LARGE-SCALE PERIGLACIAL CREEP FOLDS IN JURASSIC MUDSTONES ON THE DORSET COAST, UK

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The unglaciated part of southern England was subject to periglacial climates that lasted for more than 20 ka on at least eight occasions during the last 750 ka. There are large outcrops of Jurassic mudstones in south-west England, principally the Lias Group and the Oxford Clay and Kimmeridge Clay formations, and extensive exposures of these beds in the cliffs on the Dorset coast. Notwithstanding the susceptibility of this type of mudstone to permafrost damage and deformation, there is no published record of large-scale folding in the region that has been attributed to periglacial disturbance. Three examples of folding are described here, in the Lias Group at Charmouth and Seatown in west Dorset, and in the Kimmeridge Clay on the Isle of Portland that are attributed to intermittent downhill creep of surface layers up to 20 m thick when in a partially frozen condition. The style of folding in the mudstones and the geometry of the disturbed deposits indicates that they are not tectonic in origin, nor were they formed by valley bulging or landsliding. These are the first large-scale structures of their kind to be recorded in southern England: similar folds elsewhere have been interpreted as valley bulges or tectonic in origin. At the Seatown and the Isle of Portland localities, the deformed mudstones have been preserved beneath younger landslides. The absence of similar structures elsewhere on the Dorset coast is attributed to the rapid removal of similarly weakened materials by marine erosion at times of high sea level during the last *c*. 6000 years.

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INTRODUCTION

There is no evidence to suggest that the SW region was ever covered by a continental ice sheet, but intense erosion in periglacial climates during the cold phases of the Pleistocene gave rise to many of its erosional and depositonal features (Te Punga, 1957). Freeze-thaw action in the form of frost-shattering and cryoturbation produced large amounts of weathered material that was widely redistributed by solifluction processes, meltwater torrents and strong arctic winds. These processes were repeated in each of the cold phases, and on numerous occasions within the cold phases, but the denudational features that can now be observed were probably largely formed during the most recent cold phase (Marine Oxygen Isotope Stage 2 (MIS 2)). The deposits themselves may be the result of one or many erosional cycles, each of which has added new material to that which had already accumulated. The effects of frost shattering are well displayed in many of the hard-rock areas of SW England, for example the rock faces and screes in the Valley of the Rocks in north Devon and the granite tors and the streams of rock debris that descend from them (Palmer and Neilson, 1962). Cryoturbation features such as frost-patterned ground and ice-wedge casts have been recorded on Dartmoor (Palmer and Neilson, 1962) and at coastal localities including Croyde Bay and in east Devon (Keene, 1990).

Deposits that have been attributed to the mass-movement or *in-situ* disturbance of mudstones in periglacial environments under the action of freeze-thaw processes are common in the UK. They are especially numerous in the Midlands and southern England where strata weakened during earlier cold-climate phases were not removed by glacial erosion during the Devensian cold phases (MIS 2-4). Large-scale examples of *in-situ* deformation include valley bulging, first recognised by Hollingworth *et al*. (1944) in Lias Group mudstones in the Midlands, and the thermokarst 'hills and holes' topography of Fenland where springs that emerged from adjacent high ground enabled pingos to form (Sparks *et al*., 1972). Some of the large-scale folds in the glaciated parts of the UK, such as those described by Sainty (1949) in the Chalk of the NE Norfolk coast, were formed by subglacial tectonics beneath a thick ice sheet. The absence of glacial deposits in southern England excludes this mechanism as a possible cause of Pleistocene folding in southern England. Small-scale (mostly <3 m deep) *in-situ* periglacial features in mudstones in southern England include diapiric involutions in mudstones overlain by permeable deposits in valley floodplains (e.g. Gallois and Worssam, 1993, plate 14). Large-scale mass-movement deposits include the landslide complexes of the east Devon and Dorset coasts, many of which were initiated in the late Pleistocene (Brunsden and Jones, 1976).

Four examples of folding in mudstones exposed on the Dorset coast (Figure 1) that can be attributed to the action of repeated freezing and thawing in a periglacial climate are described below. One of these has been interpreted as due to landsliding, and one as a possible valley bulge. The other two examples are not explicable in terms of tectonics, valley bulging, subglacial disturbance or landsliding. The term periglacial creep folds is proposed for these previously undescribed structures and for similar large-scale folds in mudstones elsewhere in southern England.

