A fossil landslide preserved offshore at Lyme Regis, Dorset, UK

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Multidisciplinary studies carried out in advance of site investigations of the areas at Lyme Regis, Dorset most threatened by a combination of landslides and marine erosion included sidescan-sonar, bathymetric and seismic-reflection surveys in the adjacent offshore area. These revealed a large area (over 1500 m long x 700 m wide) 500 to 700 m offshore from the present-day coastline in which an irregular sea bed is strewn with rock debris. This area is underlain by a layer of heterogeneous material up to 30 m thick with traces of disturbed bedding and shear planes. Comparison of the stratigraphy and structure of the underlying *in situ* beds, as determined from seismic-reflection surveys, suggests that the disturbed material is the residue from a single large (> 10 million tonnes) landslide that resulted from a shear failure in seaward-dipping mudstones in the lower part of the Jurassic Charmouth Mudstone Formation. A reconstruction of the geology immediately prior to the landslide indicates that the failure occurred at a time when the cliff line was *c.* 350 m south of its present position, possibly in the mid Holocene 5000 to 6000 year ago when sea level was sufficiently high to re-erode a Pleistocene cliff line.

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Introduction

The 10 km-long Undercliffs National Nature Reserve (NNR) between the outfall of the River Axe at Seaton, Devon and Lyme Regis, Dorset comprises a 100 to 800 m wide coastal zone of coalescing landslides. This is the largest active landslide complex in Britain and includes examples of all the principal types of mass movement including rotational failures, mudflows, translational slides, rock falls, debris slides, and liquefied sand flows. The distribution and topographical expression of the landslide deposits in the onshore and offshore areas, together with historical records, suggests that all the debris observable at the present time has resulted from landslides that occurred in the past 200 to 300 years. At the western end of the NNR, where Cretaceous rocks rest unconformably on relatively strong Triassic rocks, the landslide debris is almost wholly derived from the Cretaceous Upper Greensand Formation and Chalk Group. In the central and eastern parts, where Cretaceous rocks rest unconformably on the Jurassic Blue Lias and Charmouth Mudstone formations, the debris includes weathered materials derived from Jurassic and Cretaceous rocks. The landslides continue eastwards beneath Lyme Regis urban area (Figure 1) where multidisciplinary studies were carried out in the onshore and offshore areas in advance of remedial engineering works designed to protect the town from the combined effects of landslides and marine erosion (Gallois and Davis, 2001). These included the preparation of geological maps of the intertidal areas and sidescan-sonar, bathymetric and seismic-reflection surveys in the offshore area.

The bathymetric survey, covering the area between high water mark and the -13 m OD contour, was used to produce a high-resolution computerised seabed image (Badman *et al.*, 2000). This showed not only the outcrops of the principal limestone beds in the Blue Lias and Charmouth Mudstone formations, but also a large area (over 1500 m long x 700 m wide) in which the sea-bed profiles were much more irregular than those of the adjacent areas. This area appeared from video surveys (albeit in poor visibility) to contain large amounts of randomly distributed rock debris including bio-encrusted angular blocks up to several metres across. This was interpreted as possible landslide debris. The side-scan sonar survey confirmed that over much of the survey area the sea bed comprised bare rock pavements of Blue Lias mudstones and limestones, that the outcrop of the Charmouth Mudstone was mostly overlain by an almost flat veneer of sand, and that the presumed landslide area contained numerous small to large blocks of unidentified rock. The disturbed nature of the material at depth was confirmed by the seismic-reflection surveys which showed a layer of heterogeneous material up to 30 m thick with traces of disturbed bedding and shear planes (Figure 2).

Geological setting

The stratigraphy of the Jurassic rocks of the Lyme Regis area is known in detail from cliff and foreshore exposures, and from site-investigation boreholes drilled as part of the remedial engineering works (Gallois and Davis, 2001; Brunsden, 2002). At the base of the succession, the Blue Lias Formation (30 m thick) forms a stable foundation composed of thinly interbedded mudstones (*c.* 60% by volume) and limestones. Above this, the mudstones of the Shales-with-Beef Member (28 m thick) at the base of the Charmouth Mudstone Formation can be divided into two broad types for geotechnical purposes. Thinly interbedded and interlaminated clay-mineral-rich and organic-rich mudstones that weather to weak fissile mudstones (‘paper shales’) and listric clays, and calcareous mudstones with widely spaced calcareous nodules and thin (mostly <0.3 m thick) beds of muddy limestone. The Cretaceous succession at Lyme Regis comprises, in ascending order, the Gault Formation (2 m thick) and the Foxmould (25 m thick), Whitecliff Chert (20 m thick) and Bindon Sandstone (8 m thick) members of the Upper Greensand Formation (Edwards and Gallois, 2005). In an unweathered state in boreholes the Gault is a relatively strong, montmorillonite-rich mudstone, but at outcrop it readily weathers to a weak swelling clay. The Foxmould consists of weakly calcareously cemented permeable sandstones that are prone to dissolution. When fresh, the Whitecliff Chert and Bindon Sandstone consist of strong calcareous sandstones and calcarenites that are resistant to weathering.

