THE INFLUENCE OF REACTIVATED FAULT MOVEMENTS ON RIVER DEVELOPMENT AND COASTAL EVOLUTION: EXAMPLES FROM THE DEVON-DORSET COAST, UK

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When viewed from the sea the coastline between Exmouth, Devon and Charmouth, Dorset comprises an almost unbroken line of cliffs of Triassic, Jurassic and Cretaceous sediments cut by the valleys of several small rivers and streams. Low (1º-5º) easterly dips in the Triassic and Jurassic rocks enable a complete succession from the earliest Trias to the early Jurassic to be examined at beach level. This gives the impression that the region has been tectonically quiescent since the earliest Triassic and that there is little faulting in the region. Seismic-reflection surveys carried out for hydrocarbon exploration in the 1980s and subsequent geological re-mapping of the area showed that this was not the case. All the river valleys and minor streams are sited above fractured rocks associated with approximately N-S trending faults. The recent (2008) acquisition by the Channel Coast Observatory of high-resolution multibeam sonar images of the near-shore subtidal area of parts of the east Devon and west Dorset coast has imaged some of the N-S faults and, in addition, several E-W trending fault zones that had not previously been recognised. Taken together the onshore and offshore data reveal a complex history of reactivated fault movements that continued from the Permian until the Miocene or later.

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INTRODUCTION

The recent geological revision survey of east Devon and the adjacent part of west Dorset included an analysis of borehole and seismic-reflection data (Edwards and Gallois, 2004). The mapping proved a large number of predominantly N-S trending faults with vertical displacements of up to 60 m at surface in Triassic to Tertiary deposits. The seismic sections showed that the more prominent of these have displacements of up to 300 m in the concealed Triassic rocks (Edwards and Gallois, 2004, figure 6). When projected southwards to their intersections with the coast, the principal faults can be seen to underlie the main river valleys (Figure 1). In most cases there is little surface evidence of faulting within or immediately adjacent to the valleys for two principal reasons. First, the onshore outcrops of the faults are overlain by drift deposits, mostly Alluvium and Terrace Deposits in the river valleys, and by Head Deposits on the adjacent slopes. Second, the vertical displacements of many of the individual faults at outcrop are relatively small (mostly <30 m) with the result that the same formation crops out on both sides of the fault.

In the offshore area much of the sea bed between the outfalls of the River Exe and River Char is sediment covered with few rock outcrops. The sea bed above the relatively uniform mudstones of the Aylesbeare Group, most of the Mercia Mudstone Group and the Charmouth Mudstone Formation (Figure 2) are sand covered. Similarly, the Budleigh Salterton Pebble Beds Formation, which breaks down to loose pebbles, and the Otter Sandstone Formation which is relatively uniform with respect to weathering, have few sea-bed outcrops. In contrast, thin beds of limestone in the Blue Anchor and the Blue Lias Formations, and in the relatively thick (9 m) White Lias limestone crop out on the sea bed as prominent reefs in which faults with displacements of as little as 1 m can be detected.

N-S TRENDING FAULTS

Otter Valley

At Steamer Steps [SY 0632 8176] on the west side of the valley, where the junction of the Budleigh Salterton Pebble Beds and the Otter Sandstone dips east at *c.* 5º, the Otter Sandstone comprises aeolian sandstones overlain by fluvial, cross-bedded, fine-grained sandstones with small (up to 50 mm) angular mudstone clasts. Six hundred metres ENE from there [SY 0703 8200], sections in a degraded sea cliff (the promenade section of Hounslow and McIntosh, 2003) expose a stratigraphically higher level in the Otter Sandstone with prominent calcrete beds and associated rhizocretions. On the east side of the River Otter, the sea cliff [SY 0774 8192] adjacent to the outfall exposes lithologically similar cross-bedded sandstones with numerous calcrete sheets and rhizocretions, and concentrations of gravel in channel lags. The lowest calcrete bed is underlain by calcified rhizocretions up to 2 m long. The lithologies and sedimentary structures indicate that there is no overlap between the highest beds at Steamer Steps and the promenade section, and between the promenade section and the sea cliff.

There is no direct evidence of faulting at the mouth of the Otter Valley other than the sudden termination of the sandstone reefs along an NNE-SSW line on the west side of Otterton Ledge [SY 0766 5063], but there is indirect evidence. The thickness of the Otter Sandstone, based on the cliff exposures at Budleigh