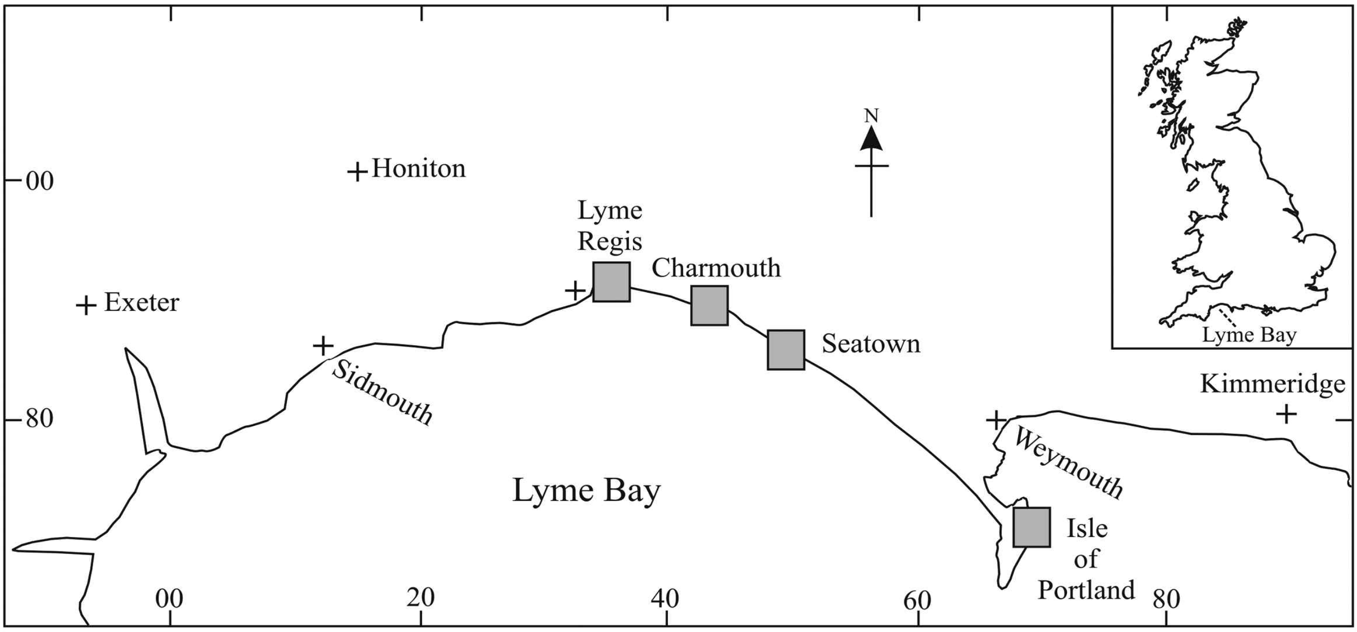

Figure 1. *Sketch map of part of the Devon-Dorset coast showing the positions of localities referred to in the text.*

Examples of periglacial deformation in mudstones on the Dorset coast

Lyme Regis

One of the few published examples of folding in mudstones that has been attributed to compression adjacent to the toe of a landslide is that of Hutchinson and Hight (1987). They described two small (1 x 2 m and 3 x 3 m) exposures in strongly folded Shales-with-Beef Member (Charmouth Mudstone Formation) in the side scarps of a small active landslide [SY 3447 9244] at the western end of the Spittles Landslide at Lyme Regis. The exposures have not been visible since 2001 when the landslide was stabilised by remedial works. They interpreted the fold structures, which included overturned chevron folds, as the result of compression at a time when permafrost in the mudstones was freshly thawed. They estimated that the permafrost active layer was at least 7 m thick.

Charmouth

Lang (1914) described a series of tight folds in the cliffs and intertidal area at, and adjacent to, the outfall of the River Char at Charmouth that he referred to as the Char Valley Disturbance (Figure 2a). He interpreted these as a tectonic feature associated with a fault which runs beneath the west side of the valley. The folds are now poorly exposed. Those in the intertidal area are almost permanently covered by gravel and boulders as a result of man-made changes to the river outfall and later floods. The tops of some of the folds in the Birchi Tabular limestone bed are visible from time to time at low tide. The folds in the lowest part of the Black Ven Marl that were visible in the river cliff adjacent to the old outfall of the River Char (Figure 2a) became degraded and vegetated following the construction of the New Cut in 1904 and the diversion to the new outfall. Minor flexures, one of which may be that recorded by Lang and Dighton Thomas (1936, plate 34B), are visible in

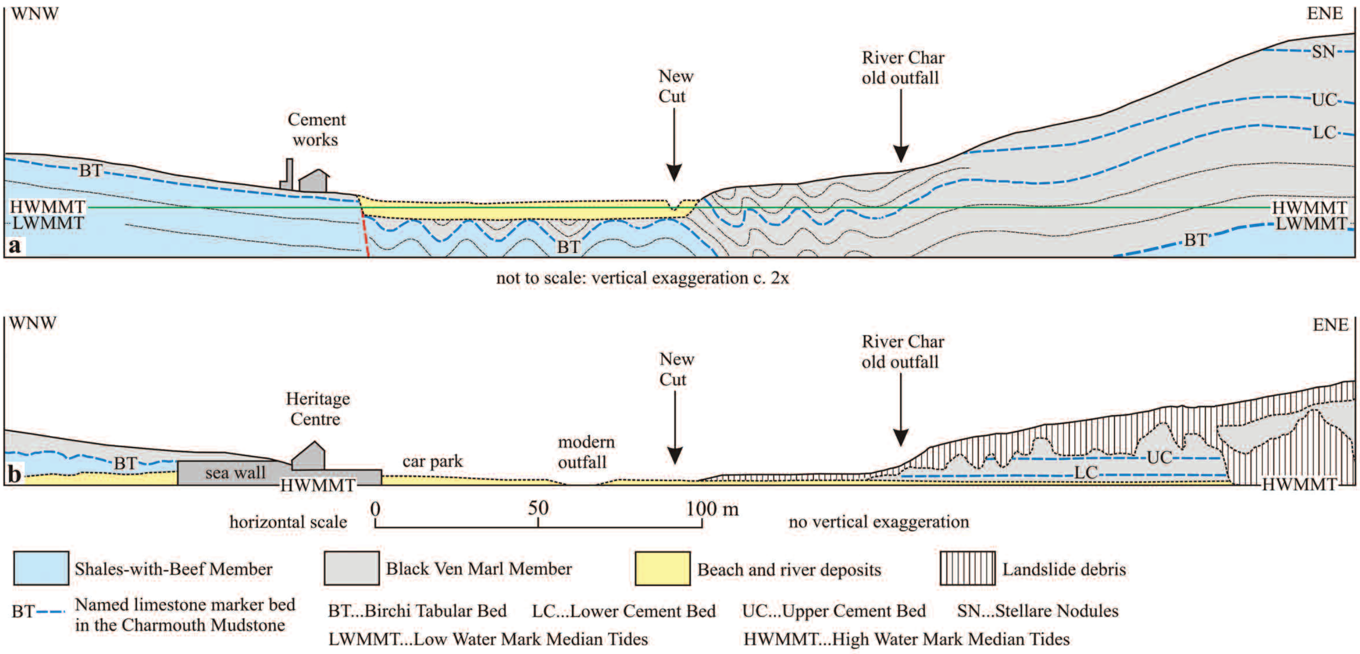

Figure 2. *Geological sketch sections to illustrate folding and faulting in the Charmouth Mudstone adjacent to the outfall of the River Char at Charmouth.* ***(a)*** *The "Char Valley Disturbance": redrawn from Lang 1914, fig. 23A.* ***(b)*** *Section based on photographs taken normal to the cliff line at low spring tide in September 2010.*

the Birchi Tabular limestone and the adjacent mudstones in the cliff immediately west of the sea wall (Figure 2b).