There is preserved evidence in the region of faulting and associated folding that was intermittently active from the late Carboniferous to the Miocene. Deep seismic-reflection surveys in the inland area recorded several approximately north-south-trending fault belts that overly major fractures in the pre-Permian basement rocks (Edwards and Gallois, 2004). These include normal faults with displacements of up to 150 m in the older Triassic rocks, and synthetic and antithetic faults with displacements of mostly <30 m in the Triassic and Jurassic rocks. A few of these were reactivated during the late Cimmerian Orogeny and gave rise to displacements in the Cretaceous rocks and in the Tertiary Clay-with-flints. A second, roughly east-west fault trend is represented by several shoreline-parallel faults exposed in the intertidal and shallow subtidal area between Seaton and Lyme Regis. In contrast to the north-south trending faults, the displacements on similar E-W trending faults inland do not appear from seismic-reflection profiles to markedly increase with depth. This suggests that their movements may date largely from the Alpine orogenic phase and that they are related to the widening of the English Channel and Western Approaches in Tertiary times.

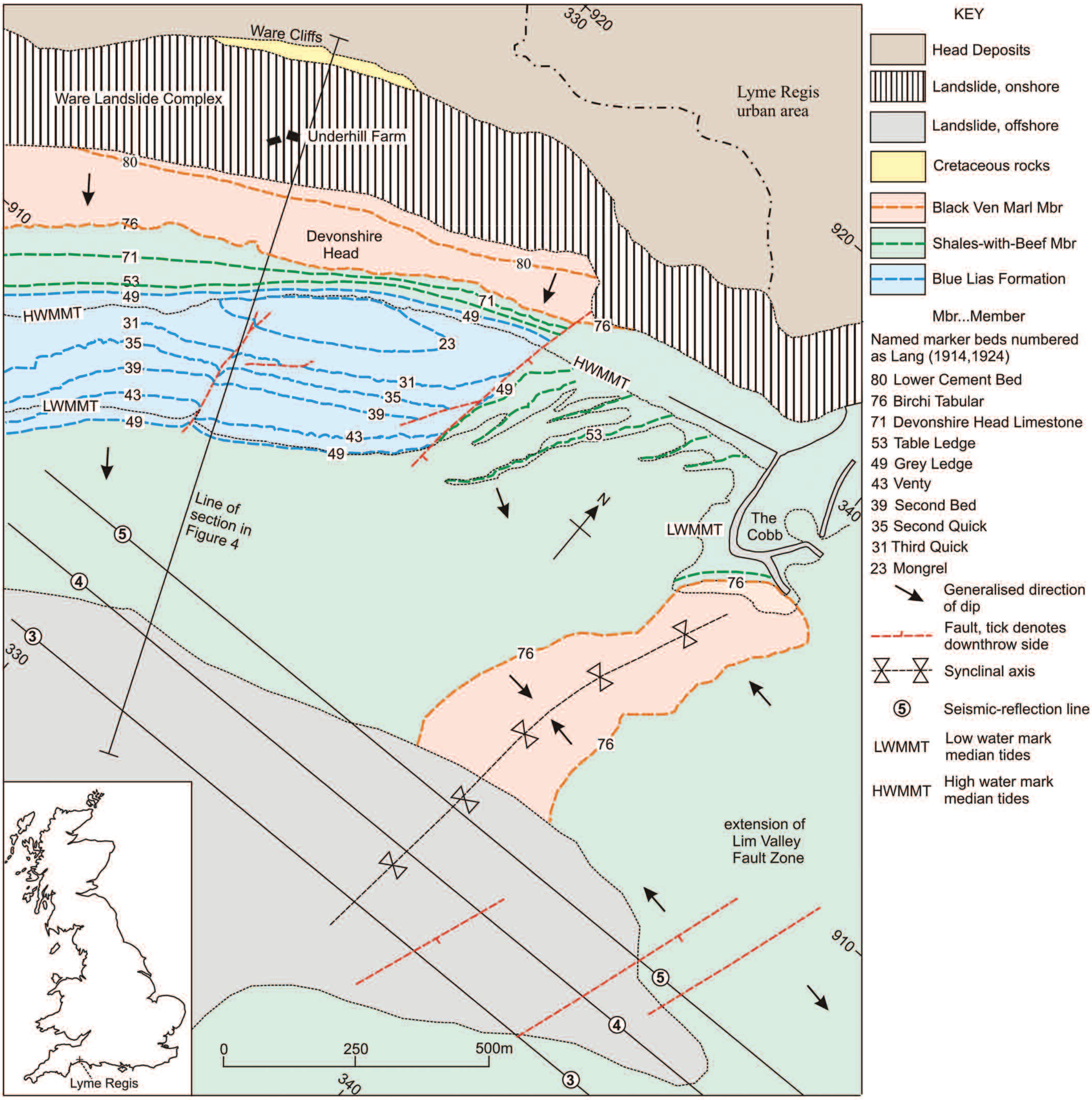

Figure 1. Geological sketch map of the onshore and near offshore areas between Devonshire Head and Lyme Regis, Dorset showing the positions of localities referred to in the text.

