Landslide mechanisms in the Axmouth to Lyme Regis Undercliffs National Nature Reserve, Devon, UK

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The Axmouth to Lyme Regis Undercliffs National Nature Reserve (NNR) on the east Devon coast contains one of the largest active complexes of overlapping and coalescing landslides in Europe. Taken together they include examples of all the more common type of landslide ranging from rock falls in sandstones and limestones to mud flows in deeply weathered clays. The most spectacular landslides during the past 200 years have been translational failures in which detached blocks of Cretaceous rocks of up to millions of tonnes have been displaced seawards by up to 500 m. There are few published detailed descriptions of most of the landslides in the reserve, the notable exception being the Bindon Landslide of Christmas Day 1839. When regarded as an evolutionary whole, the various types of mass-movement deposit in the NNR can be divided into three broad categories (primary, secondary and tertiary) based on the state of the materials involved immediately prior to failure. The present account describes how the historical and genetic inter-relationships of these categories have combined to produce the present-day complex. The major primary landslides in the eastern part of the NNR involve shear failures in montmorillonite-rich mudstones in the Cretaceous Gault Formation. Those in the western part involve failures in thin beds of similar mudstone in the lowest part of the Upper Greensand Formation. The larger secondary landslides involved the collapses in the Cretaceous rocks and bedding-plane failures in Jurassic mudstones.

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Introduction

Between the outfall of the River Axe and Lyme Regis, a distance of 10 km, the coastal zone is a complex of coalescing landslides 100 to 600 m wide that collectively form the Axmouth to Lyme Regis Undercliffs National Nature Reserve (NNR). Throughout most of its length the boundaries of the NNR are defined by sea cliffs composed of *in situ* rocks and rocks and debris displaced by landslides, and inland by the back scarps of landslides. In total, *c.* 16 km of rock cliffs. The Undercliffs NNR is the largest active landslide complex in Britain and includes examples of all the principal types of mass movement including rotational failures, mudflows, slab (translational) slides, rock falls, debris slides, and liquefied sand flows.

The NNR can be divided into six landslide areas based on the most recent large-scale failures (Figure 1): these are closely similar to the divisions used by earlier authors (e.g. Arber, 1940; Pitts, 1981a). Each complex comprises overlapping and superimposed landslides that extend back for hundreds of years, as a result of which the boundaries between them are to some extent arbitrary. A few of the larger individual events of the past 200 years have been well documented, but most of the medium and smaller failures in that period are only known from a passing reference to their occurrence (e.g. 'a landslide occurred at…') even though, taken together, they have produced an unusual topography that has attracted numerous authors and artists. Reviews of the historical accounts of the landslides in the NNR include those of Arber (1940, 1973) and Pitts (1981a, b). These accounts were reviewed in the Geological Conservation Review volume *Mass Movements in Great Britain* (Cooper, 2007) which incorrectly classified the Undercliffs as a mass-movement site in Jurassic strata.

A range of late Triassic to late Cretaceous rocks is exposed *in situ* in sea cliffs and the back scarps of the landslides in the NNR (Figure 2). Large parts of the Cretaceous succession are repeated in relatively undisturbed detached masses within the landslides. The stratigraphy and geological structure vary across the NNR: their effects on the failure mechanisms are discussed below, landslide complex by landslide complex. The principal landslides in the eastern part of the NNR involved shear failures in Cretaceous Gault mudstones and liquefaction of the overlying Foxmould sands. Those in the western part failed along thin (mostly <0.1 m thick) beds of mudstone in the lowest part of the Upper Greensand. The mechanisms of these landslides have been much described and discussed from 1840 onwards from the time of the first detailed description and analysis of a major landslide, the 1839 Bindon Landslide (Conybeare *et al.*, 1840). However, few of the subsequent descriptions took sufficient account of the detailed stratigraphy and the geological structure.