Hollingworth *et al.* (1944) thought that the folds described by Lang (1914) were suggestive of valley bulging (see below). They differ however, in two major respects from valley bulges. First, the folds in the limestone bed are indicative of tectonic deformation under a high confining pressure and are unlike the fractured diapiric structures that form under low confining pressures in valley bulges. Similar, but less complex tectonic deformation to that beneath the Char outfall, is exposed in the Blue Lias in the Lim Valley fault zone at Lyme Regis (Gallois and Davis, 2001, figure 5). Second, the folds in the valley floor have not been traced inland along the Char Valley or any of its tributaries. Valley bulging was not recorded in the site-investigation boreholes and excavations made in 1991 for the construction of the Charmouth Bypass, and valley bulging has not been recorded in the Blue Lias and Charmouth Mudstone Formation in the steep-sided valleys in the nearby Uplyme area.

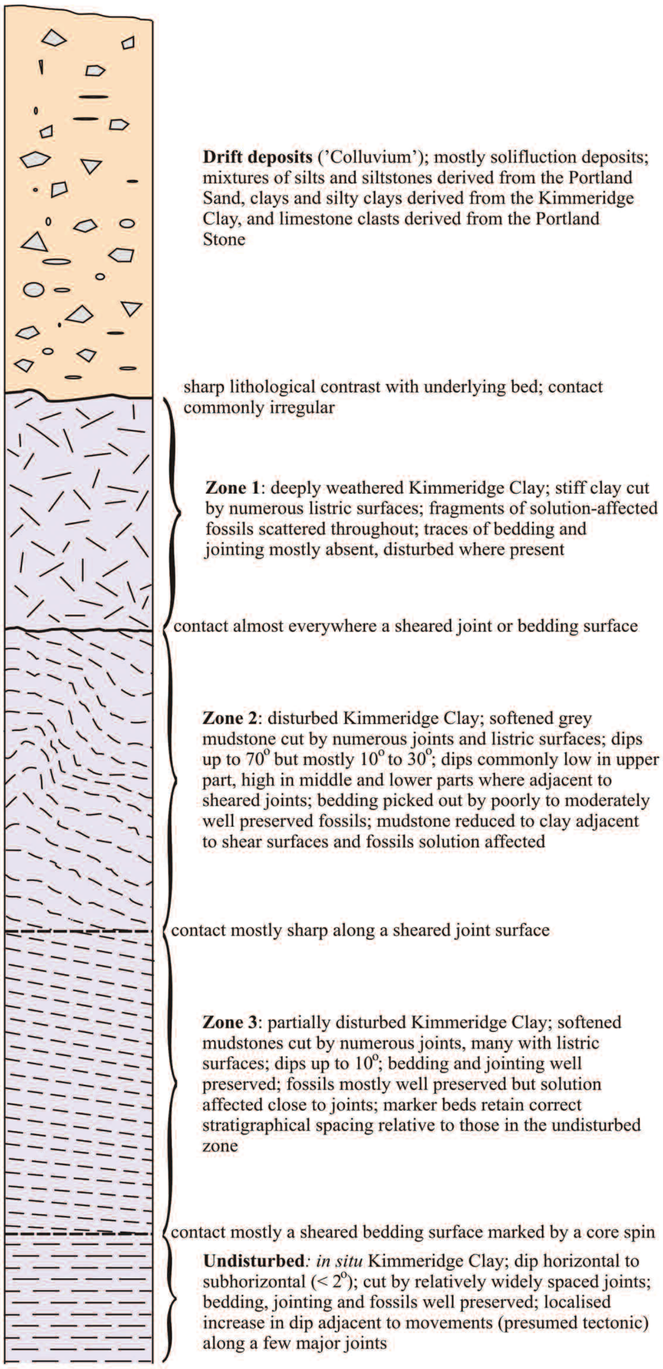

***Figure 3.** Generalised weathering and deformation profile for the near-surface layers of the Kimmeridge Clay at the Upper Osprey site on the Isle of Portland.*

Isle of Portland

The near-surface geology of a proposed underground gas storage site on the Isle of Portland [SY 700 733] was shown by site-investigation boreholes to comprise four distinctive layers. From the surface downwards, man-made deposits (mostly quarry waste), landslide and solifluction deposits derived from the Portland and Kimmeridge Clay formations, a complex zone of disturbed Kimmeridge Clay, and undisturbed Kimmeridge Clay with well preserved fossils and sedimentary structures. The disturbed beds form a discontinuous sheet, mostly <10 m thick, that can divided into three zones in which the degree of disturbance decreases with depth (Figure 3). An upper zone of deeply weathered clay with little evidence of bedding and jointing rests on a middle zone comprised of softened grey mudstone with dips of 10° to 70° picked out by listric bedding surfaces and distorted sedimentary structures (Figures 4b and 4c). This, in turn rests on mudstones with well preserved fossils, bedding and jointing in which the spacings between stratigraphical marker is mostly similar to that in the underlying undisturbed mudstones. Dip directions could not be measured from the borehole cores so the 3D structure of the disturbed beds could not be determined. However, the preservation of sedimentary features and jointing suggests that the lower and

