**Genesis of tectonic inversion structures: seismic evidence for the development of key structures along the Purbeck-Isle of Wight Disturbance**

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**Abstract:** The interpretation of a densely spaced and well-calibrated seismic grid sheds new light on the development and evolution of key regional and local structures in the Wessex Basin. The results help to resolve long-standing controversies concerning the tectonic significance of apparently anomalous outcrop patterns and the role of important, local ancillary structures with respect to the major monoclinal folds with which they are associated. Although the structures are entirely consistent with the effects of contractional reactivation (tectonic inversion) of normal faults, the subsurface data demonstrate the role that original extensional fault segmentation and associated relay ramps had on original depositional patterns, subsequent inversion geometries and resultant outcrop patterns. As well as illustrating regional controls on the formation of structures, the new seismic-based interpretations enable a reassessment of the Lulworth Crumple and the Ballard Down Fault. The Lulworth Crumple is interpreted as a parasitic fold complex generated by internal folding of the inverted, incompetent syn-rift fill in the immediate hanging wall to the Purbeck Fault, a reactivated major normal fault. The Ballard Down Fault's origin is interpreted to result from the formation of a local, late-stage 'out of the syncline' reverse fault which propagated southwards and upwards through a Chalk succession. As the Chalk had already been rotated to form the northward-dipping steep limb of the Purbeck Monocline at Ballard Down, the structure cuts down stratigraphically. The results stress the importance of understanding the nature of original extensional fault geometries and the competence of the sedimentary units incorporated in folds in gaining a full understanding of the genesis and evolution of structural styles in inverted basins.

**Keywords:** Wessex, rifting, structural inversion, hydrocarbon habitats.

The role and importance of contractional reactivation of former normal faults (tectonic inversion) is now recognized as an important mechanism of intraplate deformation (e.g. Ziegler 1989; Cooper et al. 1989; Buchanan & Buchanan 1995). Despite recent advances in the understanding of the tectonic processes involved in the formation of inversion structures, several aspects of their development and evolution remain unresolved including variability in their 3D shape, their scale variance and the spatial distribution of related macro- and meso-scale structures. It is only by the study of well-exposed inverted sedimentary basins in which subsurface data are available (e.g. well-calibrated seismic data), that insights can be gained into the outstanding problems associated with tectonic inversion.

A number of sedimentary basins exist in NW Europe that were affected by tectonic inversion during the Cenozoic (Ziegler 1989) in response to intraplate compression resulting from the combined effects of Atlantic opening and Alpine collision (Glennie & Underhill 1998). The wealth of subsurface data available from these basins as a result of their relatively high hydrocarbon prospectivity means that several represent excellent candidates in which to undertake a detailed structural and stratigraphic analysis. Of these the Wessex Basin of South Dorset and the Isle of Wight (Fig. 1) is arguably the best because of the level of coastal exposure, its well documented stratigraphy and sedimentary history and its excellent subsurface control.

Despite spectacular two-dimensional coastal exposures that are both readily accessible and much frequented by geologists, controversy has long surrounded the genesis of structures in the Wessex Basin. Not only has the mode of formation of the major zones of deformation been disputed but so too have the controls on the apparently anomalous outcrop patterns at...
Chaldon Down, south Dorset and Lillecombe Down, Isle of Wight and the genesis of well known local structures such as the Lulworth Crumple and the Ballard Down Fault. It is only with the recent availability of well-calibrated seismic data that the tectonic controls on these structures can now be determined. The aim of this paper is to integrate subsurface data with field observations to demonstrate the main controls on the development and evolution of key structures. Whilst the results explain their formation, they also give important insights into the creation of other structures found along the length of the Purbeck–Isle of Wight Disturbance, shed new light on a classic area of British geology and potentially provide new information concerning the genesis of structures useable in the structural interpretation of other inverted sedimentary basins.

The Wessex Basin: definition

The definition of the Wessex Basin as used in this paper follows that of Underhill & Stoneley (1998) who considered it to consist of a system of post-Variscan extensional sedimentary depocentres and intra-basinal highs that developed across central southern England and adjacent offshore areas. The onshore extent of the basin is effectively restricted to the ancient kingdom of the West Saxons (Wessex), which includes the present counties of Hampshire and Dorset, together with parts of east Devon, Somerset and Wiltshire, and excludes the Weald Basin of Sussex, Surrey and Kent. The Wessex Basin is bound to the southwest and west by the Armorican and Cornubian Massifs, to the north by the London Platform and includes parts of East Devon, Somerset and Wiltshire, and excludes the Weald Basin of Sussex, Surrey and Kent. The Wessex Basin is defined by the progressive westerly distribution in Dorset apparently localized along the strike of the Lower Cretaceous, Wealden Group which have a distribution in Dorset apparently localized along the strike.

