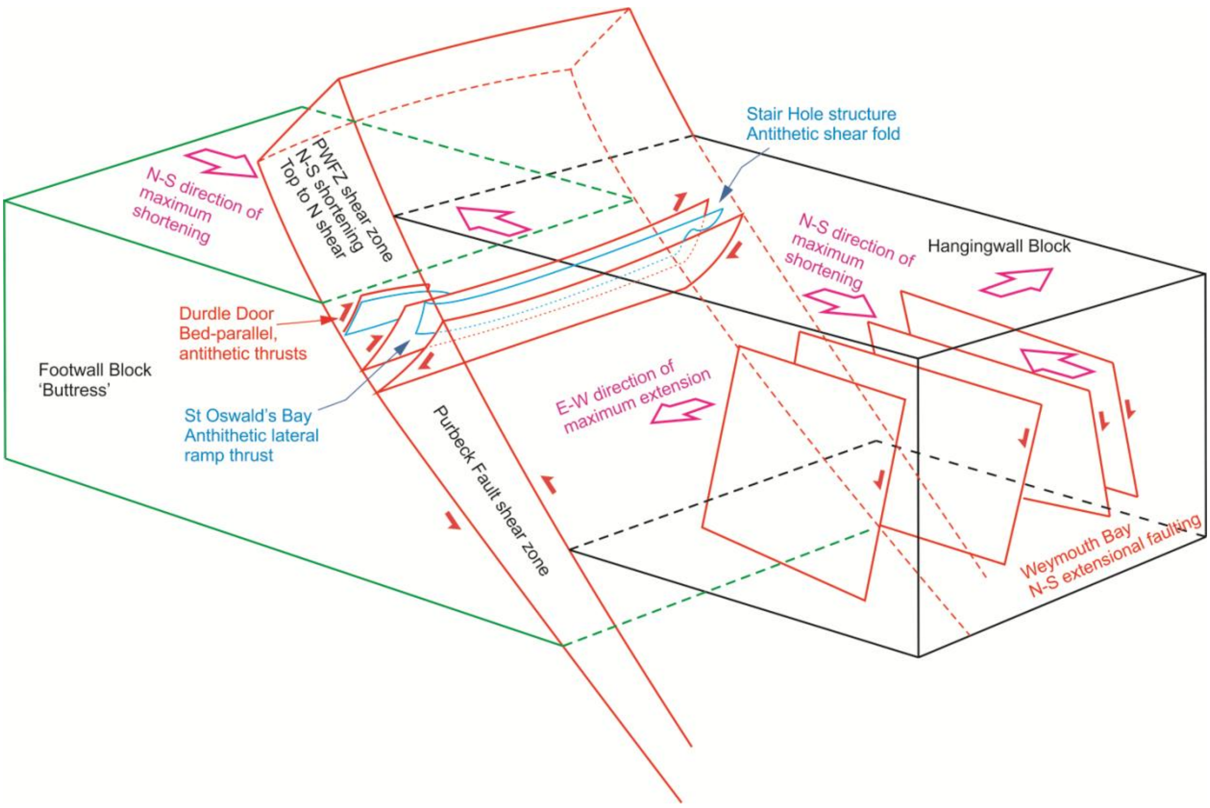


Figure 5. Structural model for St Oswald's Bay to Stair Hole coastal section, and area to the south towards Lulworth Banks, approximating to the area of the mapping in Figure 4. Viewed looking north-east.

B. Ringstead Bay

The surface mapping of Westhead et al. (2017) demonstrates a set of E-W orientated, c. 1 km long, 100-300 m-spaced faults, with several 10's m throws, with a related central periclinal anticline, affecting the Corallian sequence, and seen particularly clear in the nearshore platform (Fig. 6A). These structures are also evident in a seismic section (AUK-94-AJ060), extending N-S from onshore to offshore, showing how the northerly inclined faults (with both normal and reverse throws) in the south of the section truncate against a southerly inclined normal fault, with an intervening anticline (Fig. 6C). Chadwick and Evans (2005) describe similar structural relationships in the Upton-Poxwell area extending several kilometres onshore to the north of Ringstead Bay, including dominant southerly inclined faults (including the Abbotsbury-Ridgeway Fault itself) and associated E-W folding. They associate these with a history of early Jurassic to Early Cretaceous, largely down-to-the-south normal faulting followed by Cenozoic reversal. Underhill and Paterson (1998) describe the structures in this area as lying within the left-stepping relay ramp zone between the Purbeck Fault and Abbotsbury-Ridgeway Fault elements of the main Purbeck-Wight lineament (Fig. 2), originating during their extensional phase and modified by the later inversion.

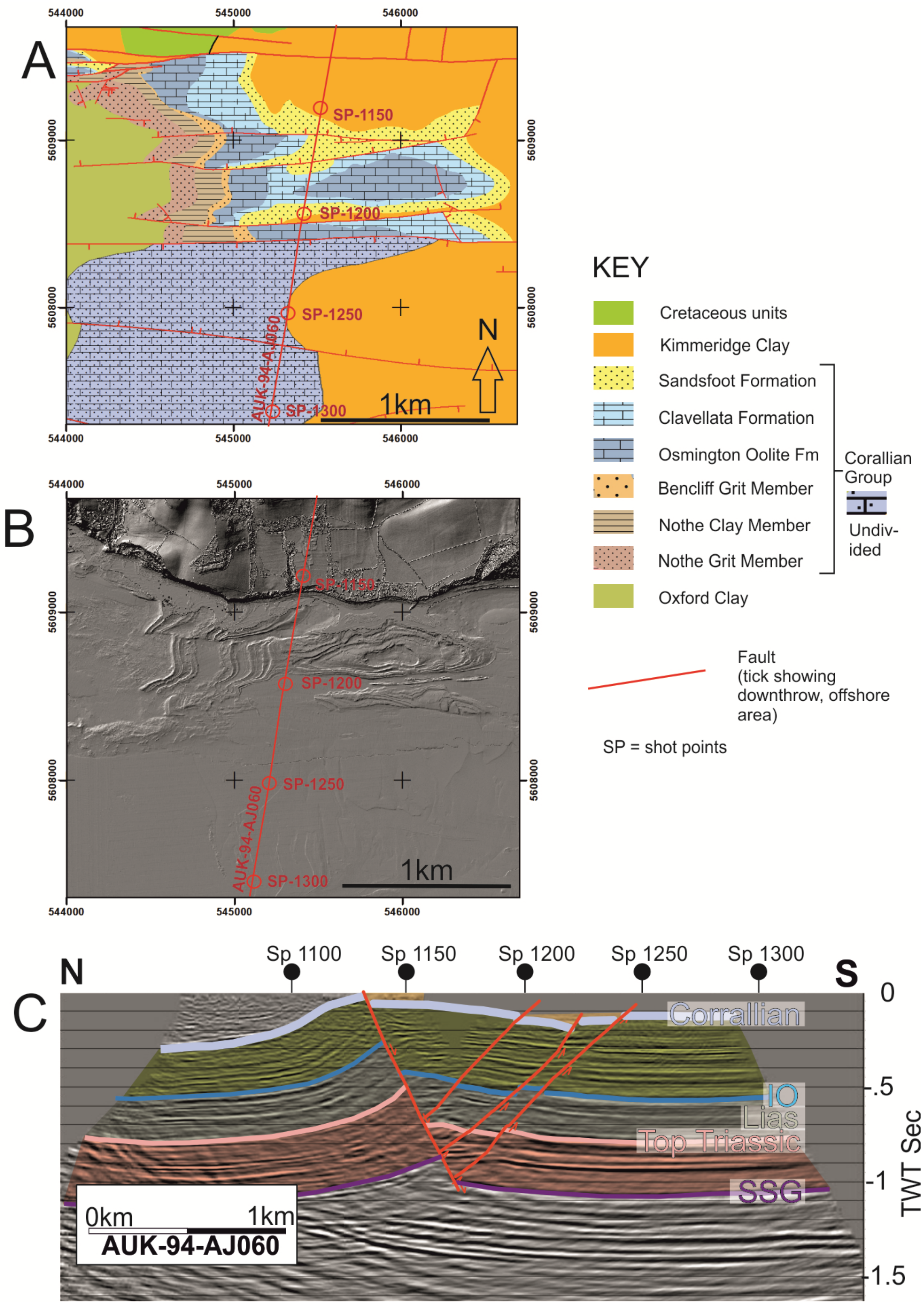


Figure 6. Ringstead Bay geological interpretation. **A.** Bedrock mapping from Westhead et al. (2017), with key as shown. Map area shown in Fig. 2. Shows position and shot points for seismic line AUK-94-AJ060 shown in C. **B.** Hill-shaded elevation surface for the same area as A, generated from bathymetric and Lidar data as described in the text. **C.** Interpretation of seismic line AUK-94-AJ060 (faults shown in red). Colours match key in Fig. 2, with geological units shown for clarity.