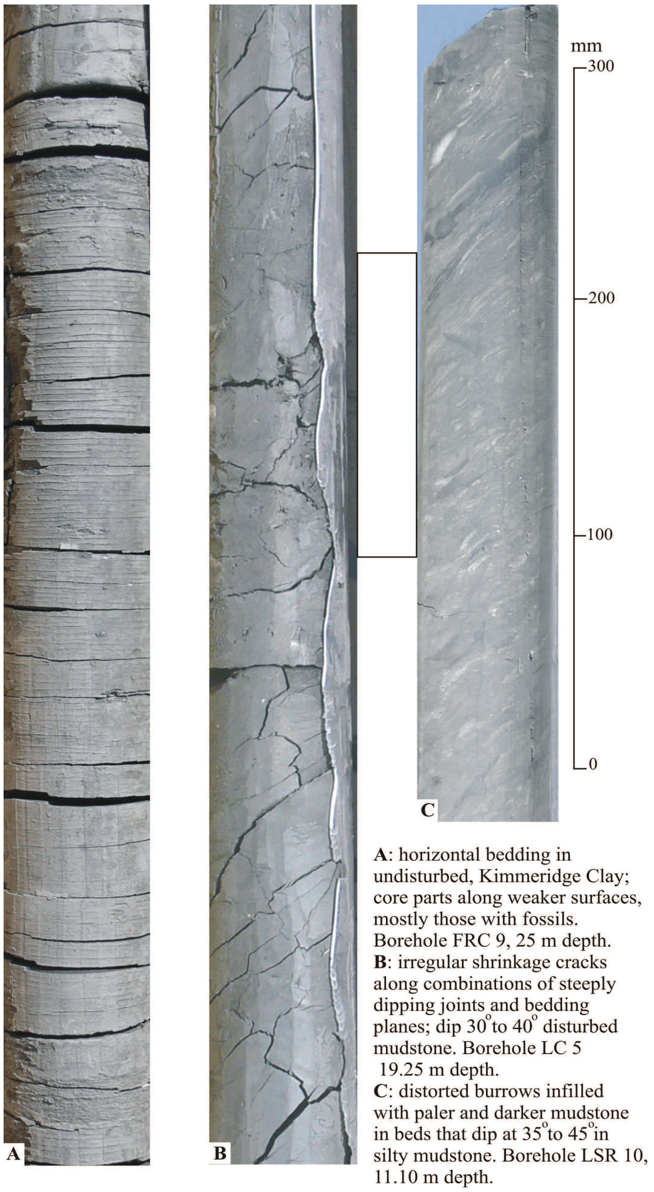

***Figure 4.** Examples of undisturbed (**a**) and disturbed (**b** and **c**) bedding in borehole cores in Kimmeridge Clay, Upper Osprey site, Isle of Portland.*

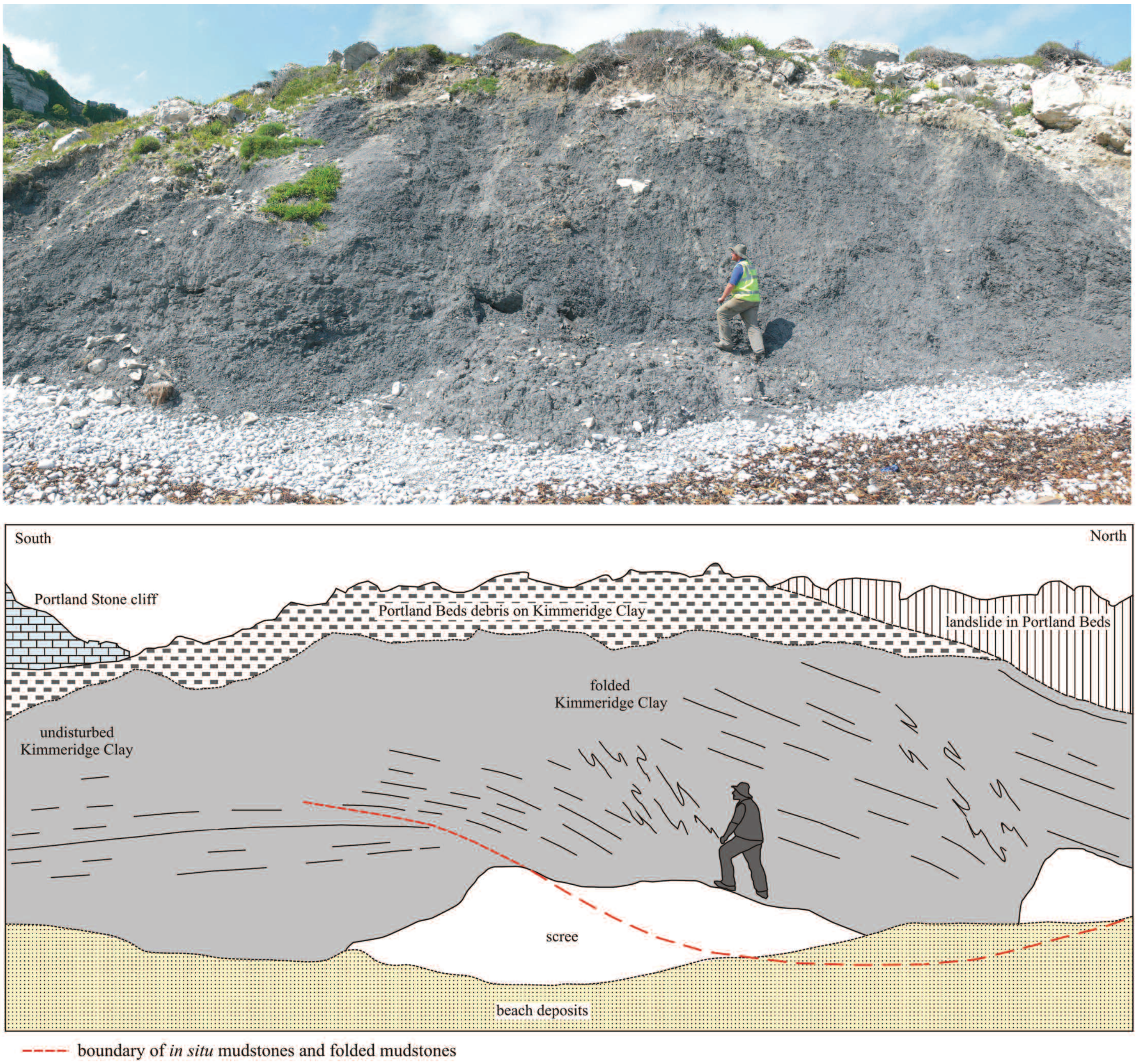

Figure 5. *Contact of undisturbed and periglacially folded Kimmeridge Clay Formation mudstones: outcrop below Grove Coastguard Station, Isle of Portland.*

middle parts of the disturbed layer have undergone little lateral movement.

The only *in situ* exposure of Kimmeridge Clay on the east coast of the island, at beach level below Grove Coastguard Station [SY 7053 7217], shows undisturbed Kimmeridge Clay overlain by up to 10 m of disturbed mudstone with similar structures to those observed in the boreholes (Figure 5). There too, the degree of disturbance is greatest in the near-surface layers and dies out with depth. It was initially suggested that the disturbed Kimmeridge Clay layer might have formed during thawing phases in the Pleistocene when the collapse of large masses (> 500,000 tonnes) of Portland Group limestone and sandstone swept across the Kimmeridge Clay outcrop at a time when the near-surface layers of the mudstones had been weakened by the same permafrost freeze-thaw activity.