Stratigraphic framework

Temporally, the sedimentary history of the Wessex Basin post-dates the development and closure of the Devonian-Carboniferous Proto-Tethys or Rheic Ocean. The deformed Devonian-Carboniferous sediments lie beneath a marked unconformity which represents the effective sedimentary basement to the Wessex Basin (Underhill & Stoneley 1998).

Extensional basin development and its component sedimentary fill history began in the Permian within the Variscan fold-and-thrust belt hinterland and continued until the Late Cretaceous in the Wessex Basin (Fig. 2; Underhill & Stoneley, 1998). The subsequent sedimentary fill of the successor Hampshire Basin, which forms a local but important component part of the Wessex Basin, is entirely Tertiary in age with the youngest sediments being of Oligocene age.

In general terms, field relations enable the Permain-Oligocene succession to be separated into three internally conformable but unconformity bound mega-sequences (Fig. 2; Underhill & Stoneley 1998): the Permain to Lower Cretaceous, Upper Cretaceous and Tertiary megasequences.

Permian–Lower Cretaceous megasequence

Field relations also enable the Permain to Lower Cretaceous megasequences to be subdivided into three component parts based upon their respective environments of deposition (Underhill & Stoneley 1998; Fig. 2).

The lowest division consists of Permain and Triassic non-marine sediments dominated by continental (red bed) sediments. Deposition was initially restricted to intramontane basins that developed due to extensional collapse of the former Variscan mountain belt. The Permain, Exmouth and Dawlish Sands of the east Devon coast pass up into mudstones of the Aylesbeare Group which are in turn sharply overlain by Early Triassic Budleigh Salterton Pebble Beds (Fig. 2). The latter alternate with, and pass up into, sandstones ascribed to the Otter Sandstone Formation. Together the Budleigh Salterton Pebble Beds and the Otter Sandstone comprise the widespread Triassic Sherwood Sandstone Group (Fig. 2). The upper part of the sequence is formed by the extensive argillaceous Mercia Mudstone Group, known in the subsurface to include localized evaporites. The Penarth Group at the top of the Triassic succession heralds the effects of widespread Liassic marine transgression that led to the re-establishment of marine waters in the area for the first time since the Carboniferous.

The middle division contains dominantly marine sediments of Jurassic age (Fig. 3). It consists largely of a broadly cyclic repetition of shallow marine mudrocks, sandstones and limestones. Many formations have been defined and mapped but, with the exception of local facies variations, particularly in some of the carbonates, all appear to be remarkably widespread in the basin. The top of the succession records a major marine regression and the highest parts of the succession record sabkha and brackish water depositional environments (the Purbeck).

The upper division consists of largely non-marine sediments of the Lower Cretaceous, Wealden Group which have a distribution in Dorset apparently localized along the strike south of major syn-sedimentary faults. They are essentially of fluvial origin, although lacustrine environments are well represented in the considerably thicker succession in the Isle of Wight. Evidence exists for continued extensional movement on several of the E-W-trending faults during the Early Cretaceous, which in the Isle of Wight at least also appears to affect deposition of the overlying Lower Greensand.

Upper Cretaceous megasequence

An Upper Cretaceous megasequence can be defined which is separated from the underlying Permain-Lower Cretaceous megasequence by an important Albian-Aptian unconformity, which is marked regionally by the progressive westerly
truncation of Mesozoic and Permian strata (Underhill & Stoneley, fig. 8). The lowest part of the Upper Cretaceous megasequence actually extends into the Lower Cretaceous (pars) since it consists of westerly-onlapping and diachronous, Albian marine clays and sandstones (Gault and Upper Greensand). They pass up into the Chalk (of Cenomanian–Senonian age), which shows evidence of thinning in western parts of the basin. The base of the Upper Cretaceous megasequence could conceivably be extended down to include the Lower Greensand. However, evidence that the latter are more closely associated with syn-sedimentary movement on normal faults tends to suggest that the Lower Greensand has a closer affinity with the underlying Permian-Lower Cretaceous megasequence than the Upper Cretaceous megasequence.

In general terms the Upper Cretaceous megasequence shows little thickness variation and may be considered synonymous with a post-rift sequence. It is only the highly localized evidence for lateral variation in thickness and Chalk lithofacies, including the development of slumps, slip scars and
local lacunae (Gale 1980; M ortimer & Pomero y 1997), that demonstrates that the post-rift episode was not entirely quiescent. Their close spatial association with the E-W-trending buried faults suggests that some of the structures either retained limited activity either in extension or, more likely, began to show the effects of contractual reactivation during the late Cretaceous.