C. South Lyme Bay

Our new mapping traces a WNW-ESE striking fault zone for over 45 km across the southern extent of Lyme Bay (Fig. 2), from late Triassic (Penarth Group) to Kimmeridge Clay stratigraphical levels. In its eastern part (Fig. 7), the fault zone comprises a series of left-stepping, overlapping c. 10 km long WNW-ESE trending segments, with intervening NW-SE to N-S orientated linking faults. Here it affects both the Cornbrash Formation and Corallian Group marker units, the latter being folded into a narrow syncline between the *en echelon* principal fault segments. The fault zone is mapped as dying out into the Kimmeridge Clay outcrop south of the Isle of Portland. The outcrops of both the Cornbrash Formation and Corallian Group are offset to the west by 5 km on their southern side of the faults, which could be explained by a downthrow to the south in the order of 300 m (allowing for a general 3° eastward dip as measured from limestone beds in the Corallian Group outcropping at the seabed). This is consistent with the throws apparent in the seismic section crossing the structure (Den-60, Fig. 9). However, the overall geometry might also suggest an element of right-lateral strike slip but this cannot be proven. The displacement in the western extent of the fault zone appears to diminish or even reverse to a minor down-to-the-north where it displaces the Penarth Group.

Our seismic interpretation suggests that the fault zone could be steeply southward dipping. In the east (section Den-60; figs. 7, 9), some growth faulting has been interpreted, with a slight southward increase in thickness apparent in the Lias Group. The Great Oolite Group as a whole does not appear to change thickness across the faults, suggesting that any growth faulting ceased after early Jurassic times. A seismic section further to the west (Den-62; Fig. 9) does not suggest any discernible variation in TWT, suggesting that the syn-depositional movement at early Jurassic levels was variable along the fault length. This is consistent with the observations of Harvey and Stewart (1998) who imply dominantly late Jurassic to early Cretaceous movement on several of the Lyme Bay faults, but with some local thickness changes at Lower Jurassic levels, suggesting spatially limited growth faulting in this period. A further observation from the seismic interpretations is that, while the early Jurassic strata show generally consistent thickness across Lyme Bay (apart from the localised thickness changes across specific faults), the Great Oolite Group appears to thin significantly (by up to two thirds) from east to west, but does not display any localised thickness changes across individual faults.

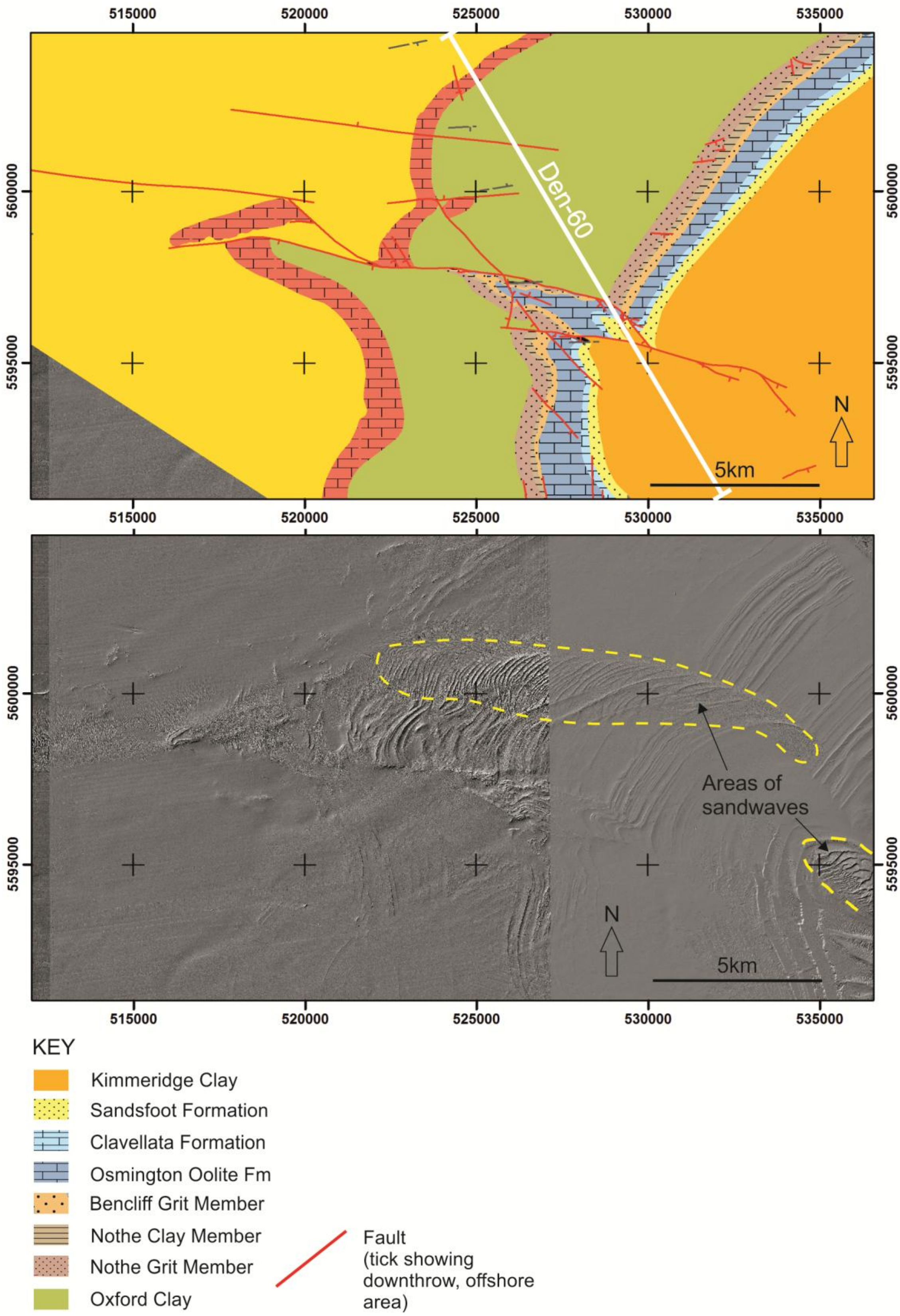


Figure 7. Geological interpretation for an area of South Lyme Bay; location shown in Figure 2. **A.** Bedrock mapping partly (eastern half of map area) from Westhead et al. (2017), and partly our new mapping (see Fig. 2 for areas). The location for seismic line Den-60, shown in Figure 9, is indicated. **B.** Hill-shaded bathymetry for the same area as A. Most of the seabed area is exposed bedrock, obscured in places as shown by mobile sand wave complexes.

D. North Lyme Bay

The structural framework at outcrop level in the northern part of Lyme Bay, and onshore to the north, is complex, with a network of intersecting and anastomosing E-W and SW-NE striking, laterally persistent (several 10's km in length) faults affecting strata from late Triassic (uppermost Mercia Mudstone) to mid Jurassic (Oxford Clay) age (Fig. 8). Our interpretation is supported by both our own mapping (including using the new high resolution bathymetry) and that of Darton et al. (1981) who used a variety of techniques including seabed sampling, side-scan sonar and sparker seismic for approximately the same area as shown in Figure 8.

The Abbotsbury-Ridgeway segment of the PWFZ extends offshore into the east of Lyme Bay, and can be traced for at least 10 km offshore to the west, with down-to-the-south displacement of Oxford Clay and Cornbrash formations against Great Oolite strata (Fig. 2). This implies downthrow at surface level of at least several hundred metres, which is consistent with the interpretation of seismic line Den-60 which crosses the structure as shown in figures 8 and 9. For much of its onshore section, the Abbotsbury-Ridgeway fault demonstrates dominantly down-to-the-north, reverse throw, most evident in displacement of the late Cretaceous Chalk against late Jurassic (including Kimmeridge Clay) strata. The relative throw reverses close to where the fault tracks offshore at lower stratigraphical levels, which is consistent with the interpretation of Chadwick and Evans (2005) for partial reversal but still net normal displacement for the westerly offshore section of the fault at lower stratigraphical levels. The seismic section crossing the structure in the east of Lyme Bay (line Den-60, Fig. 9) suggests that it is steeply southward-dipping, and comprises several parallel fault segments at depth. A series of northward dipping antithetic faults link up to the series of E-W faults mapped at surface (there displacing Oxford Clay against Great Oolite). These latter faults are part of the complex of broadly axis-parallel faults affecting the core of the Weymouth Anticline (Chadwick and Evans, 2005). The main fault is known to detach at depth into the Triassic salt layer, but also relate to deeper basement fault steps (Chadwick and Evans, 2005; Harvey and Stewart, 1998).

Our surface mapping also demonstrates three sub-parallel, 2km-spaced, laterally persistent (by 10's km), WSW-ENE striking faults, which can be traced from onshore to offshore to the north of the Abbotsbury-Ridgeway Fault (Fig. 8). The southernmost of these, which we call the North Lyme Bay Fault (NLBF), overlaps the Abbotsbury-Ridgeway Fault in a left stepping fashion, and can be traced for nearly 35 km from the onshore to the west across the full width of the northern offshore part of Lyme Bay, displacing strata from Penarth Group to Great Oolite levels. The seabed mapping shows that this fault comprises several anastomosing segments, and that the outcrop of the Inferior Oolite is offset laterally on its south side by a cumulative total of nearly 15 km to the west. The two northerly faults converge and merge with the North Lyme Bay Fault in the centre of Lyme Bay (Fig. 8).