However, examination of the landslide debris exposed over a distance of 2 km between the site and Grove Point suggested that all the observed landslides in that area had occurred within the past few hundred years. In the absence of a published description of similar structures in mudstones, Professor Denys Brunsden suggested that they might be comparable to structures in Charmouth Formation mudstones exposed in the cliffs at Seatown. The Seatown structures were photographed by Hugh Prudden in 1994 and tentatively suggested by him (*pers comm.*) to be an example of either tectonics related to faulting along the line of the Winniford Valley or associated with valley bulging.

Seatown

A layer of complexly folded Charmouth Mudstone (Green Ammonite Member) up to 20 m thick is exposed in the cliffs [SY 4153 9184 to 4188 9175] at Seatown over a distance of 140 to 500 m west of the outfall of the River Winniford (Figure 6). Westwards from there, up to 45 m of undisturbed Belemnite Marl and Green Ammonite members with a regular, low (01-02°) easterly dip crop out over a distance of *c.* 350 m (Figure 7). The detail that can be observed in the sections has varied considerably in recent years depending on the extent to which they are covered by a veneer of weathered mudstone and dust. The structures are well exposed from time to time following periods of heavy rain and strong winds. In the cliffs east of the outfall of the River Winniford, which are separated

Figure 6. *Cliffs of Jurassic (Charmouth Formation) Belemnite Marl and Green Ammonite Members between Golden Cap and Seatown, Dorset, view east. Periglacially folded Green Ammonite Member mudstones crop out in the low cliffs at the eastern end of the section.*

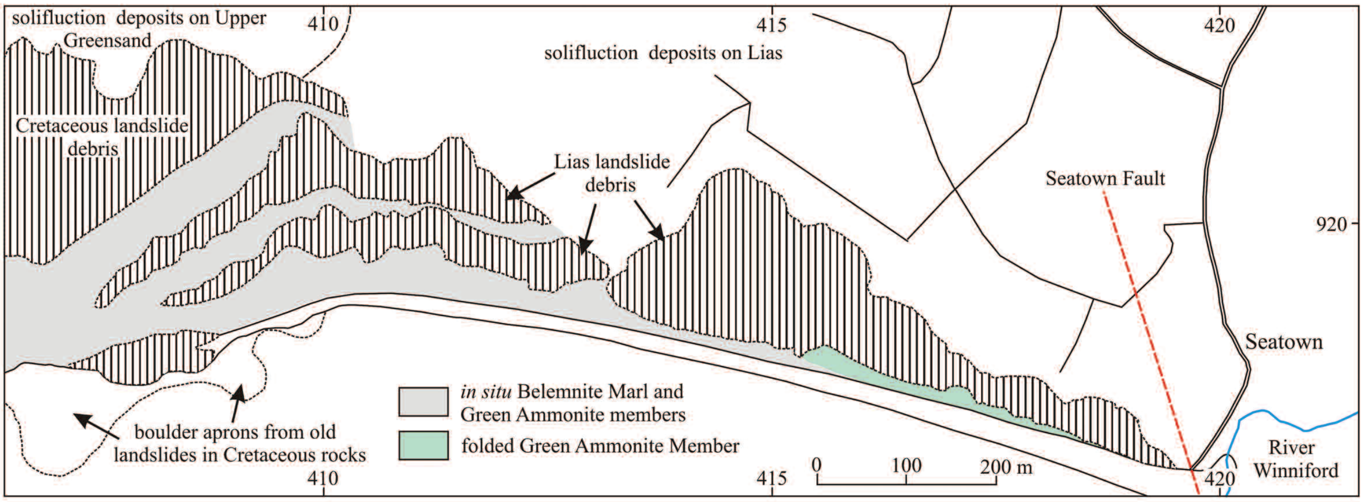

Figure 7. *Air photograph (**a**) and geological sketch map (**b**) of the area between Golden Cap and Seatown, Dorset showing the showing the relationship of the folded Green Ammonite Member mudstones to the underlying in situ beds and the overlying landslides. Photograph copyright Google Images Plc.*

from the outcrop of the Green Ammonite Member by the Seatown Fault, the lithologically similar mudstones of the Eype Clay Formation are deeply weathered, but are not deformed.

At the western end of the folded section the boundary between the undisturbed beds and the folded beds is a transitional zone in which unweathered mudstones with well preserved bedding, jointing and fossils rapidly pass up into similarly unweathered mudstones with gently curved bedding planes (Figure 8a). Eastwards from there, the boundary locally comprises one or more shear surfaces, but these do not combine to form a single basal surface. In the most easterly sections, a transitional junction is again exposed from time to time at the foot of the cliffs indicating that the deformed layer has an undulating, sub-horizontal base. When traced eastwards, the disturbed mudstones rapidly become complexly folded with local overturning (Figure 8b) and kink bands (Figure 8c), and remain so throughout most of the section. In some of the most easterly sections, the mudstones have locally