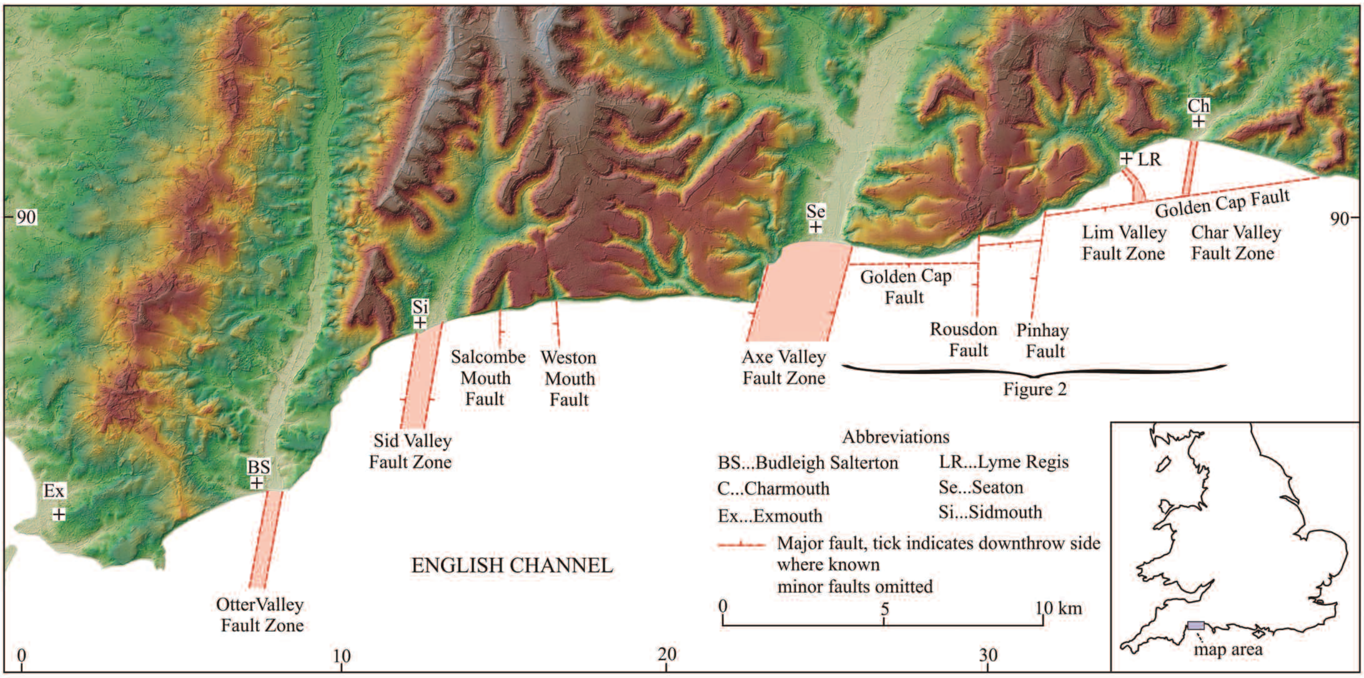

Figure 1. *Digital Terrain Model (DTM) of the coastal zone between Exmouth and Charmouth showing the relationship of the shape of the coastline and the positions of the valleys to the principal faults. DTM prepared by Michael Hall, British Geological Survey, using NEXTMap Britain elevation data from Intermap Technologies. Copyright BGS.*

Group	Formation Fm.	Thickness m	Lithology
Lias	Charmouth Mudstone	150	mudstone with a few thin (0.3 m thick) limestone beds
	Blue Lias	30	mudstone and limestone
Penarth	White Lias	9	limestone
	Cotham Mudstone and Westbury Mudstone	8	mudstone
Mercia Mudstone	Blue Anchor Fm.	30	mudstone with a few thin (0.3 m thick) limestone beds
	Branscombe Mudstone	220	mudstone
	Dunscombe Mudstone	40	mudstone
	Sidmouth Mudstone	200	mudstone
Sherwood Sandstone	Otter Sandstone	170	sandstone
	Budleigh Salterton Pebble Beds	35	gravel
Aylesbeare	Littleham Mudstone	250	mudstone
	Exmouth Mudstone and Sandstone	200	mudstone with lenticular sandstones

Figure 2. *Simplified lithostratigraphy of the Triassic and Jurassic rocks that crop out on the east Devon-west Dorset coast.*

Salterton and the unbroken line of cliff exposures between the River Otter and Sidmouth, has been estimated to be 120 m (Benton, 1997). Near Otterton, the nearest inland borehole [SY 0916 8480] to the cliff sections, the full thickness of the formation was up to 210 m (Edwards and Gallois, 2004). In the Honiton area an NNE-SSW trending fault imaged on seismic profiles has displacements of up to 200 m at the base of the Budleigh Salterton Pebble Beds. No evidence has been recorded of displacements in the overlying Cretaceous rocks at the surface, but between Gittisham [SY 132 977] and near Colaton Raleigh [SY 107 909] the fault appears to underlie the unusually linear outcrop that marks the western limit of the preserved Upper Greensand in east Devon. If the fault continues SSW with the same trend it would intersect the coast close to the outfall of the River Otter.