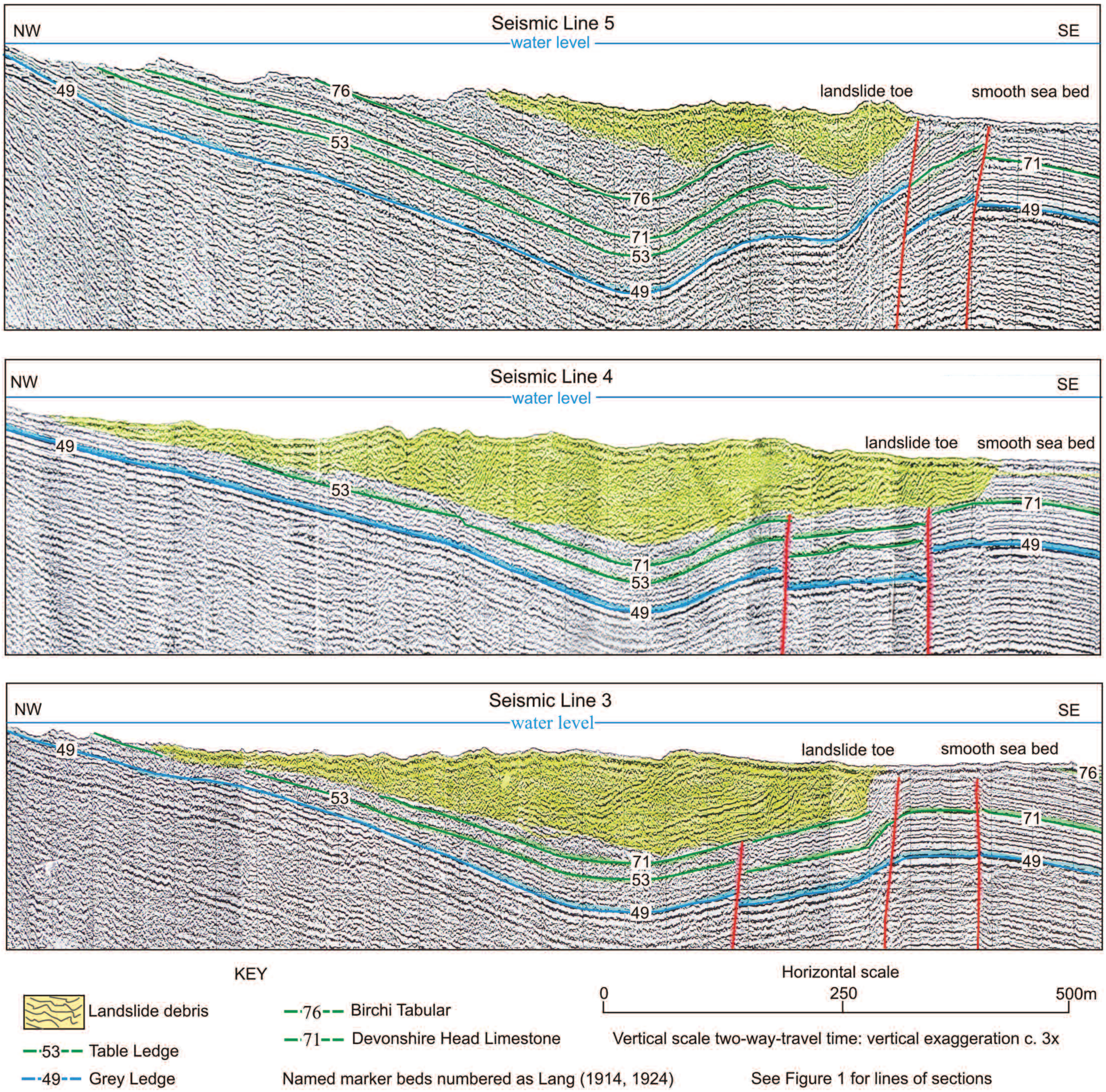

Figure 2. *Seismic-reflection survey lines 3 to 5 showing the relationship of the offshore landslide debris to the underlying Blue Lias and Charmouth Mudstone formations. Images copyright of and reproduced courtesy of West Dorset District Council.*

All the N-S trending fault zones in the east Devon and west Dorset coastal zone underlie valleys, and therefore influence the lateral (E-W) extents of the landslide complexes. For example, the Lim Valley Fault Zone (Gallois and Davis, 2001) separates the Ware Landslide Complex from the Spittles-Black Ven Complex. Several of the E-W trending faults that crop out in the intertidal area pass beneath the landslides in the NNR. The extent to which they may have influenced the initiation of failures cannot be determined because they are everywhere covered by landslide debris.

Failure mechanisms

During the past 200 years, the time during which geological accounts have been available, landslides involving thousands to millions of tonnes of material have been described on the east Devon and west Dorset coasts. The larger landslides in the Lyme Regis area can be divided into two distinct parts. Those in which the principal failure surface has been in fissile-weathering mudstones in the Shales-with-Beef, and those in which the failure surface has been in mudstones close above the base of the Cretaceous succession. Examples of the former include the 1908 (Jukes Browne, 1908) and 2008 Spittles (Gallois, 2009) landslides. Examples of the second include the 1839 Bindon Landslide (Gallois, 2010) and the 1840 Dowlands Landslide (Arber, 1940).

When failures occur in the Gault, the decalcified Foxmould commonly combines with the overlying beds to produce matrix-supported debris flows that pour over the Jurassic rocks. The larger of these contain intact masses of Upper Greensand and Chalk that have been transported tens to hundreds of