The principal factors that influence the formation of landslides are the geotechnical properties of the unweathered and weathered rocks, their stratigraphical relationships,

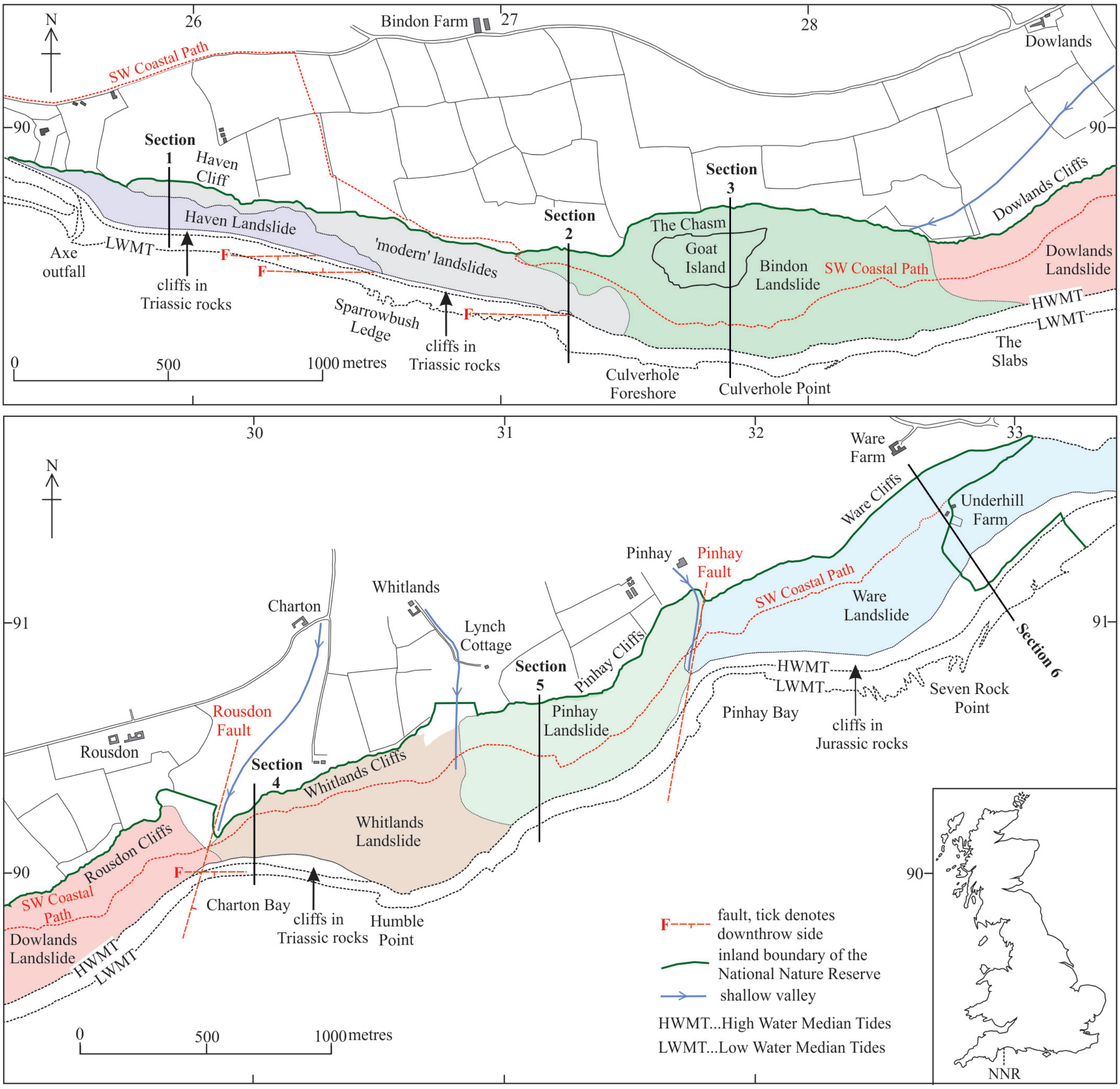

Figure 1. *Geographical sketch map of the Axmouth to Lyme Regis National Nature Reserve (NNR) showing the principal landslide complexes.*

geological structure and moisture contents. Climatic events, in particular the occurrence of periods of unusually high rainfall, are common to the whole of the site. They have been identified as the primary trigger for some of the historically documented major landslides including the 1839 Bindon landslide (Conybeare *et al.*, 1840; Arber, 1940) and numerous landslides on the south coast of England in 2000-2001 and 2012-2013 (Table 1). For example, June 2012 (279 mm), the wettest South-West England month in the 138-long Meteorological Office records (Table 1), was followed in early July by extensive landslides along the south coast. Those in the NNR resulted in the temporary closure of the coastal path at the western and eastern ends of the reserve, and the closure of the beach adjacent to the NNR at Lyme Regis. Continuing higher than average rainfall led to 2012 being the second wettest year on record (Table 1), and resulted in the reactivation in January 2013 of many of the July landslides and renewed closures of the coastal path and beach.