Sid Valley

The western boundary fault intersects the coast at Jacob's Ladder [SY 1195 8694] where it comprises a narrow fault zone with a combined westerly downthrow of *c.* 60 m that brings the Otter Sandstone into contact with the Sidmouth Mudstone. Inland, a fault proved by seismic-reflection surveys to run NNE from Sidford towards Honiton that downthrows the base of the Budleigh Salterton Pebble Beds *c.* 50 m to the west may be the continuation of that at Jacob's Ladder. On the upthrow side of the Jacob's Ladder Fault, a calcrete surface with numerous rhizocretions forms a prominent marker bed in Connaught Gardens Cliff. This more resistant bed formed the base of a sea stack on the adjacent Chit Rocks ledges until it was destroyed by a storm in 1824 (Hutchinson, 1857). The same bed crops out at the base of Big Picket Rock [SY 1045 8573] 2 km south west on the downthrow side of the fault. The outcrop of the fault zone was visible in the cliff prior to 20th century landscaping, and one of the faults can still be traced across the foreshore at times when the beach is swept free of sand. Hutchinson's 1851 painting of the fault (reproduced in Butler, 2000 and as figure 6 in Mather and Symes, 2006) shows a fracture zone *c.* 10 m wide with five or more faults that appear to have opposing displacements as a result of multiple movements. There is no evidence for the position of the eastern boundary fault at the coast. It is presumed to lie close to the canalised River Sid at the foot of the valley side. Supplementary faults within the valley give rise to repeated outcrops of the Otter Sandstone that crop out as higher ground.

Axe Valley

The fault zone includes the major Seaton and Membury Faults (Figure 3), and associated sub-parallel minor faults in the Mercia Mudstone beneath the valley and in the Triassic and Cretaceous rocks in the valley sides. Geological and seismic-reflection surveys have shown displacements of up to 300 m at the base of the Triassic rocks across the Seaton and associated faults; up to 100 m at the base-Cretaceous unconformity (Edwards *et al.*, 2005); and up to 60 m at the base of the Tertiary Clay-with-Flints (Gallois, 2009). On the west side of the valley that part of the Seaton Fault which brings the Cretaceous Upper Greensand into contact with the Mercia Mudstone is exposed

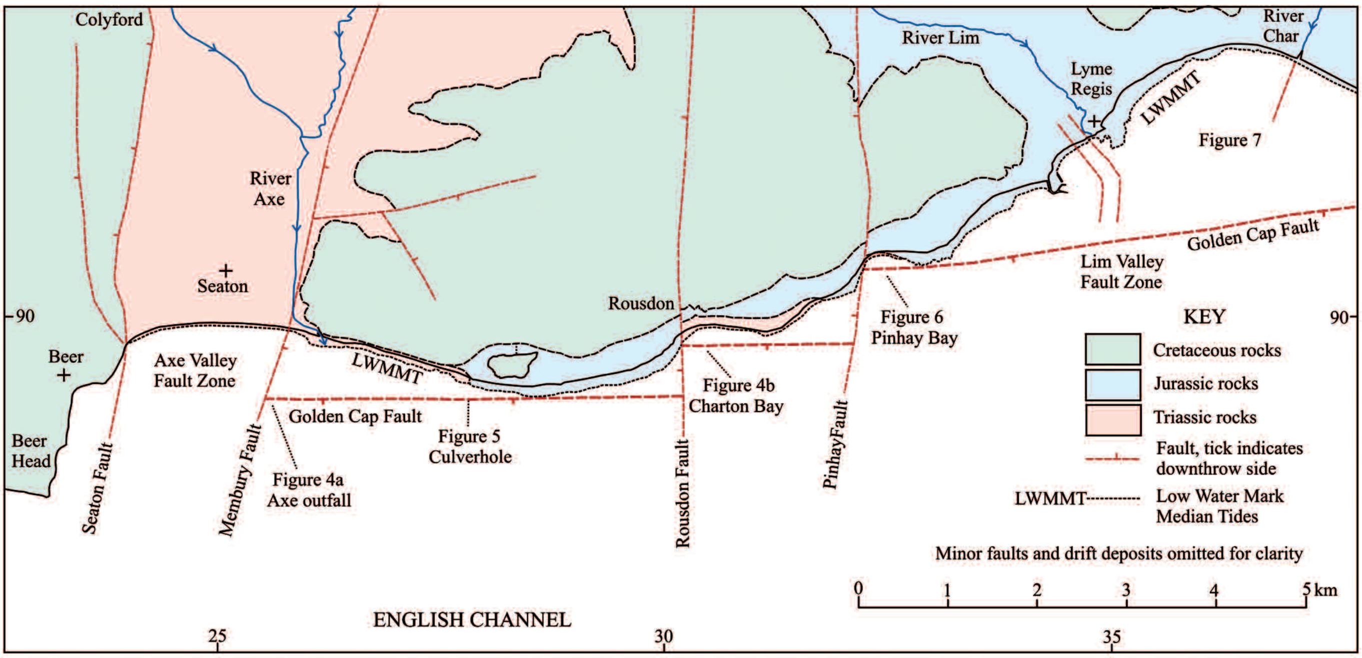

Figure 3. *Geological sketch map of the area between the Axe and Char Valleys to illustrate the effects of faulting on the drainage system and the shape of the coastline.*