**Tertiary megasequence**

The Tertiary succession is separated from the underlying megasequence by an important, but subtle, regional disconformity. The stratigraphic break covers the M aastrichtian and most of the Palaeocene. The overlying sediments that comprise the Tertiary megasequence consist of nearshore marine and non-marine sediments which reach a maximum thickness of over 600 m in the north of the Isle of Wight (Hamblin et al. 1992; Underhill & Stoneley 1998). Depositional facies analysis demonstrates that the post-rift episode was not entirely quiescent. Their close spatial association with the E-W-trending buried faults suggests that some of the structures either retained limited activity either in extension or, more likely, began to show the effects of contractual reactivation during the late Cretaceous.

**Seismic stratigraphy**

Hydrocarbon exploration has led to the widespread acquisition over the past two decades of seismic data and drilling activity in both onshore areas of South Dorset, Hampshire and the Isle of Wight and adjacent offshore waters of the English Channel and Bournemouth Bay. As a result the Wessex Basin is covered by a well-calibrated dense grid of 2D seismic data and at least one 3D seismic survey. Correlation between well and seismic data indicates that the three stratigraphic megasequences recognized from field relations may also be recognized in the subsurface (e.g. Hawkes et al. 1998). The subsurface data also demonstrate that many important stratigraphic markers may be mapped across the basin (Fig. 2), thus enabling the basin’s tectonostratigraphic development and evolution to be determined. These markers not only include the Base Tertiary and Base Upper Cretaceous megasequence (Base Gault) boundaries, but also many other conformable horizons that form a component part of each megasequence. In total, fifteen seismic events have been mapped regionally (Fig. 2): Base Tertiary; Base Chalk; Base Upper Greensand and Gault; Top Purbeck Beds; Top Kimmeridge Clay Formation; Top Corallian; Top Oxford Clay; Top Kellaways Beds; Top Inferior Oolite (proxy for Top Bridport Sandstone); The Junction Bed; Top Green Ammonite Beds (a prominent Intra-Liassic marker); Top Penarth Group; Top Mercia Mudstone Group; Top Sherwood Sandstone; Base Sherwood Sandstone Group (Top Aylesbeare Mudstone Group). A further two events have been mapped in eastern parts of the basin (primarily in the Isle of Wight area): Top Wealden Group (Base Lower Greensand) and Top Great Oolite, which appears due to a facies change in the Middle Jurassic (Hawkes et al. 1998).

**Origin of the zones of disturbance**

As is commonly the case, problems associated with the acquisition of onshore seismic data (e.g. statics and spatial density of data acquisition) have hindered the larger scale structural observations normally possible using seismic data. Given the additional limitations caused by the difficulty in imaging steeply-dipping reflectors in the subsurface, understanding of the structural geology of onshore areas has only really been possible in areas characterized by relatively gentle structural dips (e.g. away from the main structural lineaments). In these regions, integration of well data has often enabled good control on fault-block stratigraphy and geometry (Fig. 4).

In contrast to the land data, acquisition of closely spaced seismic data from offshore areas provides an excellent control on large-scale structural geometries. Significantly these data can also be used to gain a better understanding of important ancillary structures found along them such as the Ballard Down Fault and Lulworth Crumple. Before placing these local structures into their proper regional context, the seismic data will first be used to demonstrate large-scale structural geometries and hence confirm the mode of formation of the prominent monoclinic folds with which they are associated. Structural relations are particularly clear in the area between Swanage and the Isle of Wight where a dense grid of 2D seismic data enables good control on the major zones of disturbance both in cross section and in plan view.

**Cross section.** Integration of well data with the seismic data demonstrates that the zones of disturbance are underlain by steeply dipping faults which are characterized by important thickness changes especially during Jurassic and Early Cretaceous times (Whittaker 1985; Penn et al. 1987; Hamblin et al. 1992; Ruffell & Garden 1997). Their interpretation is consistent with features that initially formed significant down-to-the-south normal faults during periods of active extension (syn-rift fill), were subsequently covered by post-rift fill and well-documented, curvilinear E-W-trending zones of disturbance (Fig. 3) that are marked by steep and overturned Mesozoic and Lower Cenozoic strata (e.g. Strahan 1895, 1898; Arkell 1936, 1938, 1947; House 1961, 1989; Phillips 1964; Stoneley 1982; Bevan 1985; Chadwick 1993). At outcrop, the best known zone affected by the folding extends the length of the basin from Abbotsbury in the west to Whitecliff Bay in the east and consists of at least five main structural elements: the A bbotsbury-R idgewater F ault, the L itton C heney F ault, the Purbeck D isturbance and the two Isle of Wight monoclines (Fig. 3). The zone is characterized by a series of northward-verging asymmetric anticlines that include the Weymouth, Purbeck, Brixton and Sandown anticlines (Fig. 3).