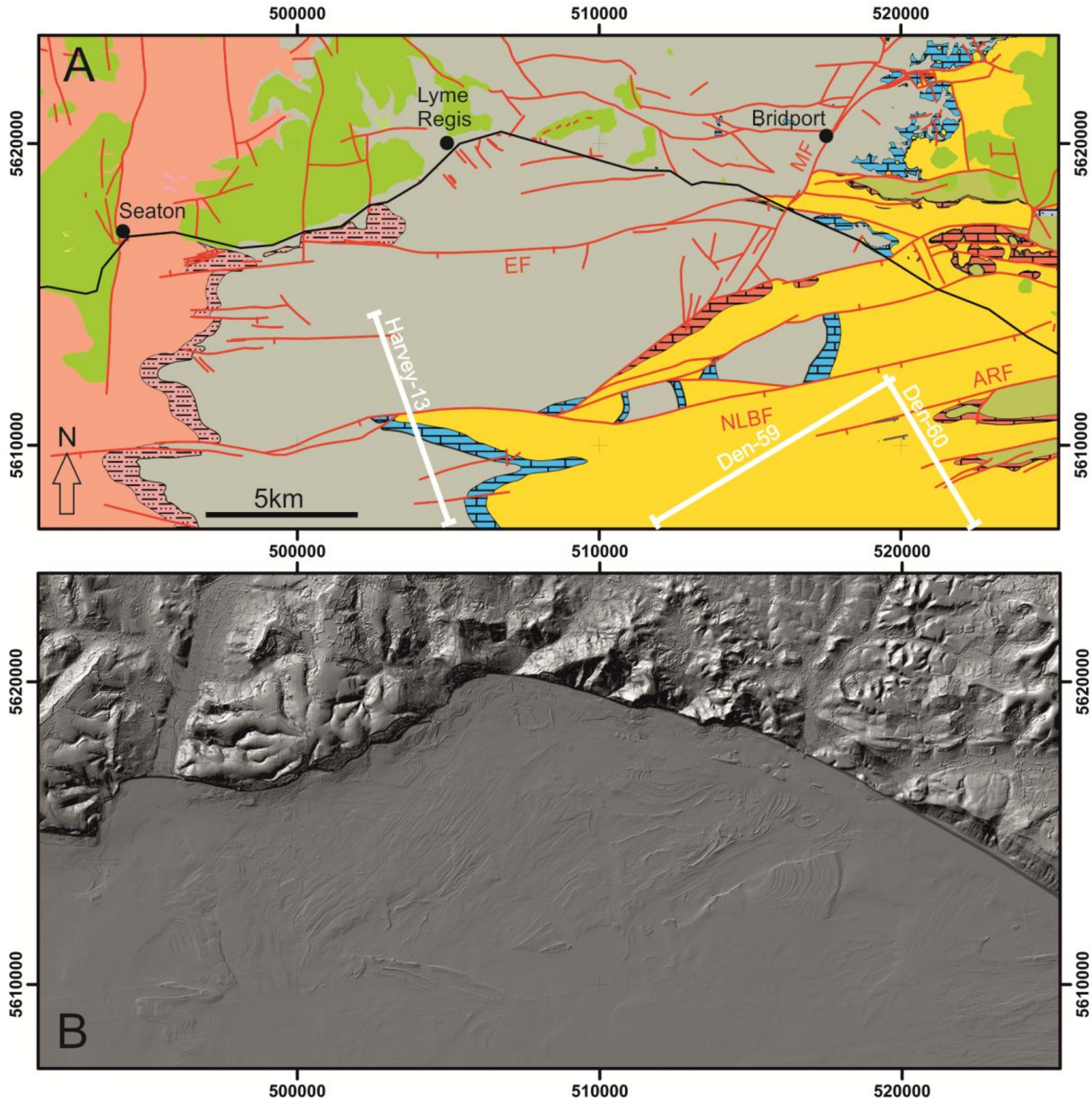


Figure 8: Geological interpretation for the northern part of Lyme Bay; location shown in Figure 2. **A.** The new bedrock mapping, with key faults marked (MF = Mangerton Fault; EF = Eypemouth Fault; NLBF = North Lyme Bay Fault; ARF = Abbotsbury-Ridgeway Fault). This shows position of seismic lines used for the subsurface interpretation of Figure 9. Key to geological units as shown in Figure 2. **B.** Hill-shaded elevation surface for the same area as A, generated from bathymetric, Lidar and IFSAR (NEXTMap) data as described in the text. NEXTMap Britain elevation data from Intermap Technologies.

A seismic line crosses the North Lyme Bay Fault in its central extent (line Harvey-13 on figs. 8 and 9, taken from Fig. 13 of Harvey and Stewart, 1998) and indicates a southward downthrow in the order of 200-300 m, consistent with the surface mapping which shows Inferior Oolite thrown down against mid-Lias levels close to the line of the seismic section. The northernmost of the three parallel WSW-ESE striking faults described above shows a similar southerly downthrow of 300m displacing Cornbrash against what is interpreted as uppermost Lias Group (faulting out the Inferior Oolite at the surface level). The intervening WSW-ENE fault shows an opposing down-to-the-north displacement of similar order, throwing uppermost Lias against mid-Great Oolite Group strata (although precise identification of stratigraphical level within the latter strata is difficult in this area due to patchy thin seabed sediment cover). Bedding dips across northern Lyme Bay are generally low-angle (at less than 5 degrees) and towards the east, although with local dip direction variations due to open folding, and it is possible that the mapped surface strata displacements could be accommodated with normal fault displacements alone. However, the unusual anastomosing geometry of the fault zone represented by these three persistent faults, could suggest an additional element of possibly right-lateral strike slip (similar to that suggested for the South Lyme Bay fault zone), although this cannot be proven from our analysis.

Our new mapping also allows the Mangerton Fault to be traced from the onshore for 3 km offshore to the SW, where it merges with the northernmost of the WSW-ENE faults discussed above, suggesting a possible coeval relationship (Fig. 8). The Mangerton Fault is part of the conjugate set of NW-SE and NE-SW striking faults in this part of S England, including the Char Fault ~8 km to the west and the Poyntington Fault ~30 km to the NE near Yeovil, and faults affecting the Chalk to the NW of the Compton Valence Dome, which are associated with the Watchet-Cothelstone-Hatch Fault Zone discussed earlier (Chadwick and Evans, 2005). The Mangerton Fault is sub-vertical and observed to displace the E-W striking Eypemouth and Bridport faults in a left-lateral sense by up to 1 km, and is thus thought to be of Miocene age (Fig. 8; Harvey and Stewart, 1998, Barton et al., 2011).

An interpretation of the Mangerton Fault merging with the WSW-ESE faults in northern Lyme Bay further concurs with Darton et al. (1981) but adds significant detail in the faulting patterns and strata displacement obtained from use of the new high-resolution bathymetry. This interpretation, however, is converse to that of Harvey and Stewart (1998), who suggest (largely on the basis of seismic evidence) that the Mangerton Fault cuts and is therefore later than the offshore continuation of the Abbotsbury-Ridgeway fault system.

Further detail from our mapping shows that the E-W striking Eypemouth Fault, shown to be displaced left-laterally by up to 1 km by the Mangerton Fault (Harvey and Stewart, 1998; Barton et al., 2011), can also be traced offshore to the west for 16 km across the northern part of Lyme Bay past Lyme Regis, to where it displaces the Penarth Group down-to-the-south (Fig. 8).

Seismic section 'Harvey-13' (figs. 8 and 9) intersects a further fault structure ~3 km to the north of the N Lyme Bay Fault, with a downthrow in the order of 300 m to the south. This occurs within the mapped extent of Lias rocks, but the seismic interpretation suggests that the fault could downthrow Great Oolite Group level rocks against Lias at the surface level but this cannot be resolved from the mapping due to indistinct bathymetric data in this part of the bay.