from time to time in the intertidal area at Seaton Hole [SY 235 896]. The juxtaposition of strong Upper Greensand calcarenites and fractured Triassic mudstones gives rise to a 90° change in the orientation of the cliff line (Figure 3). For *c.* 400 m eastwards from Seaton Hole up to five sub-parallel, roughly N-S trending faults crop out in the Branscombe Mudstone exposed in the cliffs. All the individual displacements probably exceed 15 m and may be much greater, but they are difficult to estimate because the beds affected are all within lithologically similar mudstones. None of the minor marker beds within the fault-bounded sections is repeated in the other blocks. As with the Jacob's Ladder Fault at Sidmouth, the presence of multiple fracture planes is evidence of reactivation of the principal fault. On the opposite side of the valley, the outcrop of the Membury Fault is hidden beneath drift deposits. Inland, the predominantly N-S trending outcrop of the fault is locally displaced by E-W faults (Edwards *et al*., 2005). Minor fractures at the western end of Haven Cliff that cause the outcrop of the Upper Greensand to dip west towards the valley are probably sub-parallel to the main fault. Offshore from the outfall of the River Axe, the sudden termination of reefs in the Branscombe Mudstone seen in multibeam sonar images made for the Channel Coast Observatory (CCO) in 2008 probably marks the offshore continuation of the Membury Fault (Figure 4a).

Lim and Char Valleys

A zone of a NNW-SSE trending faults up to 100-m wide underlies the Lim Valley at Lyme Regis where it gives rise to dips of up to 30° in the Blue Lias in the intertidal area. When traced offshore in seismic-refection profiles (Gallois and Davis, 2001) and in the multibeam sonar images the fault zone intersects N-S trending faults (Figure 3). Similar small faults and disturbed bedding associated with the Char Valley Fault Zone are exposed in the Charmouth Mudstone at the mouth of the River Char at low tide at times when there is little beach sediment (Lang, 1914). In the intervening area between the two river outfalls, faulting and folding are visible in the multibeam images (Figure 7), but the data do not extend as far offshore as the Golden Cap Fault (Figure 3).

E-W TRENDING FAULTS

The limited amount of seismic reflection data available for the nearshore area adjacent to the east Devon-west Dorset coast indicate that the predominant structures are E-W trending normal faults that were initiated during an early post-Variscan phase of lithospheric extension (Chadwick, 1986). The best documented of these faults, the Bride Fault *c.* 6 km south of the coastline appears to terminate the N-S trending faults described above (Edwards *et al*., 2005). The sub-parallel Golden Cap Fault (Figure 1), *c.* 2 km south of Charmouth, has been seismically imaged between Golden Cap and Lyme Regis. The 2008 CCO multibeam-sonar survey of the nearshore zone has shown that the fault can be traced westwards from there to its intersection with the Membury Fault on the east side of the Axe Valley. Westwards from there the fault lies offshore from the sonar imaging, where it is either hidden beneath sea-bed sediments or terminates against the Membury Fault.

Throughout its observed length the Golden Cap Fault downthrows Charmouth Mudstone to the south. The formation contains few resistant beds that give rise to sea-bed features in contrast to the limestones in the Blue Anchor, White Lias and Blue Lias Formations on the north side of the fault which form reefs. These pick out compressional folds cut by E-W trending faults (Figures 4b, 5, 6 and 7).

TECTONIC HISTORY

The post-Variscan evolution of southern Britain was predominantly influenced by four tectonic phases, the early, middle and late stages of the Cimmerian phase and the Alpine phase (Chadwick and Evans, 2005). Although Stille (1924) originally introduced the name Cimmerian Orogeny to describe a succession of earth movements related to the build up and destruction of the Cimmerian Plate in the Middle and Far East (Turkey to Tibet), the name has become widely used in Europe in a modified form to describe tectonic phases that resulted in widespread rifting and uplift. These ranged from the Permian to the end Cretaceous when they overlapped with the early part of the Alpine phase (e.g. Ziegler, 1978). In the more stable platform areas such as that in South-West England, regional uplift and tilting accompanied by the reactivation of