Geological setting of the NNR

At outcrop in the NNR, a conformable succession of late Triassic mudstones and limestones passes up into early Jurassic mudstones. These are overlain with marked unconformity by mid Cretaceous mudstones and sandstones that overstep the Triassic and Jurassic rocks in a westerly direction with the result that they rest on the Charmouth Mudstone Formation at the eastern end of the NNR and on the Blue Anchor Formation at the western end (Figure 2). The geological structure is relatively simple overall, but is locally complicated by faulting.

Triassic rocks

The Mercia Mudstone Group formations that crop out in the sea cliffs and intertidal areas in the western part of the NNR largely comprise relatively strong red and green silty mudstones which give rise to joint/bedding bounded rock falls in the cliffs, but rarely give rise to shear failures even when weathered. The principal exceptions are beds of dark grey mudstone in the upper part of the Blue Anchor Formation and in the Westbury Mudstone. Small, shallow-seated landslides have been recorded in the Blue Anchor Formation in inland areas (Edwards and Gallois, 2004), but none has been recorded in the NNR. Weathered pyritic laminated mudstones in the Westbury Mudstone break down to clays that give rise to shallow-seated landslides and mud flows.

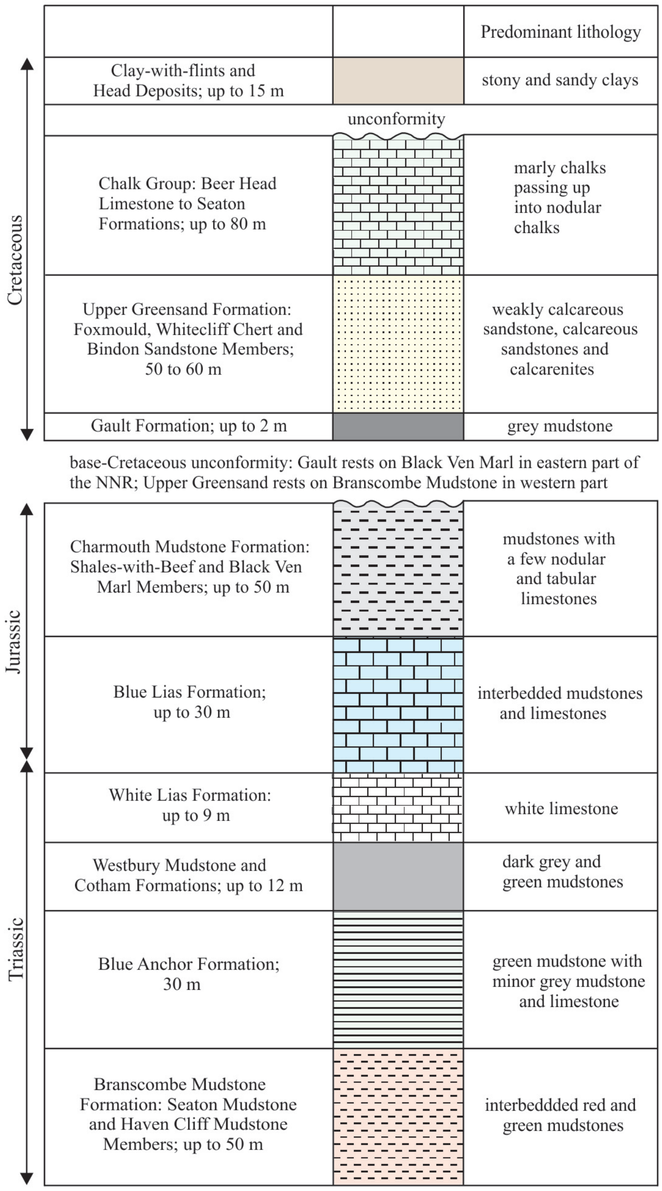

Figure 2. *Generalised vertical section for the strata that crop out in the NNR.*