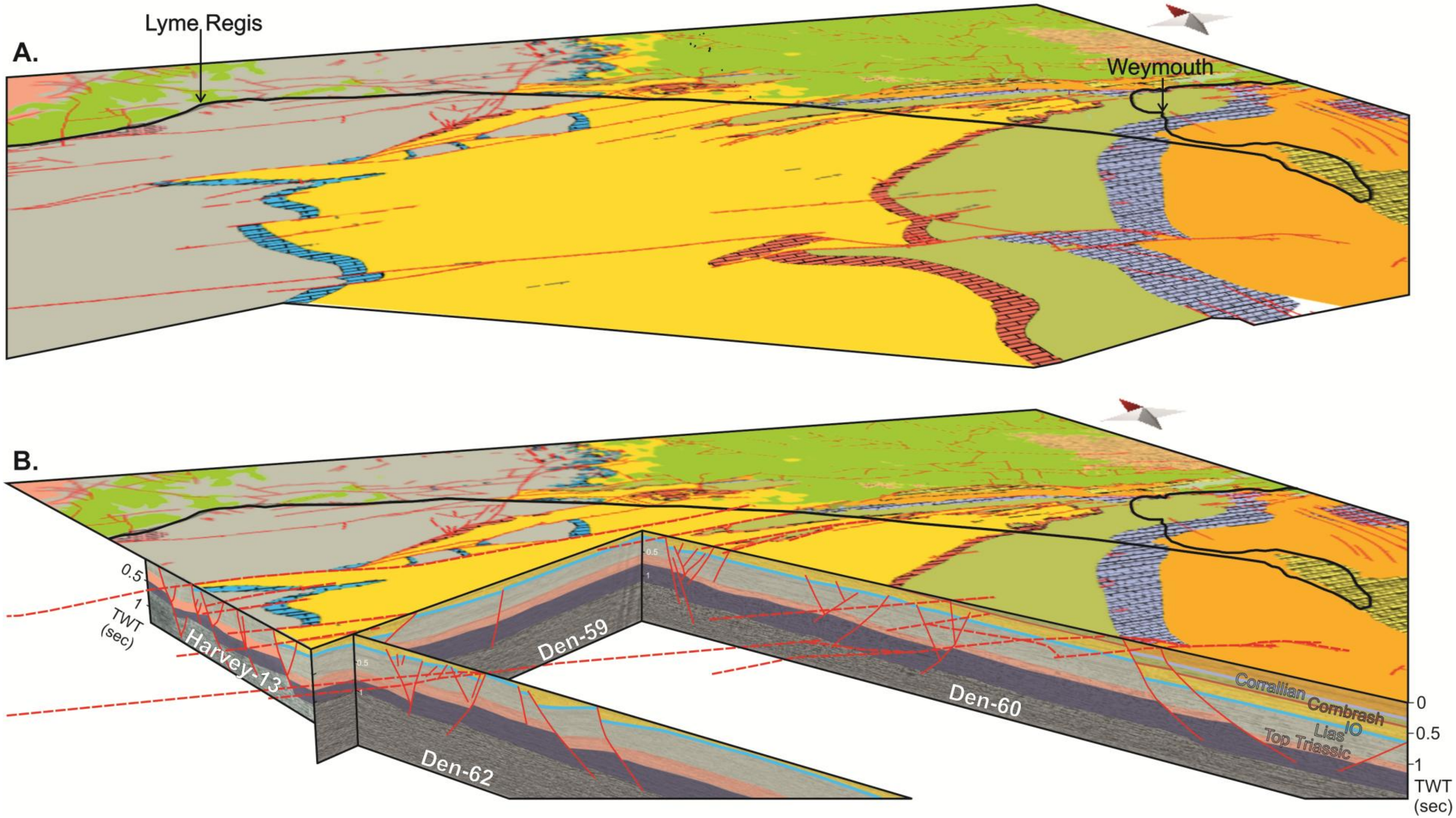


Figure 9: Subsurface interpretation for the Lyme Bay study area, shown in oblique view looking towards the north-east. **A.** Onshore-offshore bedrock map (key as shown in Fig. 2) **B.** Cut-away of the same surface map, showing key seismic section described in the text. Surface faults are traced across the cut-away area to show links between structures shown in seismic sections. Colours are the same as for the surface mapping (with additional labels on sections for clarity).

5. Discussion

Our mapping and seismic interpretation work allows us to discern the westward projection and diffusion of the PWFZ, which our regional review demonstrates to be a critical structure in the long-term tectonic evolution of the southern UK. Of particular interest is the contrast between the deformation style, picked out by faulting (and associated folding) styles and orientations, between the Weymouth Bay area (including the coastal sections around Lulworth) and the Lyme Bay area to the west (figs. 2 and 9). Prior to the high-resolution (1:10k scale) onshore-offshore bedrock mapping of Sanderson et al. (2017) in Weymouth Bay, and our westward extension of the same into Lyme Bay, it was only possible to get a partial picture of the PWFZ and associated structures. The offshore seabed mapping, published at the 1:250k scale by the BGS (DigRock250, available via the BGS Offshore GeoIndex web service http://mapapps2.bgs.ac.uk/geoindex_offshore/home.html), provided a window into the lateral variations in structural style but only at a low resolution. Previous detailed subsurface interpretations, based primarily on seismic interpretation, have been published across the area, and have provided a picture of the structural history and setting (e.g. Underhill and Paterson, 1998 for the eastern part of the PWFZ between Weymouth and the Isle of Wight, and Harvey and Stewart, 1998, extending further westwards into Lyme Bay). However, these previous studies have been restricted by low-resolution surface mapping in the extent to which they are able to link the subsurface interpretations to lateral variations in structural style demonstrated particularly by the faulting networks exposed at the surface in the crucial offshore areas. We have concentrated on improving the interpretations in two key areas: the coastal sections along the Isle of Purbeck coastline on the north side of Weymouth Bay, and the wider offshore area of Lyme Bay.

For the Weymouth Bay coastal exposures, interpretation of the structures associated with the Purbeck Fault seen in the coastal sections west of Lulworth Cove has previously been restricted by poor mapping in the nearshore zone. The term 'White Ribbon' has been used for the gap between onshore and offshore mapping in this shallow-water coastal strip (Mason et al., 2006; Leon et al., 2013). Key structures in the coastal sections at Ringstead, Durdle Door/St. Oswalds Bay and Stair Hole are only partially exposed in the cliff sections but the new onshore-offshore mapping has enabled us to complete the picture. Building on the work of Sanderson et al. (2017), we describe complex faulting and folding structures exposed particularly well in the nearshore sub-tidal platform at Ringstead (Fig. 6), and relate these to synthetic and antithetic faulting originating in the relay ramp zone between the en echelon (left-stepping) Purbeck and Abbotsbury-Ridgeway segments of the main PWFZ, as described by previous authors (Underhill and Paterson, 1998; Chadwick and Evans, 2005). We also offer a new interpretation of the structures between Durdle Door, St Oswalds and Stair Hole, occurring in the immediate hangingwall of the southerly dipping Purbeck Fault. A southerly directed thrust structure is mapped beneath St Oswald's Bay, passing along strike towards Stair Hole, offering a revised explanation for the 'Lulworth Crumple' fold structure as a south-verging fold developed in response to antithetic shearing during inversion of principal underlying Purbeck Fault (figs. 4 and 5). These observations at Ringstead and St. Oswald's Bay concur with the model of Sanderson et al. (2017), of lower Cenozoic reactivation of the southerly dipping PWFZ under N-S shortening accompanied by dominantly top-to-the-north shear but with significant antithetic faulting in the immediate hangingwall. Further to the south, as described by Sanderson et al. (2017), the majority of the PWFZ hangingwall in Weymouth Bay is characterised by more distributed N-S shortening driving the development of the N-S striking extensional faulting seen there (Fig. 2). The transition from the E-W-dominated faulting close to PWFZ to the N-S faulting in its broader hangingwall is demonstrated in our interpretation of the St Oswald's Bay-Stair Hole coastal section and the Lulworth Banks area to its south (figs 4 and 5).

In the Lyme Bay area, the most comprehensive prior structural study is that of Harvey and Stewart (1998), who used primarily seismic interpretation to discern the faulting networks, and to look in detail at the tectonic influence of thick subsurface Triassic salt (Dorset Halite in the Mercia Mudstone). Their principal conclusion is that variation in structural style, in particular the degree to which the major E-W orientated faults are linked to faulting in the 'basement' (meaning pre-salt), relates to the presence of thicker salt. They conclude that the saliferous horizon is at its thickest (over 400 m) beneath the centre of Lyme Bay, thinning significantly to the north, south, and to the east towards Weymouth Bay (reducing to zero thickness between Swanage and the Isle of Wight. They conclude that the principal E-W faults in the north Weymouth Bay area, including the main Purbeck Fault, are 'hard-linked' to the pre-salt levels (and deeper to pre-Permian basement levels), whereas the major E-W faults in Lyme Bay, including the Abbotsbury-Ridgeway Fault, are 'soft-linked', detaching into the salt horizon and variably linked to fault steps in the pre-salt levels. Our work demonstrates that this east to west variation in structural style also includes a westward loss of any N-S striking faulting, suggesting that the influence of the salt may in part be a driver for the deformation style in the hangingwall zone to the south of the main PWFZ lineament.

Our interpretation of the Lyme Bay area reveals a contrast in the structural style to Weymouth Bay (figs. 2 and 9). No evidence is seen for N-S striking faulting in Lyme Bay, and the principal faulting is dominantly E-W striking, but also with significant development of NE-SW anastomosing faults (figs. 8 and 9). Two principal E-W fault zones are seen in the south and north of Lyme Bay, both demonstrating overlapping and anastomosing fault segments. The seismic evidence demonstrates dominantly down-to-the-south normal fault movement, possibly representing strain distribution into en echelon fault segments at the termination of the PWFZ in the north Lyme Bay (Fig. 9). The left-lateral Mangerton Fault (and accompanying NE-SW striking structures) appear to become asymptotic to the E-W faulting structures. This conclusion differs from that of Harvey and Stewart (1998), who propose that the NE-SW faults (and suggested relatively minor NW-SE conjugate structures in the centre of Lyme Bay), cut the E-W faulting, and therefore represent accommodation of N-S shortening in the late-stages of the Alpine inversion phase. Our interpretation suggests the strike-slip dominated movements on the Mangerton Fault were likely to be synchronous with at least the late stage of movement on the E-W faults in Lyme Bay, and hence by implication, with the late stage Alpine inversion deformation in these structures.