metres. The more resistant lithologies, the sandstones and calcarenites in the Whitecliff Chert and Bindon Sandstone, are commonly preserved as cuboidal blocks up to several metres across. These form debris aprons that extend out for up to 100 m across the intertidal area and into the shallow subtidal area. Many of the larger blocks in that area are known to have been deposited by a particular landslide and have remained *in situ* for over 100 years. For example, Sherborne Rocks [SY 221 879], angular blocks of Upper Greensand up to several hundred tonnes in weight in the subtidal area adjacent to Beer Head, east Devon were deposited during the 1790 Hooken Landslide (Conybeare *et al*., 1840). A concentration of similar-sized blocks of the same beds in the intertidal area at Humble Point [SY 305 899] was deposited by the 1840 Dowlands Landslide (Arber, 1940).

The fossil landslide

At their north western end, close to southward dipping outcrops of the Blue Lias in the cliffs and intertidal area adjacent to Devonshire Head, the landslide deposits seen in the seismic-reflection profiles rest on the Shales-with-Beef (Figure 2). In Seismic lines 3 and 4 the base of the deposits cuts across the bedding in the *in situ* strata at a low angle, rising from a level just above Table Ledge (Bed 53) to a level just above the Devonshire Head Limestone (Bed 71), a stratigraphical difference of 10 m in *c*. 250 m. Seismic Line 3 shows well-developed landward-dipping discontinuities in the middle part of the section, and at their south-east end all three profiles show contorted strata. The overall architecture of the landslide debris, in particular the nature of the contact with the Shales-with-Beef, the landward-dipping discontinuities and the disturbed strata in what is interpreted here as the toe of the landslide, all suggest that the initial failure surface was a bedding-plane shear in mudstones close above Table Ledge.