Across the Wessex Basin many of the seismic lines are oriented perpendicular to the E-W-trending main structural lineaments thus providing the potential to investigate the tectonic development and evolution of the zones of deformation (e.g. Colter & Harvard 1981). It is primarily the integration of these data with field observations that has led to a better understanding of the structural geometries which enable the origin and evolution of the main zones of disturbance that dissect the Wessex Basin to be determined (e.g. Colter & Harvard 1981; Stoneley 1982; Whittaker 1985; Sellwood et al. 1985).

**Genesis of the Wessex Basin structures**

**Regional considerations**

Structural interpretation of field exposures demonstrates that the Wessex Basin is transected by several important and well-documented, curvilinear E-W-trending zones of disturbance (Fig. 3) that are marked by steep and overturned Mesozoic and Lower Cenozoic strata (e.g. Strahan 1895, 1898; Arkell 1936, 1938, 1947; House 1961, 1989; Phillips 1964; Stoneley 1982; Bevan 1985; Chadwick 1993). At outcrop, the best known zone affected by the folding extends the length of the basin from Abbotsbury in the west to Whitecliff Bay in the east and consists of at least five main structural elements: the A bbotsbury-R idgewater F ault, the L itton C heney F ault, the Purbeck D isturbance and the two Isle of Wight monoclines (Fig. 3). The zone is characterized by a series of northward-verging asymmetric anticlines that include the Weymouth, Purbeck, Brixton and Sandown anticlines (Fig. 3).

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finally reactivated in compression in the Late Cretaceous and Cenozoic (Plint 1982, 1983, 1988; Chadwick 1986; Lake & Karner 1987; Hamblin et al. 1992; Gale et al. 1999; Figs 5, 6, 7 & 8).

Despite having been reactivated in compression, most of the original extensional structures remain in net extension below the syn-rift to pre-rift unconformity, a characteristic of many structurally inverted sedimentary basins (Cooper et al. 1989).

In contrast the post-rift sediments in the immediate footwall of the structurally inverted faults occasionally show evidence for contractional deformation including local folds and reverse faulting. It is our view that some of the low-angle reverse faults present in the immediate footwall to some of the structurally inverted faults may be reinterpreted as footwall short-cut faults (sensu Cooper et al. 1989). Examples include those structures developed at East Hill, Sutton Poyntz (Arkell 1947) and the southward-dipping (‘group 3’) shear planes of Arkell (1947) and Phillips (1964) that occur along the coast between Durdle Cove and St Oswald’s Bay.

It is only in one or two of the footwall locations lying further to the north of the major zones of disturbance that the effects of Cenozoic contraction have been felt. Where more than one terrace-bounding fault has been reactivated additional monoclinal folds affect the post-rift sequence (Figs 5 & 6). However, as reactivation of the buried extensional faults that dissect the Triassic and Jurassic section in areas to the north of the main lines of disturbance is not the norm, the Cretaceous or Cenozoic stratigraphic sections show little or no sign of the underlying structure. Significantly, it is in these areas that the most important hydrocarbon discoveries have been made to date where (unbreached) extensional tilted fault block closures have been preserved (e.g. Wytch Farm and Wareham oilfields, Figs 2, 5 & 6; Colter & Harvard 1981; Stoneley 1982; Penn et al. 1987; Underhill & Stoneley 1998).

Not only have the post-rift sediments been folded in some footwall locations as a result of the tectonic inversion process, but so too have sediments that were originally deposited in the hanging-wall depocentres, with the development of broad open northward-verging asymmetric anticlines that are parallel with and lie adjacent to the reactivated faults (e.g. Fig. 3). Interpretation of seismic, well and outcrop data enable the internal structure of each of the hangingwall folds to be determined either on a regional or local scale (e.g. the Lulworth Banks and Weymouth anticlines; Figs 8 & 9). Indeed, in the case of the Weymouth Anticline it is now possible to produce a detailed subsurface interpretation of the structure (Fig. 9), which improves upon anything previously possible using surface data alone (e.g. House 1961).
zones of disturbance. They demonstrate the importance of fault segmentation within the zone affected by reactivation with the consequent formation of discontinuous fault block terraces (Figs 2, 5, 6, 7, 8, 9 & 10).

Importantly, the occurrence of en-echelon fault segments appears not to be limited to offshore areas but appears to characterize onshore regions too. The presence of fault arrays comprising numerous discontinuous individual fault segments may help explain apparently anomalous outcrop patterns that characterize Lillecombe Down in the Isle of Wight (Fig. 11a) and Chaldon Down in Dorset (Fig. 11b) that had been thought to result from an offset along a strike-slip fault. Both areas are marked by regions lying between the steep limbs of two overlapping monoclinal folds in which structural dips are low (less than 10°). The seismic data from the Isle of Wight indicate that the northern monoclinal fold lies immediately above a steep, planar and southerly-dipping reactivated normal fault (e.g. Fig. 12), the extensional throw on which originally diminished westwards in to the Lillecombe Down structure (Figs 11a & 13). Similarly, the outcrop pattern demonstrates that the reverse displacement on the reactivated faults progressively diminishes towards the west on the northern monocline and towards the east on the southern monocline (Fig. 11a).