Jurassic rocks

The stratigraphy and geotechnical properties of the Jurassic rocks in the NNR are well documented from cliff and foreshore exposures, and from site-investigation boreholes in the Lyme Regis area (Gallois and Davis, 2001; Brunsden, 2002). At the base of the Jurassic succession, the Blue Lias Formation forms cliffs composed of thinly interbedded mudstones (*c.* 55-60% by volume) and limestones that are prone to small rock falls and larger joint-bounded failures. Above this, the Charmouth Mudstone is divided into members partly on the basis of gross lithology and partly arbitrarily at thin (mostly <0.4 m thick) limestone marker beds. The mudstones of the Shales-with-Beef Member, and to a lesser extent the Black Ven Marl Member, 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 nodules and beds of muddy limestone. Analyses of landslides at Lyme Regis (Davis *et al.*, 2002) and the adjacent Spittles (Gallois, 2008) have shown that the principal failure surfaces occur in fissile-weathering mudstones a little above thin (<0.3 m thick) laterally persistent limestone beds in the Shales-with-Beef and Black Ven Marl. The classification of the failure surfaces horizons into 'major', 'widespread' and 'minor' is arbitrary (Gallois, 2009) and varies from locality to locality due to lateral variations in the stratigraphy and, most importantly, the local geological structure.

Cretaceous rocks

The Cretaceous succession in and adjacent to the NNR can be divided into three lithologically distinct parts (Figure 2). In ascending order the Gault Formation, the Foxmould Member, and the Whitecliff Chert and Bindon Sandstone Members of the Upper Greensand Formation. In southern England the argillaceous Gault passes westwards into the arenaceous Upper Greensand until it is replaced in east Devon. East of the NNR, Jukes-Browne and Hill (1900) recorded up to 5 m of Gault at Stonebarrow, Charmouth, 2 m at Black Ven, Lyme Regis and, within the NNR, deeply weathered Gault clay in landslide debris on the foreshore at Humble Point [SY 306 899]. Up to 3 m of sandy clay that is lithologically similar to beds classified as Gault at Lyme Regis is patchily exposed in the lower part of the Upper Greensand in the intertidal area that fronts the Dowlands Landslide (Richard Edmonds pers. comm.), but the formation has not been recorded on the coast west of there. Inland, beds of clay and sandy clay in the lower and middle parts of the Upper Greensand that have been attributed to the Gault were recorded a railway tunnel [ST 188 012] at Honiton (Jukes-Browne and Hill, 1900) and in site-investigation boreholes in the same area (Hart and Williams, 1990). Large landslides in the Upper Greensand in the steep sided valleys between there and Northleigh [SY 196 960] were almost certainly the result of shear failures in mudstone beds in the lower part of the Upper

Year	Winter (DJF) Rank (mm)	Spring (MAM) Rank (mm)	Summer (JJA) Rank (mm)	Autumn (SON) Rank (mm)	Whole year Rank (mm)
1839	188 (195)	206 (142)	8 (351)	28 (358)	26 (1076)
1840	74 (270)	234 (114)	154 (213)	106 (283)	204 (801)
2000	38 (371)	14 (275)	204 (172)	2 (558)	5 (1355)
2001	17 (424)	17 (271)	93 (187)	85 (281)	84 (1003)
2012	96 (266)	37 (236)	3 (394)	17 (415)	2 (1396)
2013	19 (417)	67 (204)	124 (146)	41 (352)	80 (1075)

Table 1. *Rainfall for 1839 and 1840 compared to the England and Wales record for 1766 to 2014 (248 years), and for 2000 to 2002 and 2010 to 2013 compared to the South-West England record for 1876 to 2014 (138 years). Based on Hadley Centre data at www.metoffice.gov.uk/hadobs/hadukp/data/download.html. Note that winter includes December of the previous year. Seasonal/yearly ranking refers to wettest (low ranking) to driest (high ranking): e.g. summer 1839 was the 8th wettest on record; summer 2000 one of the driest.*

Greensand. The distribution of Gault lithologies in east Devon, including within the NNR, is patchy and probably related to penecontemporaneous activity on some of the major faults. When in an unweathered state, the Gault comprises relatively strong montmorillonite-rich mudstones that readily weather to weak swelling clays. Shear failures in these clays give rise to all the larger coastal landslides in Cretaceous rocks in southern England including those at Folkestone Warren, Kent (Trenter and Warren, 1996), Ventnor, Isle of Wight (Hutchinson, 1991), White Nothe (Damon, 1884), and Black Ven, Dorset (Brunsden and Jones, 1976).