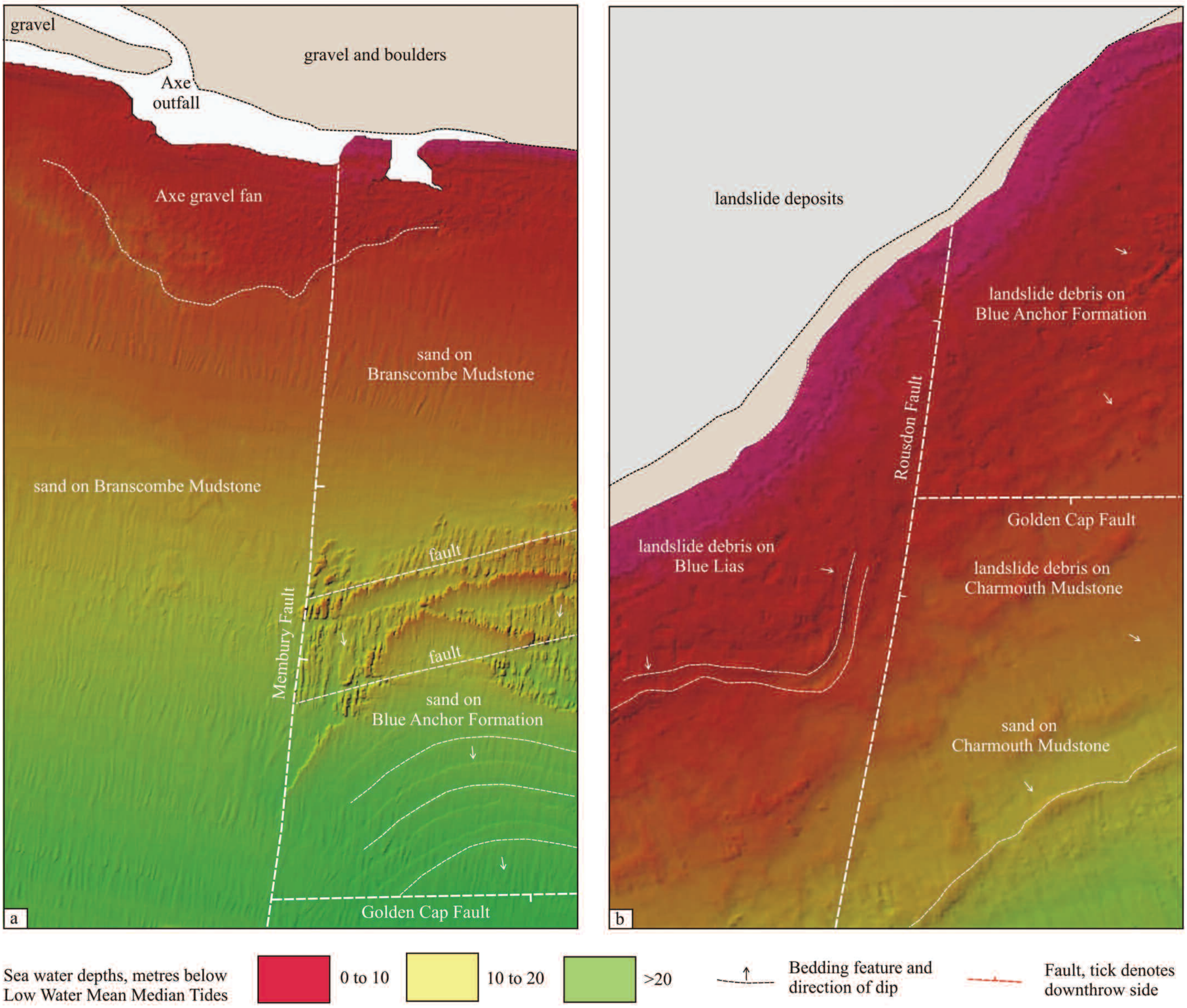

Figure 4. *Multibeam sonar images courtesy the Channel Coast Observatory (CCO) (www.channelcoast.org.). (**a**) Offshore area adjacent to the outfall of the River Axe to illustrate the termination of the Golden Cap Fault against the Membury Fault. (**b**) Charton Bay to illustrate the sinistral displacement of the Golden Cap Fault by the Rousdon Fault.*

pre-existing faults during the Cimmerian phases produced local and regional unconformities, and lateral variations in the stratigraphy adjacent to penecontemporaneously active faults.

In South-West England, the early Cimmerian phase is represented by periods of lithospheric extension in the Permian and early Triassic that resulted in the opening of the Bristol and English Channels, and the deposition of thick terrestrial red-bed successions in extensional basins sited over major E-W trending thrusts in the Variscan basement rocks (Chadwick, 1986). Inland in Devon, the Crediton and Tiverton Permo-Triassic grabens formed over similar structures. In the English Channel, the Bride and Golden Cap faults were formed at this time, and the N-S trending faults beneath the Axe were reactivated as evidenced by their effect on thickness variations in the Permo-Triassic sediments.

Renewed movements on E-W trending faults in the latter part of the early Cimmerian resulted in the deposition of thick halite deposits in the Bristol Channel and English Channel, and in inland grabens in Wessex (Gallois, 2003) in the mid Triassic (Carnian); seismically induced slumping in the late Triassic Blue Anchor, Cotham Mudstone and White Lias Formations (Gallois, 2007), and fault-related lateral variations in the early Jurassic Shales-with-Beef (Gallois, 2008).

In the mid Cimmerian, uplift and tilting of western Britain produced a regional easterly dip in the Permian to early Cretaceous rocks that was followed by the transgression of the mid Cretaceous sea. In east Devon this resulted in the westerly overstep of the base Cretaceous unconformity which brought the Upper Greensand to rest on Jurassic rocks at Lyme Regis, on Triassic rocks at Sidmouth and on Permian rocks in the Haldon Hills. Reactivation of the N-S trending faults in the Axe Valley Fault Zone in the later part of the mid Cimmerian phase controlled the fault-bounded distribution of the Cenomanian Beer Stone and Wilmington Sand, and lateral variations in the chalk succession on either side of the valley (Mortimore *et al.*, 2001). Further uplift in the late Cimmerian raised the whole of southern England and began a period of widespread erosion in which up to 1000 m of Chalk was removed prior to the deposition of Palaeocene freshwater and shallow-marine deposits.