Further information can be gained from the regional geophysical data for the region. Comparison of the fault networks from our interpretations with the gravity data shows a strong correlation (Fig. 2B), suggesting a link between basement involvement and development of the Weymouth-Lyme Bay structures associated with the PWFZ. In a study further to the east along the PWFZ, Busby and Smith (2001) conclude that the gravity high to the south of the lineament in the Isle of Wight area relates to higher density basement. They conclude that even with the modelled removal of higher density basin fill (due to up to 5km burial of Permian to Cretaceous sequences) the positive gravity high anomaly remains. It is possible that the gravity high continuing to the west into the present area to the south of the PWFZ also relates to the basement. A similar gravity high is seen to the south of the

South Lyme Bay fault zone. A possible conclusion therefore is that this fault zone is also basement-involved, with the high to the south potentially relating to higher density basement rocks. Smith and Hatton (1998) do suggest that this gravity high may be due to compaction of thicker sedimentary fill to the south of this fault, and indeed our seismic interpretation does identify some thickness changes in to the south of this fault (in Lias age rocks) which may be indicative of longer-lived growth movement. However, the thickening identified does not suggest significant levels of growth faulting, which may not be enough to produce significant density changes in lower level strata of the same order as suggested by Busby and Smith (2001). This supports the conclusion that this gravity high is also related primarily to basement density variations across a possibly Variscan-aged structure. Harvey and Stewart (1998) 'soft-link' the Lyme-Portland fault and other E-W principal faults to the north in Lyme Bay through the Triassic salt (Dorset Halite, Upper Triassic Mercia Mudstone) to faulting in the pre-salt Permian and Triassic strata. The quality of the seismic data in Lyme Bay precludes any firm conclusions regarding deeper continuation of the faults into the pre-Permian 'Variscan' basement.

The N-S striking faulting identified in Weymouth Bay and to its east appears to correlate geographically with the positive gravity anomaly beneath the bay (Fig. 2). By contrast, the lack of N-S faulting in Lyme Bay (as identified by our extended mapping) occurs above a 'flat' area of no significant gravity anomalies. As described above, the gravity high to the south of the PWFZ points to involvement of high density basement in the hangingwall of the inverted structure. So there appears to be a spatial relationship in the hangingwall of the PWFZ between the distributed strain (with N-S shortening and E-W extension) that Sanderson et al. (2017) imply to be driving formation of the N-S faulting, and potential basement involvement. The periclinal form of the Weymouth anticline (Fig. 2) may also be a factor in driving formation of the N-S faulting through enhanced E-W extension.

It is worth noting that the apparent lack of N-S striking faulting in the onshore area to the west of Swanage (Fig. 2), above the most pronounced gravity high in the PWFZ hangingwall, is potentially an artefact of the mapping process. The N-S faults in the offshore here are mapped as extending into the exposed cliff sections, and may be expected to continue inland, but bedrock mapping is limited here by superficial deposits cover, including soil, head and landslide deposits, and seismic section data in this area is not of sufficient resolution to discern these relatively small-scale (10's m throw) faults.

In the north of Lyme Bay, the clearest relationship between potential basement variations and faulting structure is seen where the Mangerton Fault correlates with a left-lateral step in the gravity highs (Fig. 2). The North Lyme Bay Fault, into which the Mangerton Fault merges as described above, appears to have developed on the southern flank of the broad gravity high to the north-west of the area (which correlates with the exposed Permo-Triassic sequences), and therefore with relatively near-surface Variscan basement. The eastward termination of the Abbotsbury-Ridgeway Fault and the apparent north and westwards stepping of the faulting into the North Lyme Bay fault zone, also correlates with the northward transfer of the gravity highs, again suggesting a basement control to the development of the E-W faulting.

6. Conclusions

We review the regional tectonics of part of the southern UK in terms of the development of major deformation lineaments, which affect the post-Carboniferous 'cover' sequences, and their relationship to the principal Variscan-Cimmerian-Alpine tectonic phases. Key observations from this review include:

- The Variscan basement in southern Britain has a primary E-W tectonic fabric and a secondary NW-SE tectonic fabric. This basement fabric perseveres into the cover sequences, variably controlling active growth faulting in the Cimmerian phase, and inversion in the Alpine phase.
- Despite complexities in the form and trend of the NW-SE Bristol Channel-Bray Fault, it appears to broadly separate a region to the east, where deformation in the post-Carboniferous cover sequences is characterised by the dominantly E-W orientated *en echelon* lineaments, from an apparently more complex region to the west, where the E-W lineaments are commonly accompanied by NW-SE, and subsidiary NE-SW and N-S striking faults. The western region corresponds to the Cornubian basement massif, which was transported north-westwards along the Bray Fault by over 400 km against Avalon Terrane during the late Variscan phase, and includes the present study area.

The regional review places the PWFZ in its context as one of the principal (most laterally and vertically persistent) and long-lived (Variscan through to Alpine) deformational lineaments in the southern UK, dying out to the west towards the exposed Cornubian massif. Our study of the PWFZ allows us to more fully characterise the structure, and we are able to make a number of new conclusions regarding its tectonic development:

- Structures such as the 'Lulworth Crumple' relate to antithetic shearing in the immediate hangingwall of the principal Purbeck Fault, while faulting and related folding structures at Ringstead relate to deformation in the relay ramp zone between the en echelon Purbeck and Abbotsbury-Ridgeway elements of the main PWFZ. This confirms the model of Sanderson et al. (2017) of focussed higher strain along the PWFZ, contrasting with lower, more distributed strain observed in its hangingwall beneath Weymouth Bay.
- No evidence is seen in Lyme Bay for the N-S striking extensional faulting seen in Weymouth Bay, the latter related by Sanderson et al. (2017) to the distributed (N-S shortening) strain in the PWFZ hangingwall. Instead, E-W striking faulting is dominant, including the offshore extension of the Abbotsbury-Ridgeway Fault, which appears to terminate beneath Lyme Bay, with the strain taken up further to the north and west by overlapping (left-stepping) en echelon E-W striking faults.
- The NE-SW striking Mangerton Fault, thought to be mainly a late-stage (Miocene) structure truncating the E-W structures, is extended offshore in our mapping, and seen to merge with the E-W faulting complexes mapped beneath the north of Lyme Bay. This supports a conclusion that the development of the NE-SW structures (and conjugate NW-SE structures) in the area was in part coeval with the later stages of Alpine inversion-related movement on the PWFZ structures. We also tentatively suggest, from the faulting geometries, that there may also have been an element of strike-slip (possibly right-lateral) during inversion on the E-W striking fault complexes beneath Lyme Bay.
- Observations using regional geophysical data (in particular, gravity) suggest the involvement of basement variability in the control of the regional faulting pattern. For example, the N-S striking faulting identified in the Weymouth Bay area by Sanderson et al. (2017) appears to correspond to the gravity high to the south of the PWFZ, which has been interpreted

previously to relate primarily to higher density basement uplifted during the Alpine inversion. The NE-SW striking Mangerton Fault and the E-W faulting in Lyme Bay with which it merges also appear to relate to steps in and flanks of gravity highs, pointing also to basement control.

These conclusions give us an insight into the lateral variability of a long-lived deformation lineament in the southern UK, and how this relates in part to basement variability. In particular, we are able to observe how the classic Alpine inversion scenario seen in Weymouth Bay, of hangingwall buttressing against a rigid footwall (relating to N-S shortening) transfers westwards and to lower tectonostratigraphical levels into a scenario of E-W en echelon faulting development, with potential strike-slip involvement.