Taken together the structural relations at Lillecombe and Chaldon Downs are consistent with their having formerly represented relay ramps between two overlapping original (and now inverted) extensional fault segments (e.g. Fig. 14), the like of which are well known from rift basins (e.g. Larsen 1988; Underhill 1991, 1994, 1998; Gawthorpe & Hurst 1993; Trudgill & Cartwright 1994; Peacock & Sanderson 1991, 1994). Interestingly, no differences are readily apparent between the two areas suggesting that the presence or absence of low-angle décollement surfaces at deeper levels (e.g. in Triassic salt beneath Chaldon Down; Stewart et al. 1996; Harvey & Stewart 1998) has had no appreciable influence on the structural geometries above the inverted relay ramps.

Local structures

Although several contrasting models for the formation of individual local, tectonic features have been proposed on the basis of field descriptions and interpretations, it is only with the insights gained from subsurface data that many of the mesoscale structures can be placed in their proper regional context. The aim of the next section is to demonstrate that the genesis of two well-known but contentious structures may be explained by reference to subsurface interpretations.

(a) Site and genesis of the Ballard Down Fault. Structural description. Coastal exposures between Pfunfield Cove [SZ 039 810] and Studland [SZ 035 828] afford the opportunity to view the post-Wealden Group, Cretaceous and Lower Tertiary
stratigraphy in cross section. A progressive steepening in the northerly-dipping Lower Cretaceous rocks is displayed in the southern part of the section, which continues in the Upper Cretaceous succession until vertical dips are recorded at Ballard Point [SZ 048 814]. Vertical dips continue between the headland into the area immediately west of, and directly beneath, Ballard Down [SZ 049 815]. The Ballard Down Fault itself lies immediately to the east of the hillside of the same name and is well exposed in the NE-SW-trending coastal cliffs where it has a curved, N dip which parallels bedding in the Upper Cretaceous rocks (Fig. 15). Dips recorded in the beds above the fault show a progressive decrease from >60° adjacent to the structure to an angle of <10° only 200 m north of it. The gentle northerly dip continues for the remainder

Figs 5 & 6. N–S representative seismic lines across the Purbeck Disturbance in the English Channel, Bournemouth Bay (their locations are shown on Fig. 3). The data demonstrate the improved quality of offshore data relative to land seismic lines (cf. Fig. 4). As a result it is possible to make accurate structural interpretation of the subsurface even in areas characterized by steep dips. Both sections demonstrate the characteristic reactivated normal fault geometries. The controlling inverted normal faults define 2–3 km wide terraces immediately to the south of the Purbeck Fault. As well as demonstrating that many of the original extensional faults have not reactivated in the footwall, the lines also illustrate that inversion of footwall terraces has locally led to the formation of more than one monoclinal fold at Base Chalk and Base Gault levels. KCF, Kimmeridge Clay Formation; Cor, Corallian; OC, Oxford Clay; JM, undifferentiated Middle Jurassic (Kellaways beds, Cornbrash, Forest Marble, Fullers Earth); BS, Bridport Sandstone; JB, Junction Bed; M MG, Mercia M ustone Group; SSG, Sherwood Sandstone Group.
of the section, which extends to Old Harry Rocks at Hardfast Point [SZ 056 826]. Since the Chalk sequences immediately adjacent to the fault belong to the same echinoderm (Belemnitella mucronata) zone (Rowe 1901), it is not immediately evident whether stratigraphy has been cut-out or duplicated by the structure. As a result, several structural deformations have been inferred from the observed seismic data, indicating a complex tectonic history in the area. This includes the reactivation of normal faults, which may have resulted in either extension or inversion, depending on the direction of the resulting stress. The stratigraphic sections and seismic interpretations suggest a dynamic interplay between extensional and contractional forces, reflecting the evolution of the area over geological time.
models have been evoked to explain the tectonic relationships described above.

Previous structural models. Existing, published tectonic models for the development and evolution of the Ballard Down Fault fall into three main categories:

(1) a N-dipping extensional fault (Arkell 1936, 1938, 1947);
(2) a S-dipping reverse fault which subsequently suffered rotation as the Purbeck monocline developed (Ameen & Cosgrove 1990, 1991);
(3) a N-dipping reverse fault (Strahan 1895; House 1989) which Carter (1991) proposed must have post-dated development of the Purbeck monocline.