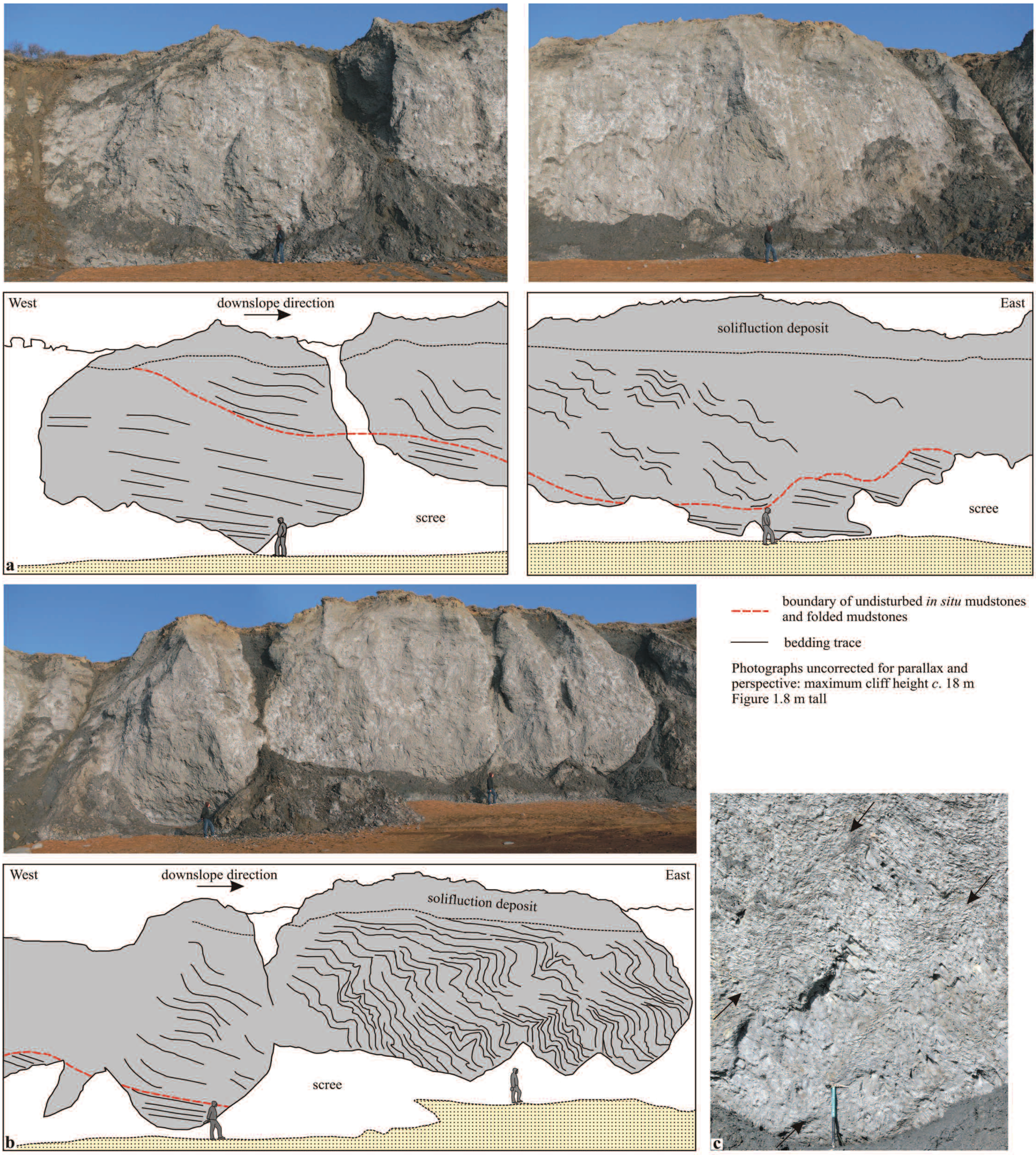

Figure 8. *(**a**) The junction of in situ eastward dipping Green Ammonite Member mudstones and the periglacially folded mudstones, 300 m west of outfall of River Winniford, Seatown. Photographed on December 30th 2007 when the sections were particularly well exposed: uncorrected for parallax and perspective. Figure 1.8 m high: maximum cliff height 18 m. (**b**) Intensely folded and partially overturned Green Ammonite Member mudstones 50 m east of (**a**): uncorrected for parallax and perspective. Figure 1.8 m high: maximum cliff height 20 m. (**c**) Detail of kink bands in mudstones 200 m east of (**a**): axe 0.7 m long.*

been reduced to a friable mélange with weak traces of highly complex, vertical to overturned bedding. The fold structures indicate movement from west to east (downslope). They are interpreted as the result of repetitive incremental plastic creep in a permafrost active layer during spring/summer melts.

In those sections where the junction between the *in situ* and disturbed mudstones can be observed, there is an upward increase in the degree of deformation that is presumed to reflect the viscous-drag gradient at the time when the rock mass behaved as a plastic flow. Similar gradients are present in the ice in glaciers, but there the development of sub-horizontal shear surfaces allows the upper layers to ride over the lower layers. The rarity of shear surfaces in the deformed mudstones suggests that the incremental movements at any one time were small enough for the bedding to be folded without fracturing, and that the rock mass was largely frozen at the time of the movements.

Periglacial deformation mechanisms

The principal processes that have been used to explain large-scale folding, as distinct from small-scale cryoturbation structures, in previously unweathered *in situ* mudstones in periglacial climates in the unglaciated parts of southern England are landsliding and valley bulging. All the larger scale rotational and translational coastal landslides described in southern England, including those in east Devon (Conybeare *et al*., 1840), west Dorset (Brunsden, 2002), the Isle of Wight (Hutchinson, 1969) and Sussex (Trenter and Warren, 1996) were initiated by failure along one or more weak (or weakened) mudstone layers. These and similar large-scale examples resulted in a layer of debris that rested on relatively undisturbed strata. Even the 1839 Bindon Landslide in east Devon, which involved the downhill movement of several million tons of Cretaceous rocks over a period of four days, did not produce folding in the underlying Jurassic mudstones (Conybeare *et al*., 1840). The best documented example of small-scale folding associated with landsliding in a periglacial climate is that described by Hutchinson and Hight (1987) at Lyme Regis (see above).

Valley bulges were first recognised geologically in the Liassic mudstones in the Northampton Ironstone Field in Northamptonshire and Lincolnshire by Hollingworth *et al*. (1944) where the structures were known to quarrymen as 'hogs-backs' or 'boil-ups'. Hollingworth *et al*. (1944) described valley bulges as the upward displacement of strata confined in valleys and subject to differential loading. They noted the similarity to the diapiric process that had been proposed to explain how salt domes form by plastic deformation as a relief of pressure. Kellaway and Taylor (1952) were the first to suggest that valley bulging was a periglacial feature related to the freezing and thawing of permafrost in mudstones that had access to water.

Valley bulges are mostly large-scale structures (up to hundreds of metres across and tens of metres deep) that can be several kilometres long. They are characterised by an intensely disturbed zone with shearing and tight folds that runs parallel to the valley floor, and by progressively lower dips when the structure is traced away from valley floor (Figures 9a and 9b). In many examples in the Cretaceous Wadhurst Clay Formation in Sussex, the strike of the beds in the disturbed zone follows bends in the valley and changes direction to follow tributary valleys (Gallois and Worssam, 1993).