In the closest onshore area to the fossil landslide, the lower and middle coastal slopes below Ware Cliffs, Shales-with-Beef and Black Ven Marl mudstones dip seaward at 1° to 2°. Their outcrop is largely overlain by landslide debris derived from the Upper Greensand and Clay-with flints as a result of shear failures in the Gault. Where deeply weathered, the mudstones give rise to extensive shallow-seated mudflows during periods of wet weather (Figures 3). Bedding-plane failures in the Shales-with-Beef have infrequently (one per 5 to 10 years) deposited up to a few thousand tonnes of debris on the beach. This material, and that deposited in the intertidal zone at the foot of the much larger Spittles and Black Ven landslides, is composed almost entirely of Jurassic rocks that are readily eroded by the sea. The debris comprises small (<0.1 m across) mudstone fragments, a few larger (up to 1 m across) blocks of stronger mudstone, and slabs of the more cemented beds up to 0.5 m thick and up to 2 m across, notably Table Ledge, the Devonshire Head Limestone and the Birchi Tabular Bed. Most of the finer grade materials and the larger blocks of mudstone are dispersed by marine erosion within a few weeks to leave a smooth sea bed with a few scattered blocks of the more resistant lithologies.

In contrast, the sea-bed profiles of landslide debris fans in the intertidal and subtidal areas that include Cretaceous rocks, for example between Sidmouth and Beer, are highly irregular due to the presence of angular joint-bounded blocks of Whitecliff Chert and Bindon Sandstone. Blocks up to 100 m^3 in size are common. The sea-bed profiles indicated by the offshore surveys at Lyme Regis are compatible with the presence of similar-sized blocks of Upper Greensand. This suggests that the fossil landslide occurred either at a time when the Upper Greensand outcrop was sufficiently close to the coast for it to be involved in the landslide or Cretaceous debris from an earlier landslide was incorporated in the new landslide.