The larger-scale structural geometries of each model are vastly different and, given the scale at which the consequent structures occur and the markedly different geometries created, led Ameen & Cosgrove (1991) to suggest that ‘seismic sections across the strike of the fault might reveal details of the fault bedding relationships and enable the validity of the various models to be determined’. As will be demonstrated in the next section, seismic data are now of sufficient quality and density to be used to determine the most plausible structural interpretation.

Interpretation in the light of seismic evidence. The overall structural geometry displayed on the seismic data from the area is consistent with that described in the cliff exposures below Ballard Down in that it comprises a well-defined monocline geometry, the steep limb of which lies wholly within the zone of Chalk subcrop (Fig. 16). Significantly the geometry of the shallower dipping limbs are well imaged, allowing a test of the structural models described earlier.

A nalysis of the seismic data shows that the N–S-trending dip lines consistently show identical structural and stratigraphic relationships to those displayed in the cliff sections (Figs 6 & 16). Recognition and correlation of seismic reflector terminations to well stratigraphy allows the sequence to be subdivided into two main components: (1) a lower Permian to Lower Cretaceous sedimentary package cut by laterally persistent steep S-dipping planar faults displaying net extension and which, from thickness considerations, evidently controlled syn-sedimentary differential subsidence, and (2) an upper Lower Cretaceous–Tertiary sedimentary package the
southern outcrop to which is defined by the Purbeck Disturbance which lies above the Purbeck Fault. The base of the upper package represents an unconformity which locally cuts down to the Oxford Clay in the footwall to the Purbeck Fault. Importantly, as well as being folded, the same surface exhibits evidence for reverse offset directly above many of the original extensional structures. The structural relationships are consistent with the lower and upper packages representing syn-rift
and post-rift sequences (Dewey 1982; Chadwick 1986; Lake & Karner 1987). Although both sequences experienced subsequent compression and fault reactivation as part of regional basin inversion, preservation of extensional displacements on the faults affecting the Permian–Lower Cretaceous megasequence indicates that the contractional deformation was not as significant as the earlier extensional movement.

What the seismic data do demonstrate, however, is a notable lack of any evidence for extensional offset of stratigraphic markers in the post-rift succession. Rather they illustrate the importance of reverse offsets at that level. The lack of evidence for any omission of stratigraphy and presence of numerous contractional faults affecting the chalk argues strongly against Arkell's gravity-driven extensional model and instead...
focuses attention on the two, contrasting compressional scenarios. Although Ameen & Cosgrove's (1990, 1991) model is consistent with the S-dipping nature of the (reactivated) reverse faults affecting the Chalk, the fact that Chalk thicknesses can be shown not to double due to contraction suggests their rotated thrust model is not sustainable. By contrast, the seismic data is entirely consistent with Carter's model which requires the least dramatic structural geometry at seismic-scale (Fig. 16). The implication from the seismic data is that the Ballard Down Fault is a local, late-stage back-thrust superimposed upon the earlier and more structurally significant Purbeck Disturbance (Fig. 17).

(b) Site and genesis of the 'Lulworth Crumple'. The Lulworth Crumple is the term used to describe a fold complex exposed at

![Fig. 14. Schematic block diagram depicting the nature and controls on structural deformation characteristic of the Lillecombe Down inverted relay ramp setting, Isle of Wight.](image)

![Fig. 15. Line drawing and location map of the Ballard Down Fault. The line drawing shows its characteristic but unusual hangingwall flat and footwall ramp geometry (Modified after Ameen 1990; Ameen & Cosgrove 1990, 1991).](image)
the eastern end of Stair Hole [SY 823 799], immediately west of the entrance to Lulworth Cove (Fig. 18a & b). The structure affects the Purbeck Formation of Late Jurassic and Early Cretaceous age and comprises two well-defined asymmetric northward-verging anticlinal folds (Figs 18a, b & 19). The Early Cretaceous and Late Jurassic successions that constitute the limbs of the Lulworth Crumple are affected by layer-parallel shortening and flexural slip movement (e.g. in the Purbeck 'Broken Beds').

On a regional scale, the structure lies on the steep, northern limb of the asymmetric Lulworth Banks anticline (Fig. 3). The regional dip displayed by the underlying Portland Limestone Formation and the overlying Wealden, Upper Greensand and Chalk beds is approximately 40°N. Comparison between the regional and local structures shows that the component folds of the Lulworth Crumple parallel the larger Lulworth Banks anticline (Figs 3 & 19).