None of the folded mudstones described above at Charmouth, Seatown and on the Isle of Portland have the overall geometry or fold characteristics of valley bulges. At Charmouth, gently folded beds on the west side of the valley are faulted against the tightly folded beds of Lang's (1914) "Char Valley Disturbance" (Figure 2). With the exception of minor disturbances caused by modern landsliding, the mudstones on the east side of the Char Valley are undisturbed. The folded beds on the west side of the valley are interpreted here as periglacial folds, and the tightly folded beds as tectonic. At Seatown, the disturbed beds are also confined to one side of the valley, and although the intensity of deformation locally increases in the direction of the valley axis, the structures show no evidence of upward (diapiric) movement. The limited exposure evidence at the eastern end of the folded outcrop suggests that the folded beds there rest on *in situ* mudstones, and that the base of the disturbed layer is a gently undulating sub-horizontal surface.

Summary and conclusions

Sheets of folded Jurassic mudstones up to 20 m thick and several hundred metres across crop out on the Dorset coast on the Isle of Portland and at Seatown. The name periglacial creep folds is proposed here for these structures to reflect their suggested method of deformation in which small incremental downhill movements of an active permafrost layer during spring/summer melts caused the rock mass to deform plastically without breaking up. The presence of overturned folds and kink bands in the folded beds supports this interpretation. Kink bands typically form in layered materials when an initiation (peak) compression stress is followed by a lower steady propagation stress (Fu and Zhang, 2006). The propagation stress in the case of periglacial creep folds was gravity acting on gentle slopes (as little as 01-02°) with a minimal overburden pressure. The creep folds differ in their overall morphology from structures generated in mudstones by landsliding and valley bulging. Unlike the structures associated with landslides, the creep folds are not underlain or overlain by an extensive shear surface, and there is no evidence to suggest that they were formed by compression beneath or in front of large landslides. Their mechanism of formation in an active permafrost layer is similar to that of valley bulges, but they are not symmetrical about a valley axis and they do not contain diapiric structures.

At the Seatown and the Isle of Portland localities, the deformed mudstones have been locally preserved beneath younger solifluction deposits and recent landslide deposits. The absence of similar structures elsewhere on the Dorset coast is attributed to the rapid removal of similarly weakened materials by marine erosion at times of high sea level during the last *c*. 6000 years. Other possible examples of periglacial creep folds in southern England include those at the former Southwater Brickworks [TQ 158 259] Horsham, Sussex. There, folds up to 10 m high in excavations in the Cretaceous Weald Clay Formation (Figure 10a) were shown to die out with depth in boreholes. They were attributed by Edmunds (1935) to tectonic activity, but subsequent detailed mapping showed that the area was unfaulted. This led Worssam (in Gallois and Worssam, 1993) to suggest that they were a fossil example of valley bulging. Their position on the upper part of a gently sloping (<02°) hillside suggests that they are periglacial creep folds. The Weald Clay mudstones are markedly less lithified than those of the Charmouth Mudstone. This has given rise in the Weald Clay to structures in which the near-surface layers have over-ridden the underlying layers (Figure 10b).

Terzaghi (1944), commenting on the way in which valley-bulge structures might be explained in geotechnical terms, suggested that the behaviour of weak mudstones (clays in his terminology) under small stress over a long duration could be likened to viscous flow in which small-scale lithological differences could give rise to complex folding. He perceptively noted that such structures could not be explained in terms of their measured geotechnical properties because laboratory strengths and their predicted behaviour bore no relation to observations in the field. His comments are equally applicable to periglacial creep folds. The importance of ice and high pore-water pressures in the deformation of unweathered mudstones in the near-surface layers was not appreciated for another ten years. Some of the structures in the creep folds are similar to those formed in strongly lithified rocks under high confining pressures, commonly that generated by several kilometres of lithostatic head. The rheological processes by which frozen rocks can be folded with little or no vertical confining pressure is poorly understood.