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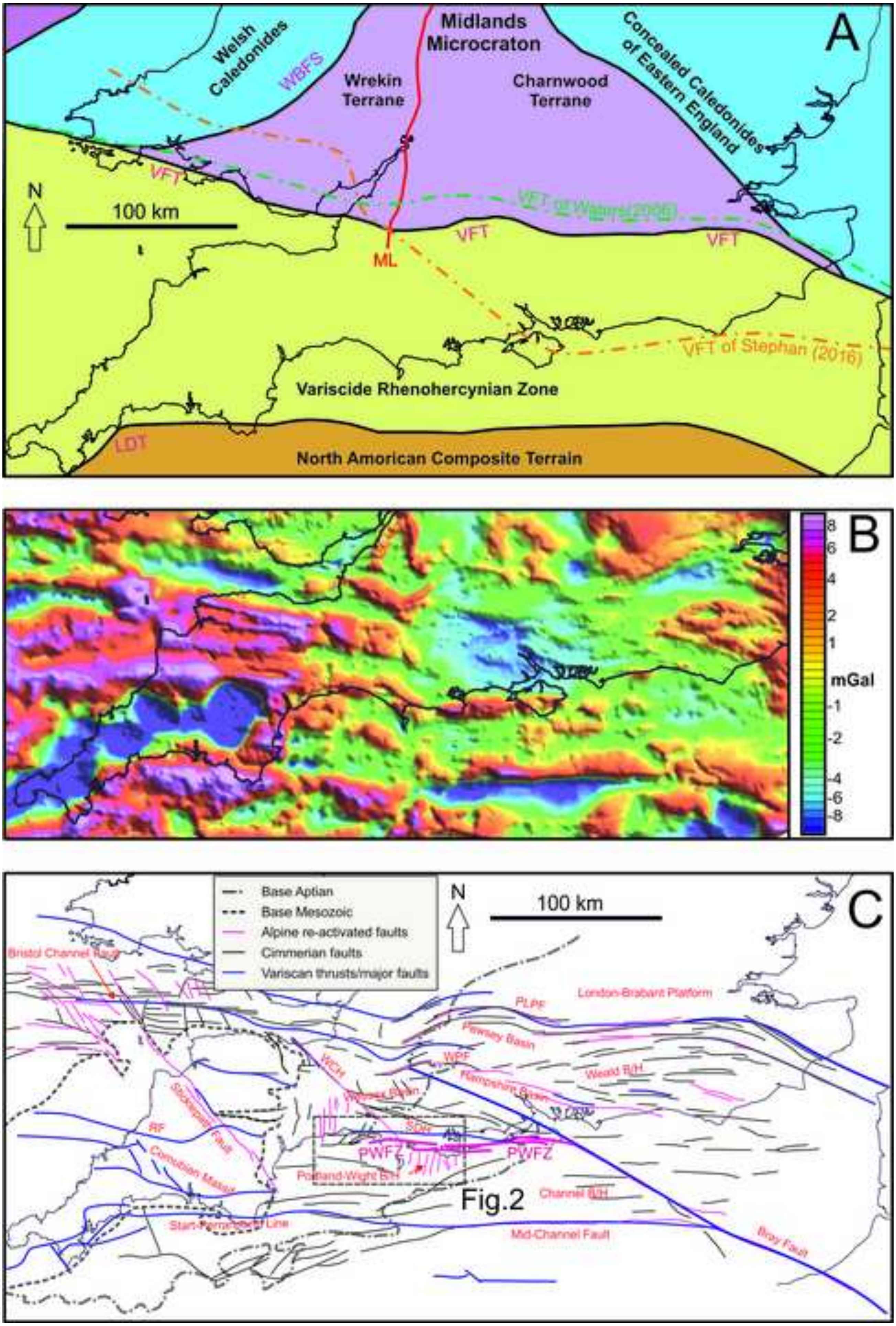

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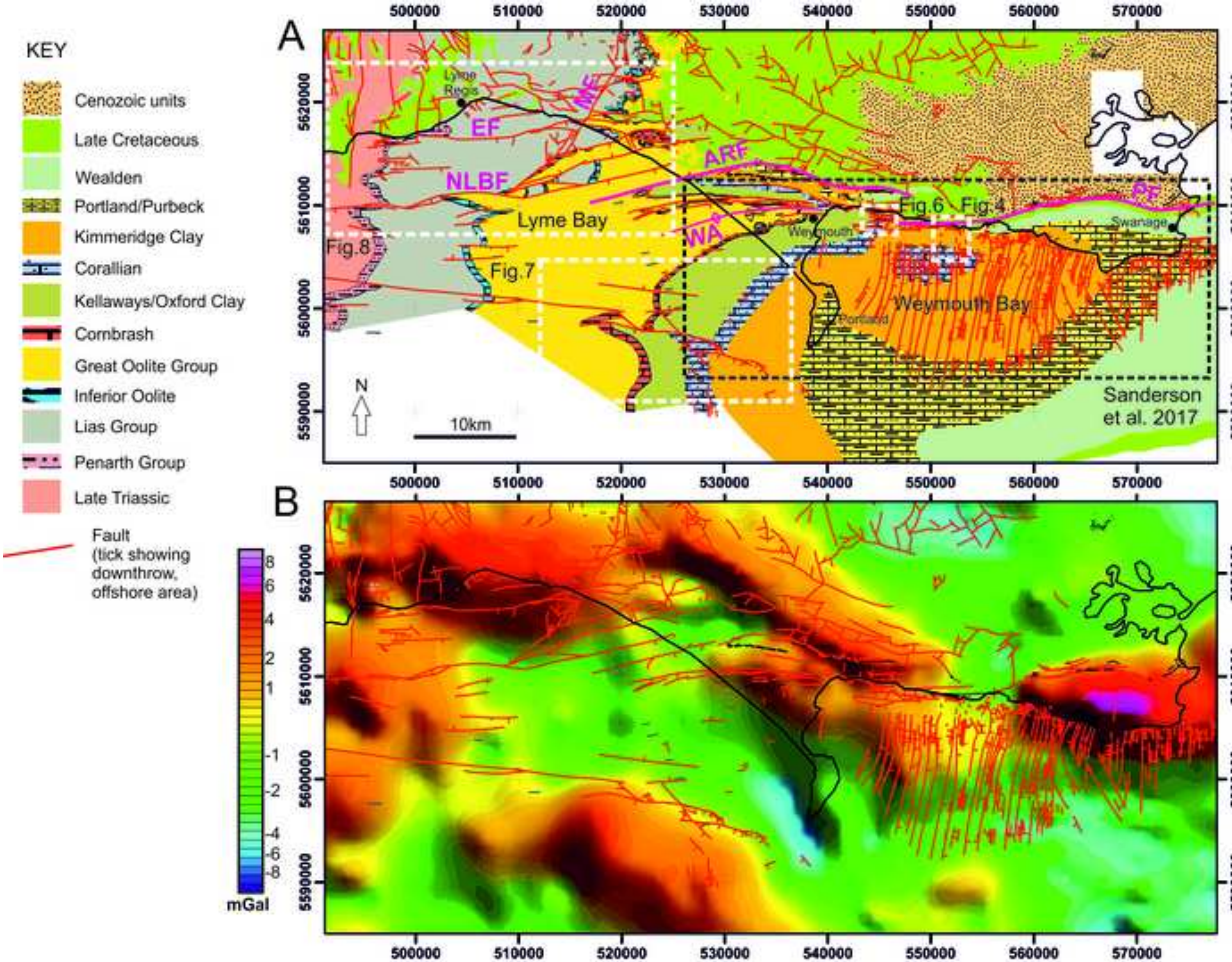

Figure 3

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	Lithostratigraphy	Thickness (m)	Summary lithology
	Cenozoic units	200+	Clay & sand
Cretaceous	Cretaceous units (post-Aptian)	500+	Sandstone & mudstone in lower part (Greensand & Gault). Chalk in upper 400m
Cretaceous	Wealden Formation	65-435	Sandstone & mudstone
Cretaceous / Jurassic	Portland & Purbeck groups (undivided)	100-190	Limestone, sandstone & mudstone
Jurassic	Kimmeridge Clay Formation	250-570	Mudstone with thin limestones ('Ledges')
Jurassic	Corallian Group	60-70	Limestone, sandstone & mudstone
Jurassic	Kellaways & Oxford Clay formations (undivided)	c. 150	Mudstone, sandy in lower part
Jurassic	Cornbrash Formation	10-20	Limestone
Jurassic	Great Oolite Group	c. 350	Dominantly mudstone with variable thin limestones
Jurassic	Inferior Oolite Formation	c.10	Limestone
Jurassic	Lias Group	c.600	Dominantly mudstone, with thin limestones (locally dominant), sandy towards upper part
Triassic	Penarth Group	20-40	Limestone & mudstone
Triassic	Late Triassic	200+	Reddish-brown mudstone