The Alpine phase, which in NW Europe culminated in the Miocene, was the most recent major phase of tectonic activity in southern Britain. Its principal effect was to reactivate many of the E-W trending fold and fault complexes in the Jurassic to Tertiary rocks that were aligned over Variscan thrusts, the most prominent example being the Isle of Wight-Purbeck Monocline

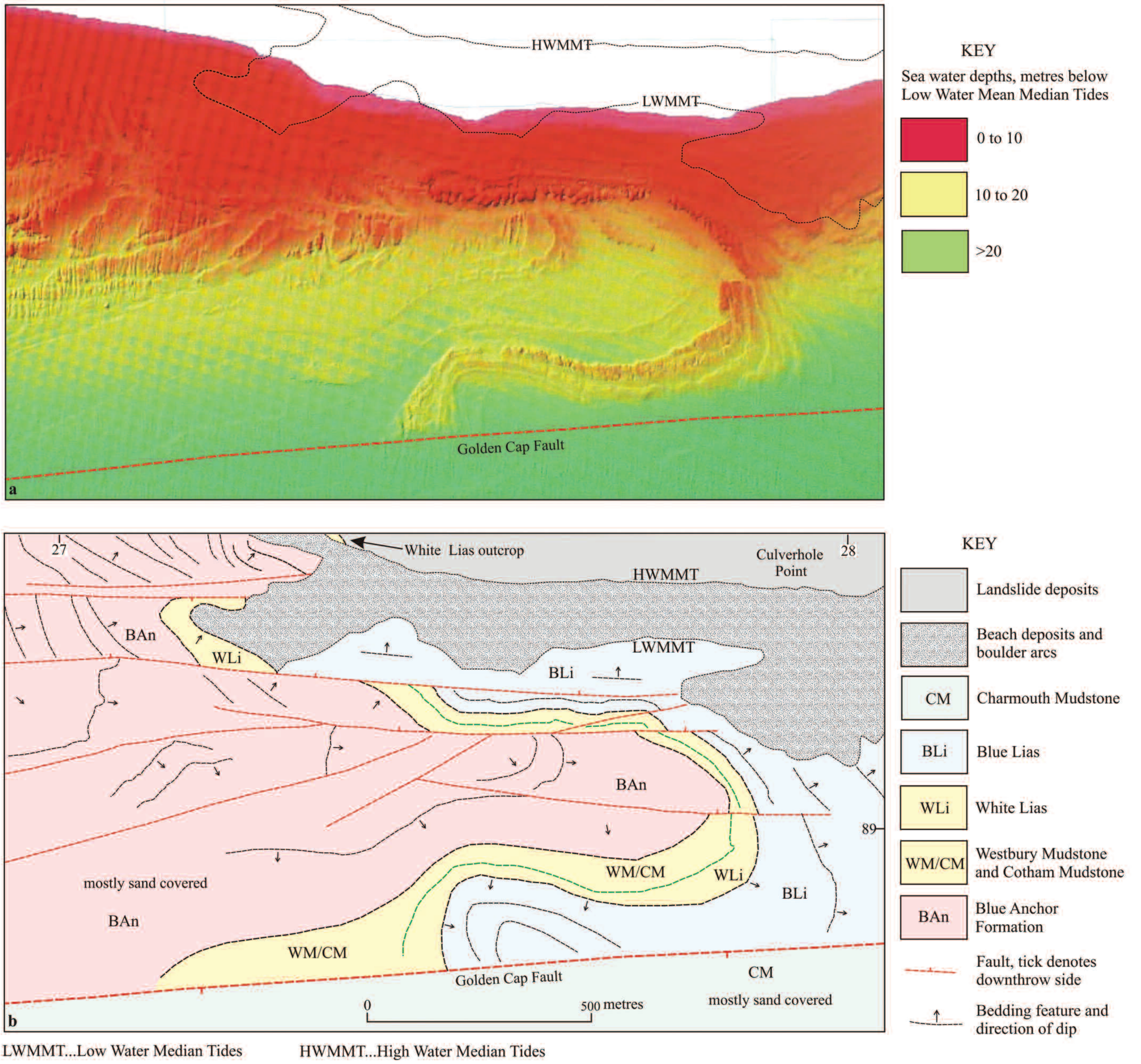

Figure 5. *Geological sketch map of the intertidal and shallow subtidal areas adjacent to Culverhole, east Devon. (**a**) Multibeam sonar image courtesy the Channel Coast Observatory). (**b**) Geological interpretation based on the sonar images, air photographs and beach outcrops.*

in Dorset and Hampshire. In east Devon, a southerly tilt and deformation of the planar unconformity surface at the base of the Palaeocene Clay-with-Flints was accompanied by reactivation of the Axe Valley, Rousdon and Pinhay Faults (Gallois, 2009, figure 5). In the offshore area, the latter two faults sinistrally displace the Golden Cap Fault (Figures 4b and 6) and give rise to marked changes in the alignment of the coastline. Between the outfalls of the Rivers Axe and Char, where the geological structures at outcrop on the sea bed are imaged in the sonar surveys, the Golden Cap Fault forms the southern boundary of a complexly folded and faulted zone that is mostly up to 1 km wide (Figures 5, 6 and 7). Similar structures have not been recorded inland in east Devon. Their relationship to the Golden Cap Fault and the N-S trending faults suggests that they were formed during the Alpine phase in response to transpressional deformation that was accommodated by the reactivation of the faults.