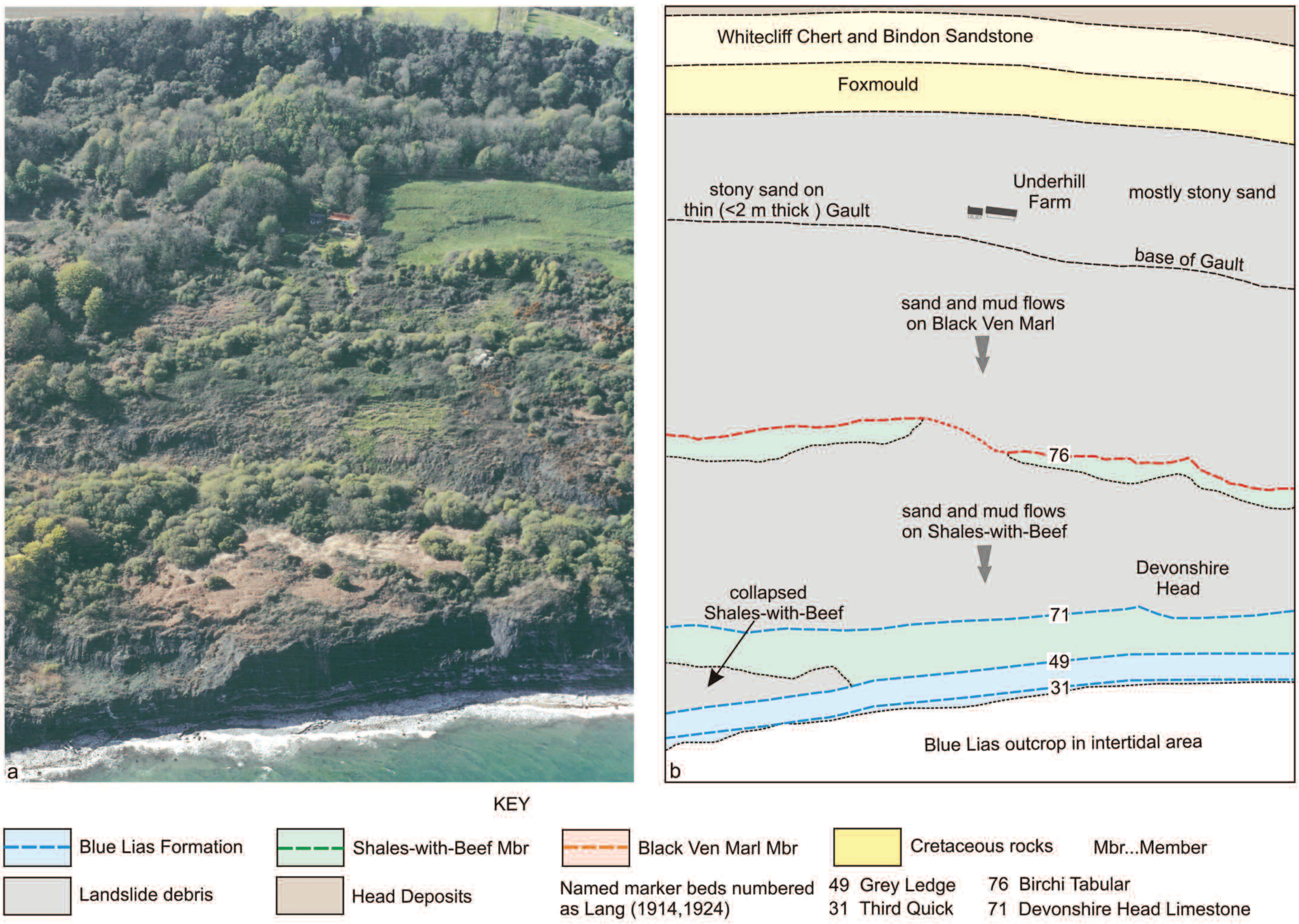

Figure 3. *(**a**) Oblique air photograph of Devonshire Head and part of the Ware Landslide complex, view north, February 2008. Photographed by Paul Whitney, BGS: copyright NERC. (**b**) Geological sketch map of the area shown in (**a**).*

A geological section through the present-day Ware Landslide Complex is shown in Figure 4a. The seaward extension of this section at the time of formation of the fossil landslide (Figure 4b) is based on the premise that the most likely time for the slope to fail would have been when the seaward-dipping Shales-with-Beef cropped out at the base of the sea cliff. This would have been when the cliff line was *c.* 350 m south of its present-day position. The geological structure of the cliff at that time would have been similar to that in the cliffs in and on the east side of Lyme Regis at times when large landslides have occurred. A succession of landslides adjacent to the sea front, notably in 1902, 1925 and 1962 (Lee, 1992), produced tens of thousands of tonnes of debris, and that at the Spittles in 2008 is estimated to have involved c. 500,000 tonnes of material (Gallois, 2009). In each case the landslide was initiated by a bedding-plane failure surface in seaward-dipping fissile mudstones in the lower the part of the Shales-with-Beef a little above Table Ledge.

Summary and conclusions

Bathymetric and sonar surveys carried out at Lyme Regis revealed a large area 500 to 700 m offshore from the present-day high-water mark in which the sea-bed profiles are markedly more irregular than those of the adjacent areas. Seismic-reflection surveys showed the anomalous area to be underlain by heterogeneous deposits with steeply dipping beds and shear zones, in contrast to the undisturbed low dips in the underlying Jurassic mudstones. The disturbed deposits are interpreted here as the residual debris of a landslide that involved >10 million tonnes of material at a time when the cliff line was *c.* 350 m south of its present position. None of the present-day landslide-debris aprons recorded on the east Devon and west Dorset coasts extends more than 150 m offshore. De la Beche (1822) recorded blocks of Chalk 7 miles south of The Cobb in water depths of *c.* 15 m, which he presumed to be landslide debris from a time when the coast lay in that area. This is unlikely for two reasons. First, the chalks of the Devon and Dorset coast are friable when weathered and are mostly not preserved as blocks of debris larger than *c.* 0.5 m across in the intertidal area. Second, the location is within one mile of an offshore Chalk outcrop and is more likely to be an outlier of that material or derived from it by fluvial or marine erosion.