Figure 4

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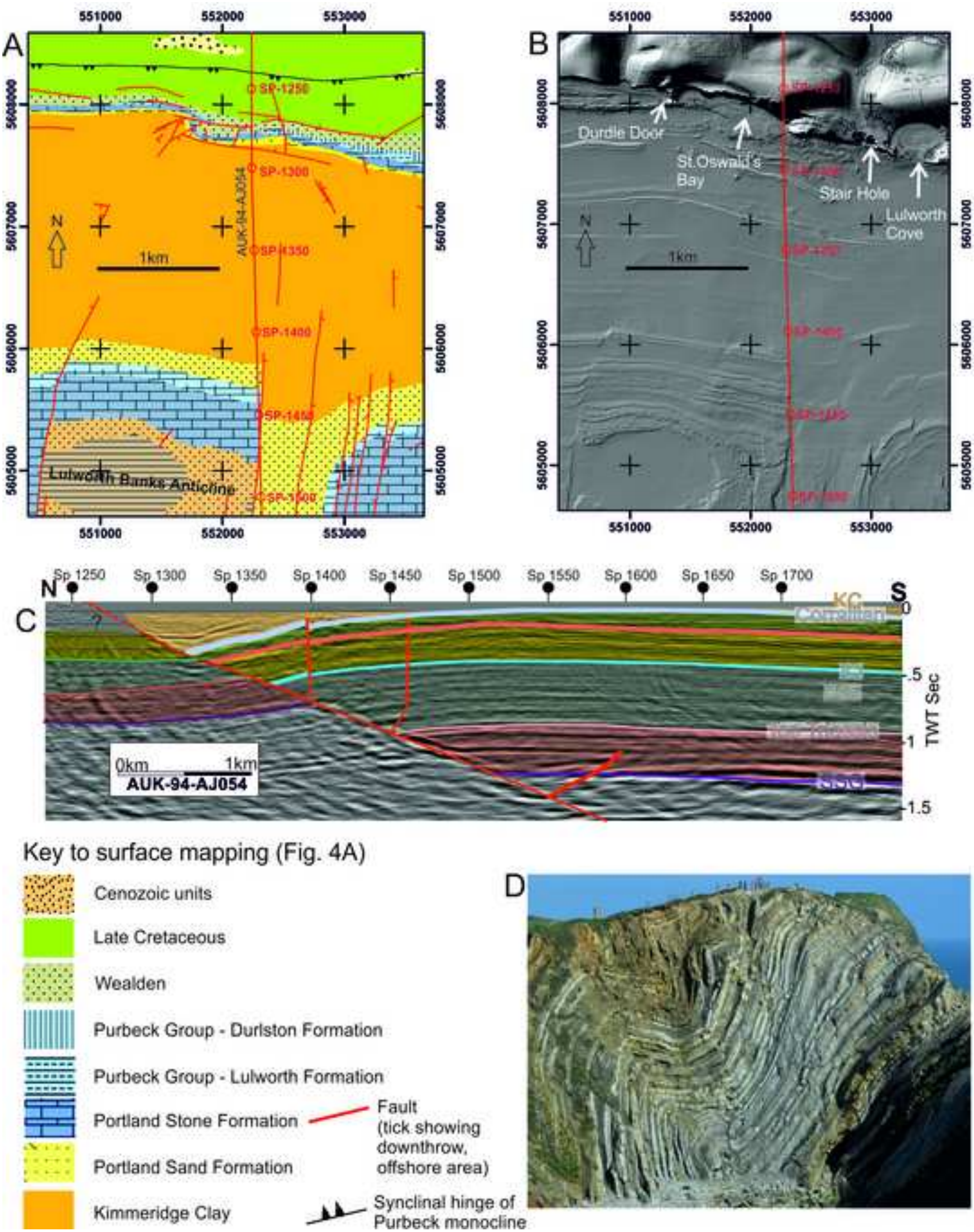

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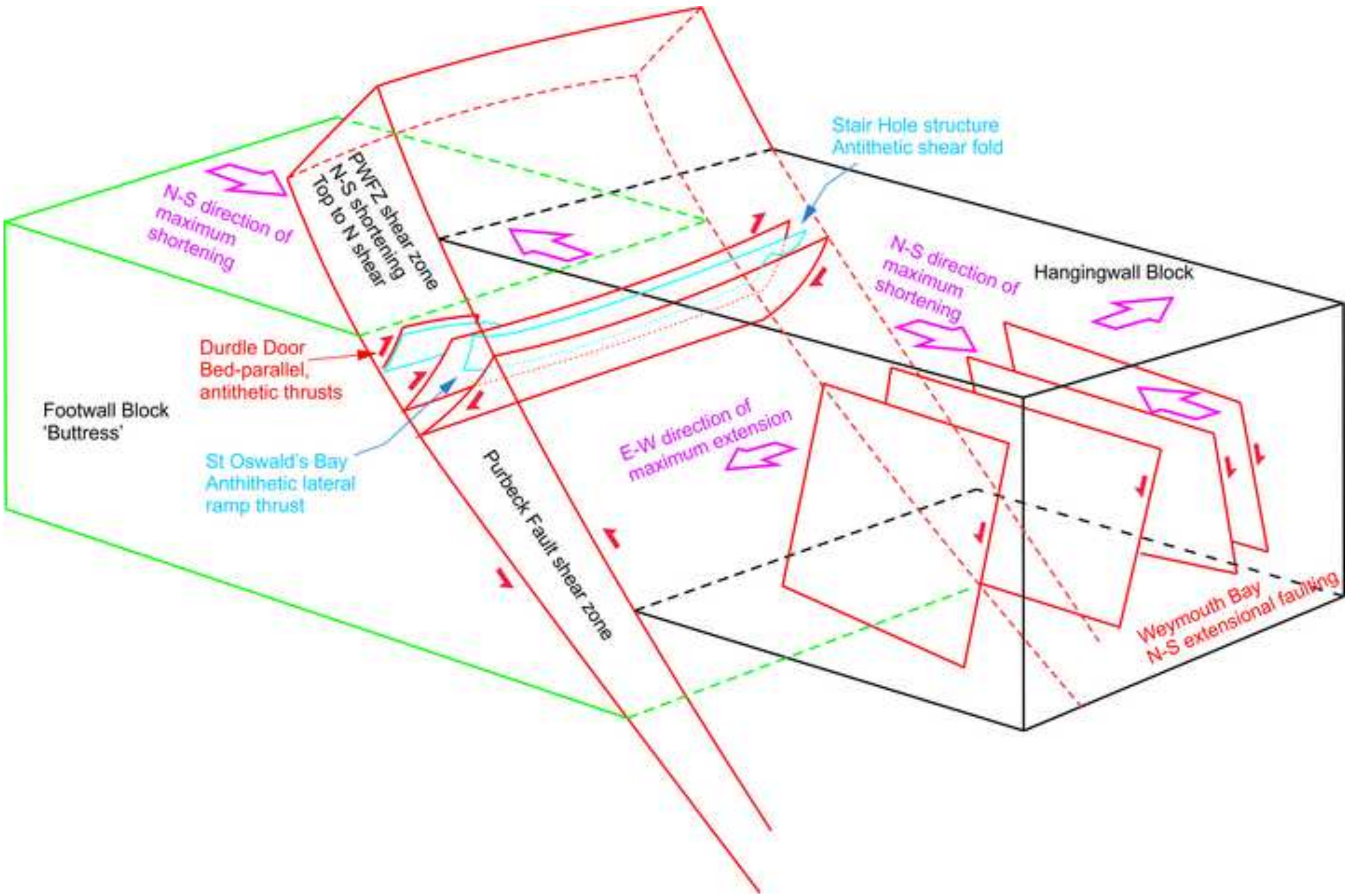

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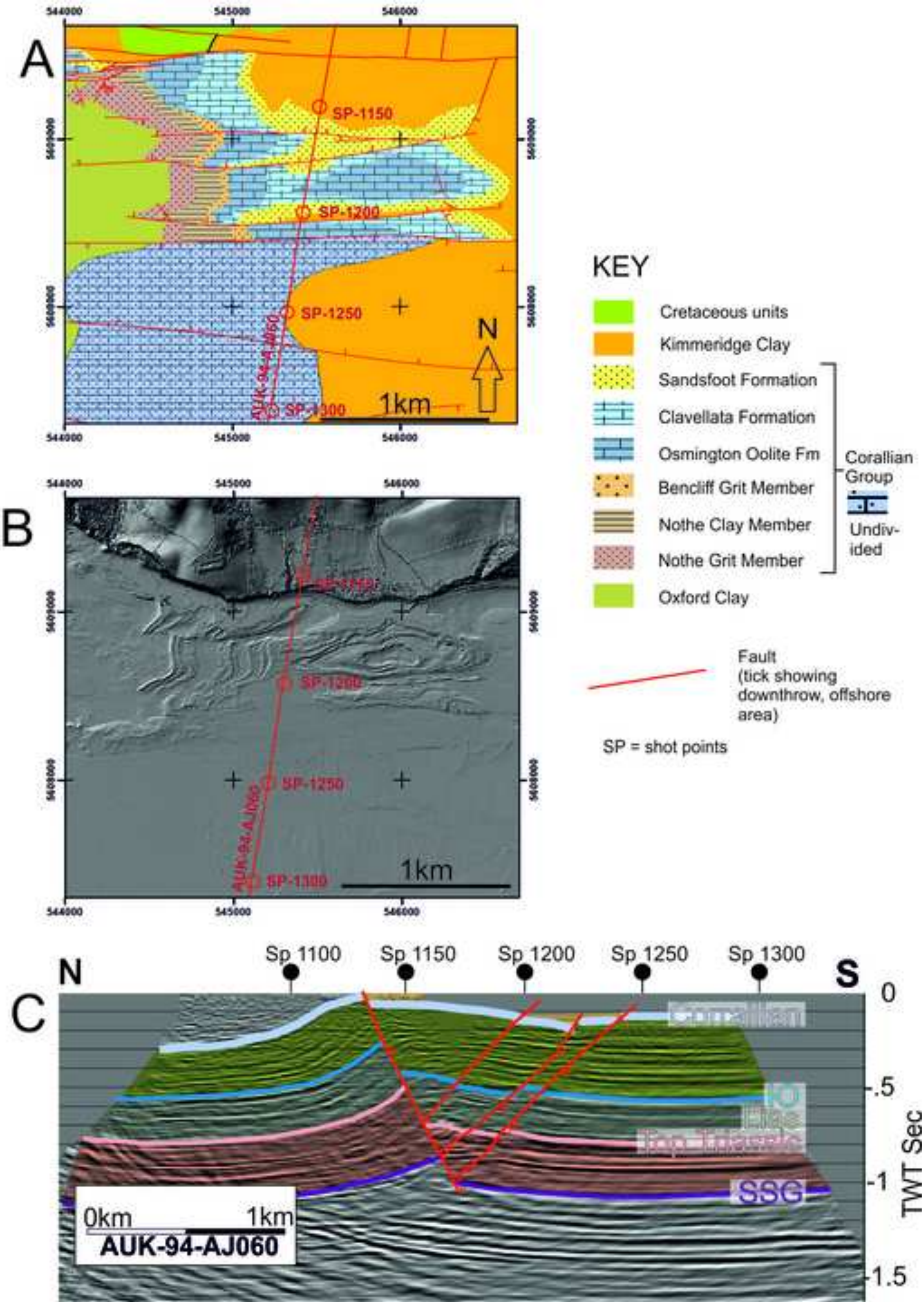