Summary and conclusions

In the SW region the major elements of the present-day scenery, including the drainage pattern and the shape of the coastline, were initiated during the Miocene when the present-day land area was uplifted and tilted. In east Devon and west Dorset, narrow zones of predominantly N-S trending faults have been shown by onshore geological mapping and seismic-reflection surveys to underlie the valleys of all the rivers and streams. Recently acquired sonar images of the sea bed in the nearshore area have shown that these fault zones intersect E-W trending fault and fold belts that are concealed beneath beach and/or landslide deposits in the intertidal area. When combined with evidence of penecontemporaneous faulting provided by lateral variations in the sedimentology of the Triassic to Cretaceous rocks exposed in the cliff sections, the offshore and onshore data reveal a complex history of fault movements that continued from the Permian (early Cimmerian phase) to late Miocene (Alpine phase) or later. The present-day positions of the river valleys and the shape of the coastline are directly related to the fault zones and their reactivation histories.

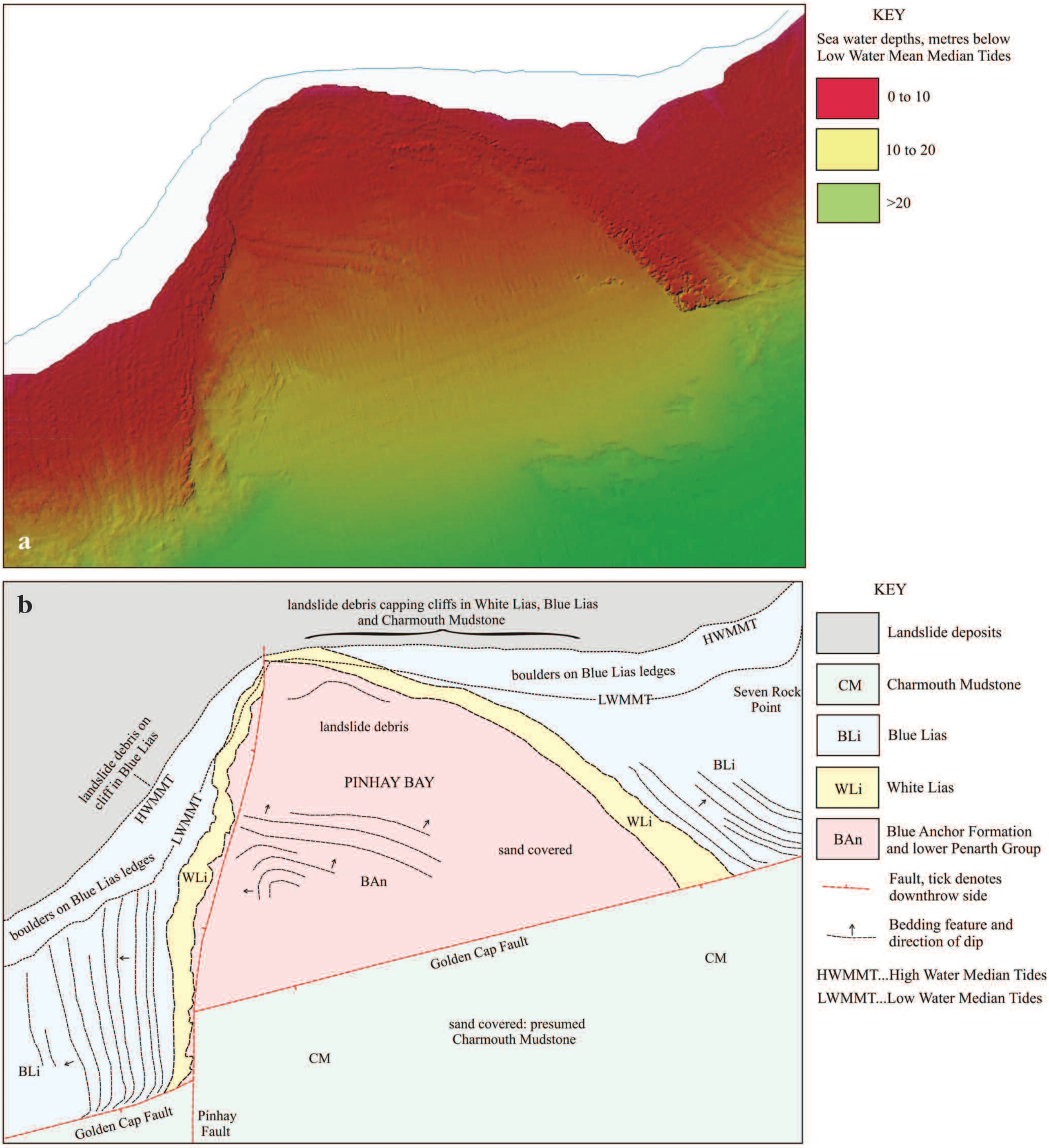

Figure 6. *Geological sketch map of the intertidal and shallow subtidal areas adjacent to Pinhay Bay. (**a**) Multibeam sonar image courtesy the Channel Coast Observatory. (**b**) Geological interpretation based on the sonar images and beach outcrops.*