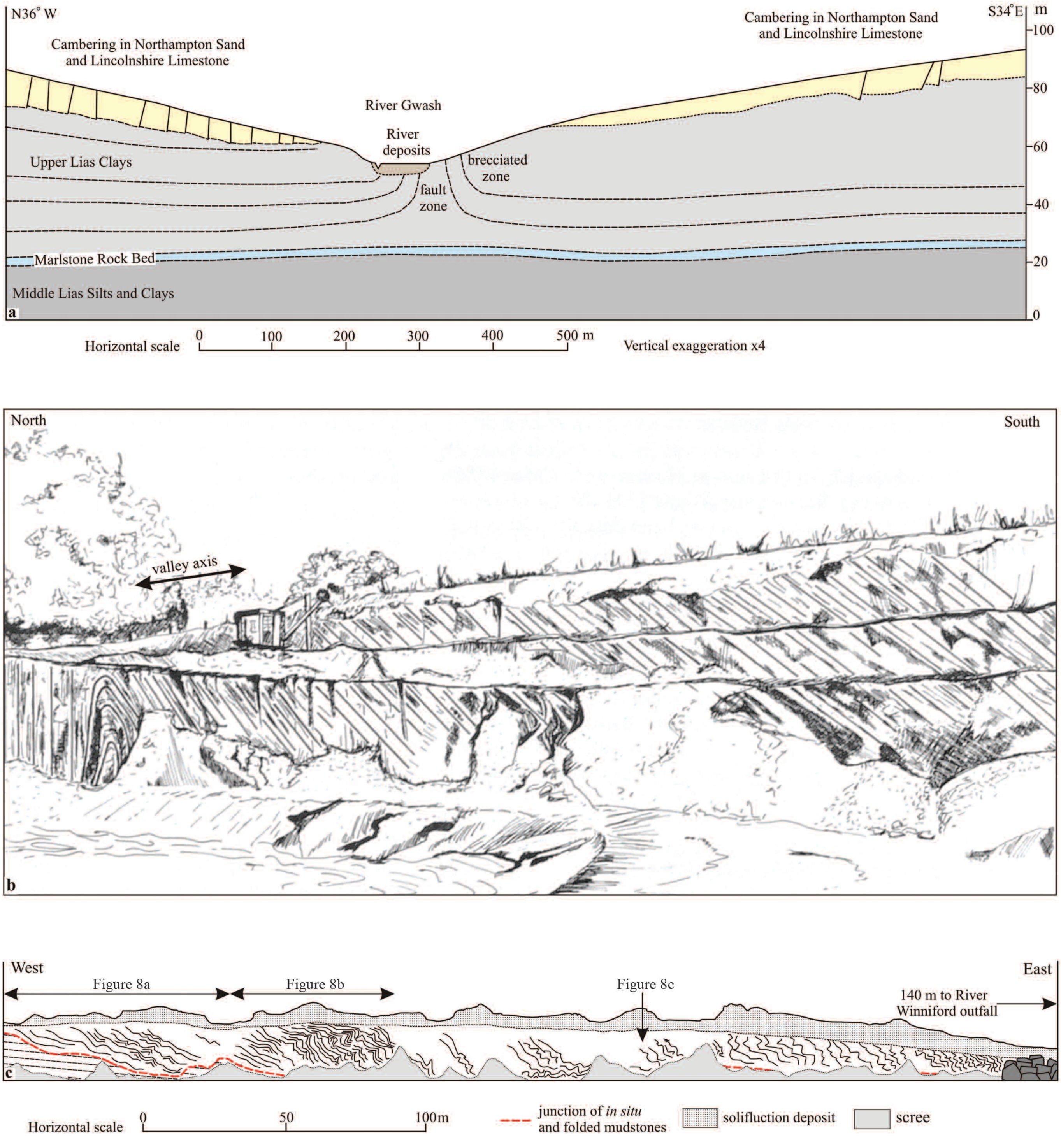

Figure 9. *Geological sketch sections to illustrate the differences in gross morphology between valley bulges and large-scale periglacial folding. (**a**) Valley bulge in Upper Lias Clays (now Charmouth Mudstone) and associated cambering in the Northampton Sand and Lincolnshire Limestone formations in the Gwash Valley, Lincolnshire (after Horswill et al., 1976). (**b**) Detail of the central part of a valley bulge in the Cretaceous Wadhurst Clay Formation showing the characteristic intense deformation along the valley axis and a steady decline in dip angle away from the axis. Freshfield Lane Brickworks, Danehill, Sussex based on BGS Photograph A 10249 oblique to the quarry face: excavator arm c. 7 m high (after Gallois and Worssam, 1993, fig.29). (**c**) Progressive downslope deformation in the periglacially folded Green Ammonite Member mudstones at Seatown based on photographs taken in 2007 to 2010: uncorrected for parallax and perspective.*

Acknowledgements

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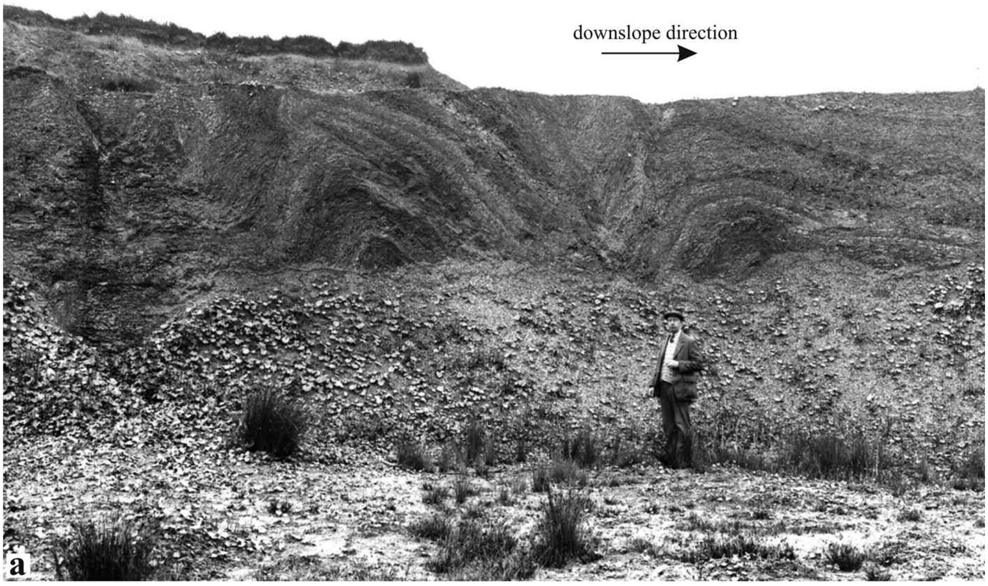

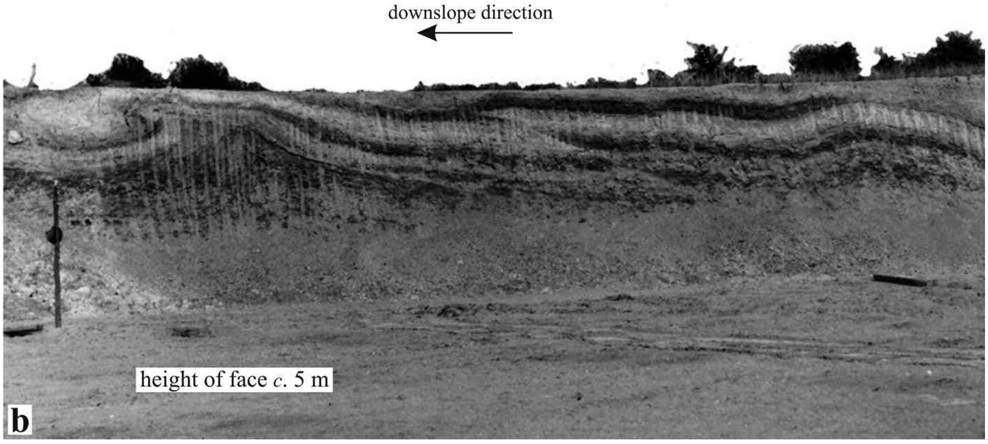

Figure 10. *Folds in Cretaceous Weald Clay Formation at the former Southwater Brickpit, Horsham Sussex. (**a**) View south west, May 1931, BGS A05368. (**b**) View east, July 1949, A 08320. Photographs by the late J. Rhodes. Reproduced with the permission of the British Geological Survey ©NERC. All rights Reserved.*

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