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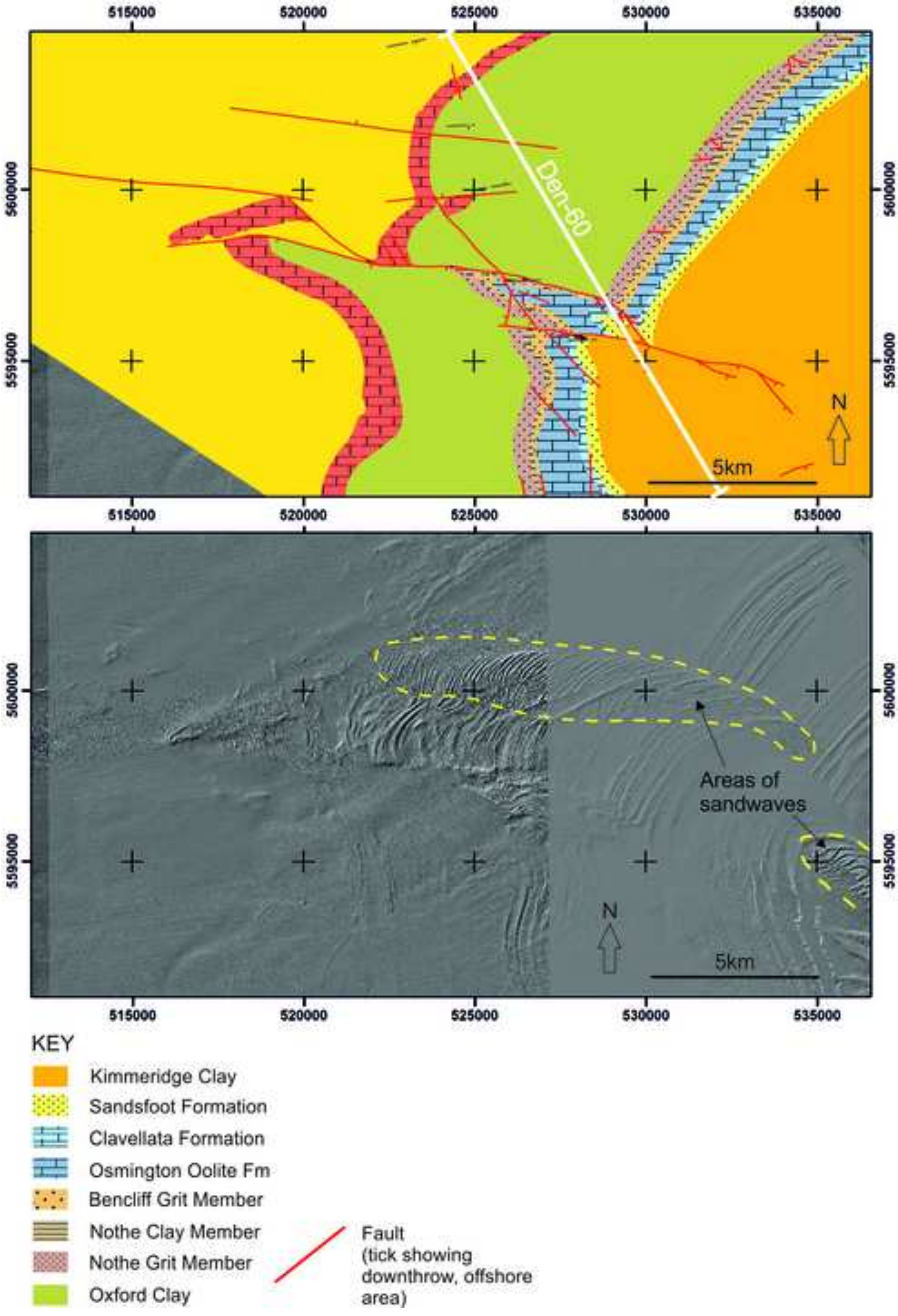

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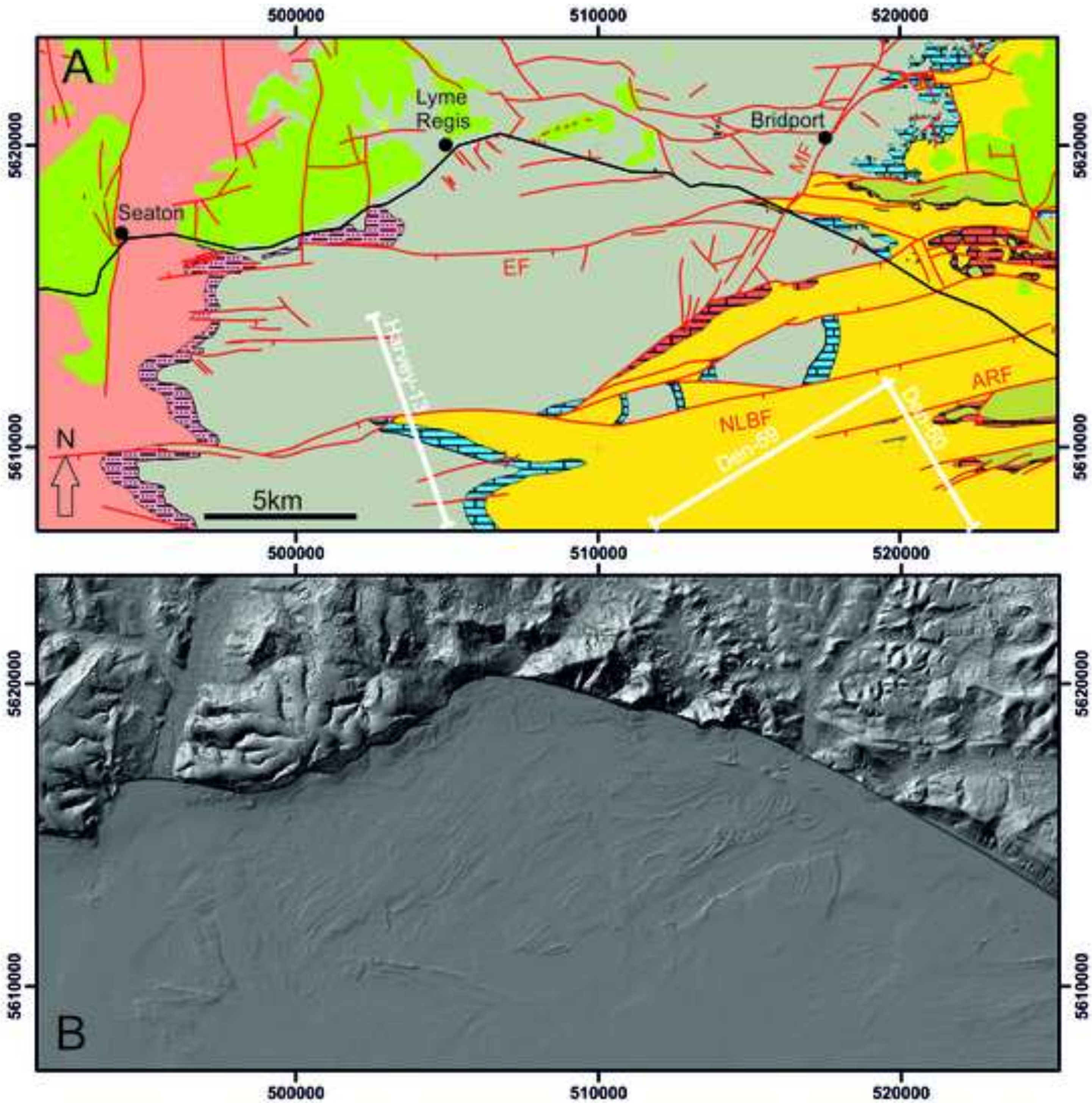

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