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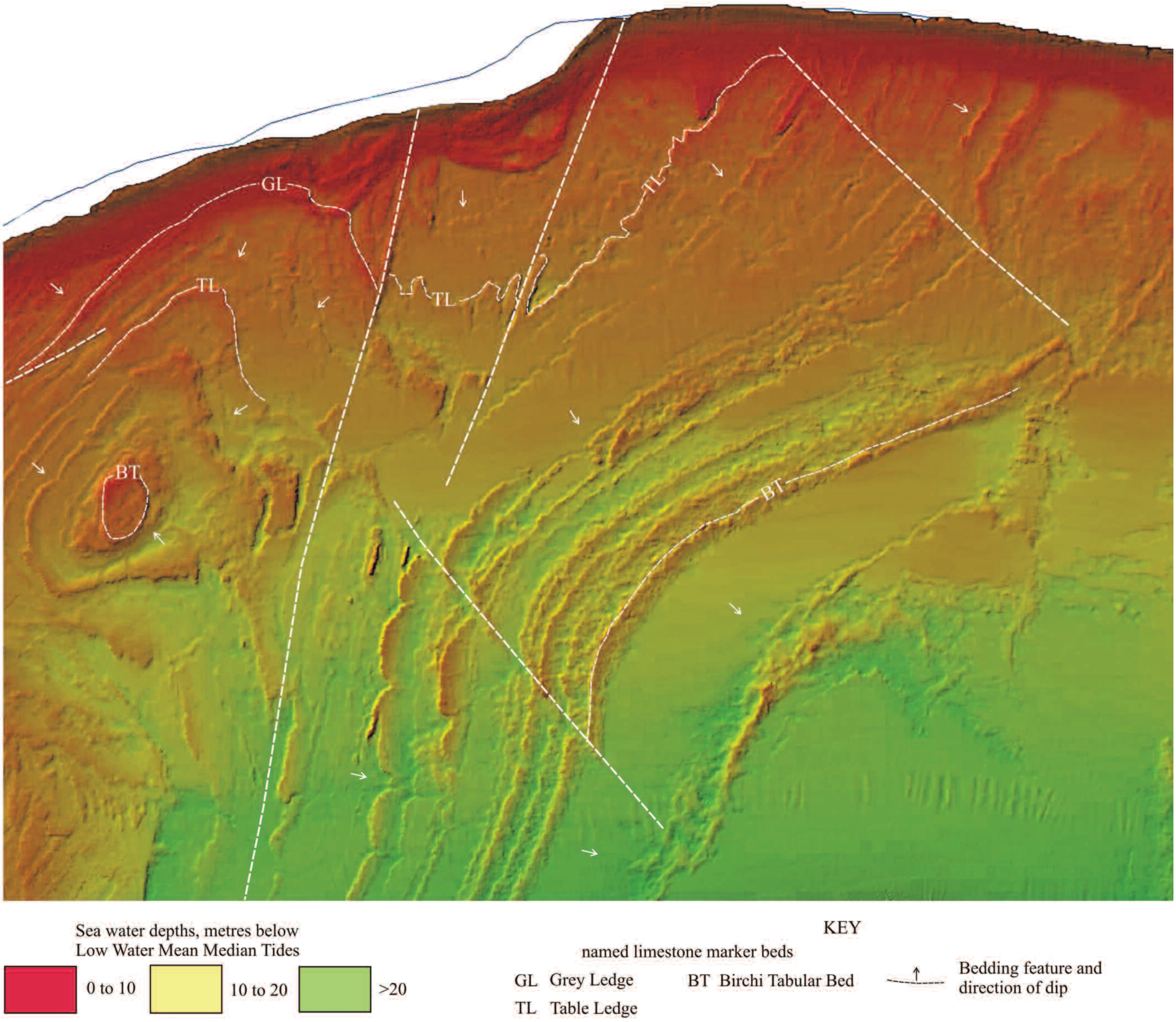

Figure 7. *Multibeam sonar image of the nearshore area between Lyme Regis and Charmouth to illustrate folding and faulting in the area adjacent to the north side of the Golden Cap Fault. Grey Ledge marks the boundary of the Blue Lias and Charmouth Mudstone Formations. Table Ledge and the Birchi Tabular are thin limestones in the Charmouth Mudstone. Image courtesy the Channel Coast Observatory.*

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