Previous structural models. Various structural interpretations have been proposed to explain the genesis of the Lulworth Crumple. Strahan (1895) originally suggested that it had a compressional origin in which the structure was the result of 'squeezing upward of the beds from a region of greater compression below'. His implication that the structure was the result of south-to-north contraction was disputed in the 1930s firstly by Lees (1935) and subsequently by Arkell (1936, 1938), who proposed two radically different models. Lees (1935) suggested an extensional origin in which the feature was akin to a gravity collapse structure analogous with those described by Harrison & Falcón (1935) in Iran, which formed as the steep limb of the monoclinal fold developed. Arkell (1936, 1938) favoured a compressional, drag fold origin. In contrast to Strahan (1895), however, Arkell proposed that the sense of contractional motion was southward-directed with overthrusting of the Wealden Group, with respect to the Portland Limestone Formation, leading to internal folding of the incompetent Purbeck Formation between. Reinterpretation of the mesoscale structures in the area led Phillips (1964) to reaffirm Lees' (1935) extensional gravity sliding interpretation and this remains the most generally accepted model.

Interpretation in the light of seismic evidence. Combination of interpreted seismic lines taken from areas immediately to the north and south of Lulworth Cove (GC86-V-30 and HEX-87-013) with field observations made in the intervening area enable a representative cross-section to be drawn across the area (Fig. 20), which allows the Lulworth Crumple to be placed into its proper regional context. The constructed section demonstrates that the sediments that now form the Lulworth Crumple were originally deposited in a hanging-wall location with respect to the Purbeck Fault, a major reactivated extensional fault, which is interpreted to lie beneath the northern shore of the cove (Fig. 20).

Important in this respect is the reinterpretation of the steeply-dipping fault exposed on the hillside that defines the northern side of Lulworth Cove (Fig. 18a & c). The structure can be traced over a distance of 4 km from Durdle Cove in the west to Mupe Bay in the east (Phillips 1964, fig. 16). In contrast to Arkell (1938, 1947), who interpreted it as one of his 'group 4' normal faults, this structure is interpreted here to be one of a group of steep contractional structures formed through the upward propagation from, and bifurcation of, the buried and structurally inverted Purbeck Fault (Fig. 20). Field
relations demonstrate that the formation of the steep reverse faults postdated the development of the Purbeck Monocline (Fig. 18c). Importantly, however, field exposures along strike in St Oswalds Bay (e.g. east side of Man-o’-War Cove) and Durdle Cove (House 1989, fig. 32) suggest that development of the steep reverse faults was superseded by the formation of shallow (30–40°) southerly-dipping thrust faults and shear planes (Phillips 1964, fig. 12), interpreted here to represent incipient footwall short-cut structures.

Evidence that the folds developed within the Lulworth Crumple lie parallel to the major contractionally reactivated normal fault and its associated Lulworth Banks anticline (Fig. 20) is interpreted to imply a causal link between the Crumple and the Cenozoic structural inversion process. Taken together with the evidence for layer-parallel shortening and flexural slip, the simplest explanation is that the Lulworth Crumple represents a contractional feature that records south-north-directed shortening of the incompetent syn-rift fill adjacent to a major reactivated fault (Fig. 21). The footwall to the original extensional fault plane is interpreted to have provided a semi-rigid buttress against which the hanging-wall syn-rift sediments buckled. As such the Lulworth Crumple structure is similar to parasitic folds that often characterize zones of structural inversion (e.g. Cooper et al. 1989). Of the various previous hypotheses for the formation of the Lulworth Crumple, Strahan’s original interpretation still appears to be the most plausible.

Further support for the parasitic fold, contractional interpretation comes from the occurrence of similar northward-verging fold pairs present in temporary exposures of early Cretaceous sediments on the eastern side of Lulworth Cove. The implication of their occurrence is that these features might be characteristic of hanging-wall deformation along the Purbeck Fault and hence, that similar asymmetric folds might be expected along the length of the zones of disturbance.

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(c) Cenozoic
“Latter stages of Structural Inversion”

Tightening of monoclinal fold interlimb angles induces ‘out-of-the-syncline’ southward-directed backthrusting with respect to underlying reactivated normal faults. Box highlights the approximate southward-directed position of the cross section given in Fig. 15.

(b) Cenozoic
“Post - rift”
Early stages of Structural Inversion

Contracted reactivation of Purbeck Fault and other extensional structures produces double monocline.

Original syn-rift sediments remain in net extension.

Fold hinges tighten leading to initiation of contractional structures in their core.

(a) Late Cretaceous
“Post - rift”

Relatively uniform deposition of Gault, Upper Greensand & Chalk.

Underlying extensional structures that affect the Wealden Group, Purbeck and Portland Beds, Kimmeridge Clay Formation and older strata have little or no effect on post - Wealden deposition.