There is no evidence of the age of the fossil landslide at Lyme Regis. However, the history of sea-level change in the late Quaternary suggests that some of the cliff lines and larger landslides on the coast of southern England formed during the

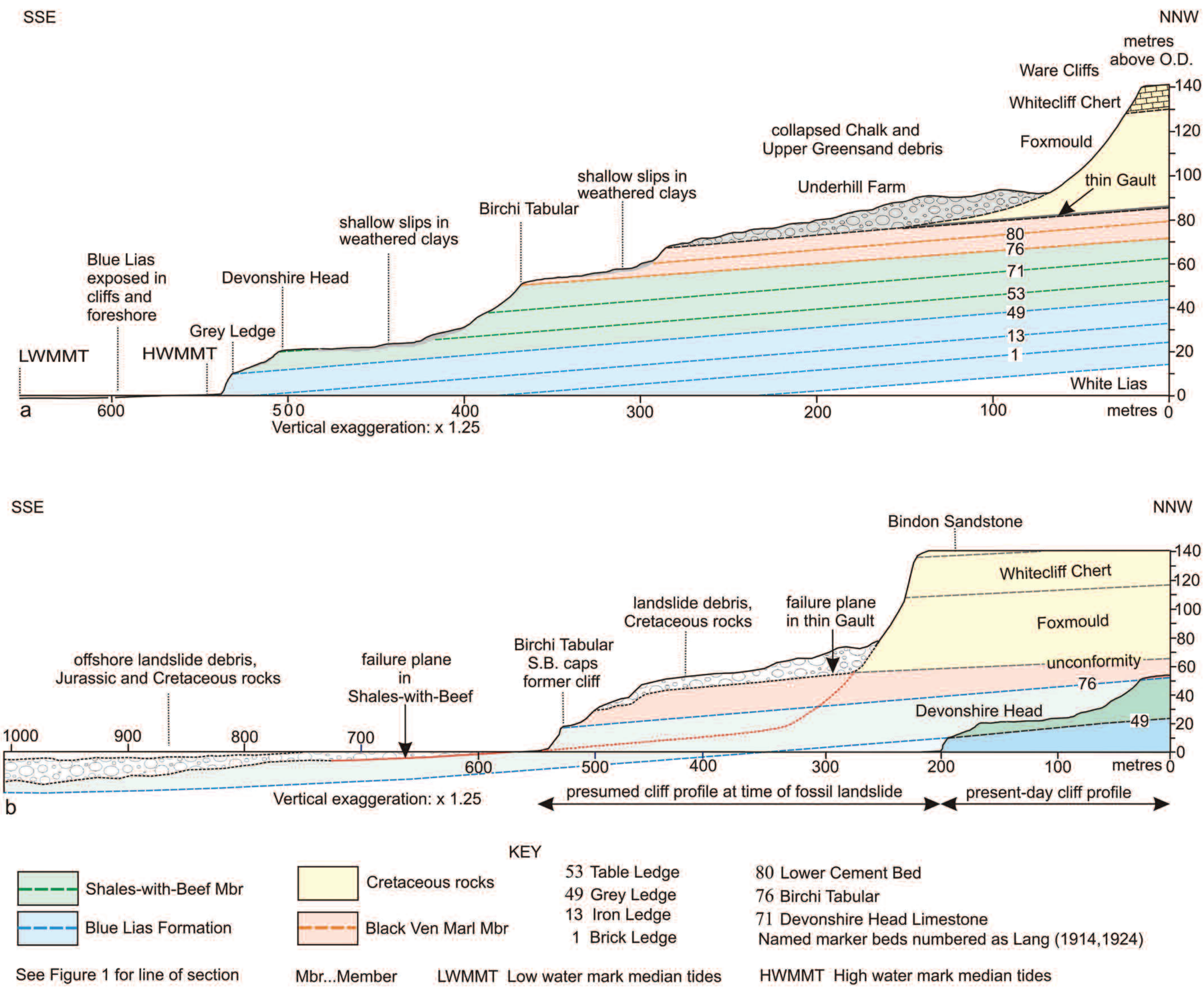

Figure 4. *(**a**) Geological cross section between Ware Cliffs and Devonshire Head showing the distribution of the principal landslide deposits. (**b**) Hypothetical geological cross section between Ware Cliffs and the offshore landslide debris shortly after the time when the fossil landslide occurred.*

last temperate phase in the Pleistocene (Oxygen Isotope Stage 5e) at a time when sea level was similar to that of the present day. The subsequent fall in sea level during the Devensian cold period (OIS 2 to 4) preserved these coastal features from marine erosion until the mid Holocene, 5000 to 6000 years ago, when sea level had risen sufficiently to erode parts of the Pleistocene coast. The fossil landslide at Lyme Regis is unlikely to date from before that time, and might have occurred several thousand years later. If it dates from 5000 years ago, the average rate of retreat of the cliff line adjacent to Devonshire Head has been *c*. 70 mm per year.

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