Fig. 17. Structural interpretation to explain the genesis of the Ballard Down Fault. The present-day cliff line is shown in (c). KCF, Kimmeridge Clay Formation; SL, sea level.
Discussion

If replicated in other inverted sedimentary basins, the field observations and seismic interpretations made in the Wessex Basin would take on a greater structural significance. The main implication of these data is to stress the importance of knowing the original extensional fault geometries, particularly the location and extent of normal fault segments.

Whilst the data are consistent with recent advances in understanding of fault displacement length variations, the vertical and lateral propagation of extensional faults and the resultant sedimentary geometries created, they demonstrate how little we still know about fault displacements and compartmentalization of strain during structural inversion. Whether coincidental or not, the Wessex data imply that, although the syn-rift remains in net extension throughout, the maximum contraction is concentrated where maximum extensional displacement previously existed. In other words relay ramps remain sites of limited structural movement during the inversion process as well as during the earlier extensional episode.

The data at both seismic-scale and outcrop-scale also demonstrate controls exerted by the nature of the hanging-wall syn-rift sedimentary fill in predetermining the nature of regional and local deformation during the inversion process. An incompetent fill, like that which characterizes the Lulworth Crumple leads to bedding-parallel (flexural) slip and the development of significant intra-formational folding. The presence of more competent lithologies results in the development of a more uniform asymmetric hanging-wall
anticline against the footwall buttress with little or no evidence for parasitic folding. High strain rates and space problems may, however, lead to the development of complex accommodation structures as the limbs of the growth folds are tightened and ramp-flat thrust geometries could result. The same is true for footwall locations where tightening of fold limbs affecting the post-rift succession may lead to localized reverse faulting in the inner bend of the developing monocline whilst extension may characterize beds contained within its stretched outer envelope.

Fig. 20. Structural N–S oriented cross-section depicting the main field observations and subsurface interpretations in the Lulworth area (Location of Line shown in Figs 3 & 11). The cross-sections forms the basis for the interpretations shown in Fig. 21. The approximate location of the Lulworth Crumple is shown. KCF, Kimmeridge Clay Formation; OC, Oxford Clay; JM, undifferentiated Middle Jurassic (Kellaways beds, Cornbrash, Forest Marble, Fullers Earth); BS, Bridport Sandstone; JB, Junction Bed; MMG, Mercia Mudstone Group; SSG, Sherwood Sandstone Group.

(c) Cenozoic “Structural Inversion”

Development of faulted monocline as a forced fold in response to contractional reactivation of Purbeck Fault to create zone of disturbance in which only the post-rift experiences contraction with formation of hangingwall reverse fault accommodating inversion. Lulworth Crumple forms in response to intraformational (flexural) slip in hangingwall.

(b) Late Cretaceous “Post - rift”

Fairly uniform deposition of Gault, Greensand and Chalk. Purbeck Fault has little or no influence on structure, sedimentary facies or stratigraphic thicknesses.

(a) Late Jurassic - Early Cretaceous “Syn - rift”

Differential Fault across Purbeck disturbance. Footwall uplift coeval with hangingwall subsidence. Some evidence for facies changes in hangingwall with development of Wealden conglomerates.

Fig. 21. Schematic cartoon depicting the proposed evolution of the Lulworth area during its syn-rift, post-rift and structural inversion history. P, Purbeck and Portland Beds; KCF, Kimmeridge Clay Formation; JM, undifferentiated Middle Jurassic (Kellaways beds, Cornbrash, Forest Marble, Fullers Earth); JB, Junction Bed; MMG, Mercia Mudstone Group; SSG, Sherwood Sandstone Group.
Conclusions

Well-calibrated seismic data provide important insights into the genesis of important tectonic inversion structures in the Wessex Basin both in plan view and cross-section. The superficial data demonstrate the important role that original extensional fault segmentation had in controlling not only the syn-sedimentary fill of the basin but also its inversion history. At least two original (and now partially inverted) relay ramps can be defined within the basin. The results allow a test of contrasting structural models for ancillary structures along the main axes of inversion. The Lulworth Crumple is interpreted to represent inversion-related, complex internal folding of an incompetent former syn-rift hangingwall fill resulting from the effects of buttressing against a more rigid footwall of a throughgoing, reactivated planar extensional fault. In contrast, the Ballard Down Fault is interpreted as having formed in the footwall to the main inversion axis as an ‘out-of-the-syncline’ fault affecting the post-rift sequence. The structure appears to have formed in response to space problems in the northern synformal fold hinge of the Purbeck Monocline during the latter stages of basin inversion. Collectively, the results not only provide the basis for understanding the deformation history of the Wessex Basin, but also have the potential to provide useful analogues for structures developed in other inverted sedimentary basins. In particular, knowledge of the original extensional fault geometries and the nature and competence of the component sedimentary units appears to be fundamental in gaining an understanding on structural deformation in inverted basins.

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