The Foxmould consists of weakly calcareously cemented, permeable fine-grained sandstones that are prone to dissolution. The lowest part of the formation contains thin (mostly <0.1 m thick) beds of mudstone that weather to weak clays. When fresh, the Whitecliff Chert and Bindon Sandstone consist of strong calcareous sandstones and calcarenites. When failures occur in the Gault or in thin layers of mudstone in the Foxmould, the decalcified Foxmould combines with the overlying beds to produce matrix-supported debris flows that pour over the underlying Triassic and Jurassic rocks. Within the NNR, the larger of these contain intact masses of relatively undisturbed Upper Greensand and Chalk that have been transported tens to hundreds of metres. The Upper Greensand and Chalk form vertical and near-vertical cliffs in the back scarps of the landslides and on the south faces of some of the detached masses in the landslides. These are prone to relatively common, shallow-seated rock-block failures (*c.* 1 per 5 years in the past 20 years) of the weathered faces and rarer (none in the last 20 years) toppling failures. The overlying Clay-with-flints and Head deposits, loose clay, sand and gravel up to 15 m thick in solution pockets in the Chalk, are prone to collapse when saturated.

Landslide classification

In many countries, particularly those with a high topographical relief and a seasonally high rainfall, landslides pose a serious threat to life and public services. Sassa (1999) recorded a landslide at Unzen, Japan in 1792 that killed 15,000 people, and a landslide in the Philippines in 2006 killed an estimated 1,800 people. It is not surprising, therefore, that these phenomena have been extensively studied world-wide and that they have given rise to an ever-expanding and increasingly complicated number of failure mechanisms and names to describe them.

Currently, the most widely used landslide classifications are those of Varnes (1978) and a modified versions by Cruden and Varnes (1996) and Cruden and VanDine (2013) in which the materials involved are classified as *rock* and *soil* (divided into, *debris* and *earth*). Rock is defined as "*a hard or firm mass that was intact and in its natural place before the initiation of movement*". Debris and earth are coarse and fine-grained variants respectively of "*an aggregate of solid particles generally of minerals and rocks which has either been transported or formed by the weathering of rock in place*". Hard and firm have not been defined, and rock and soil do not mean rock and soil in the currently defined geotechnical sense. Using this classification, materials in the NNR as disparate as the detached masses of intact Cretaceous rocks at Goat Island, Culverhole Point and Chapel Rock (see below) and heterogeneous landslide deposits are debris. In addition to the above, debris includes a wide range of *in situ* and *ex situ* materials including unlithified primary materials such as Clay-with-flints and weakly consolidated glacial tills, and accumulations of weathered material. Earth includes man-made deposits such as those in embankments, waste tips and earth dams. Alternative descriptions of these materials that are currently in use include *bedrock, engineering soil (coarse)* and *engineering soil (fine)* (United States Geological Survey, 2004) and *rock, soil, artificial fill and combinations of these materials* (World Landslide Forum, 2014). In a proposed revision of the Varnes (1978) classification Hungr *et al*. (2014) have suggested that materials should be grouped into *sorted* (gravel, silt, sand) and *unsorted* (rock, earth, mud, peat).

In the Cruden and Varnes (1996) classification the types of material are combined with landslide mechanisms that include *falls, slides, flows* and *complex* combinations of these. The following descriptions (simplified here) of landslide mechanisms, which are common to most classifications, is as follows. *Falls* are the detachment of material from a steep slope along a surface on which little or no shear displacement takes place: the material descends by falling, bouncing, or rolling. *Slides* are the downslope movement of a soil or rock mass on a rupture surface or on a relatively thin zone of intense shear strain (i.e. a failure surface). Slides are divided into rotational (curved) and translational (planar or undulating) based on the shape of the basal failure surface. *Flows* involve pulsed movements in which the displaced mass behaves as a viscous or thixotropic fluid in which the distribution of velocities varies vertically and laterally. In mountainous areas rock avalanches have been described as rock flows and/or debris flows. There and elsewhere, flows are mostly composed of the weathering products of rocks in the form of clay, sand and rock fragments, singly or in combination. *Complex* landslides are defined as those that involve more than one of the above processes.

The Varnes (1978) classification and its variants have proved to be useful worldwide in enabling common terms to be applied to different types of landslide that has allowed comparable national and international databases to be built up. However, none of the current classifications can be applied to the analysis of landslides in the NNR in such a way that they contribute to the understanding of the mechanisms or the development of a methodology for risk assessment. This is because the classification does not differentiate between *in situ* and *ex situ* materials, and unweathered, partially weathered and deeply weathered materials. As a result, all the major landslides in the NNR can be classified as 'complex rock landslides'. In the present account, the principal interest is focussed on the conditions present at the time of the initial failure based on an understanding of the principal factors that contributed to the failure. These include an understanding of the underlying geological succession, structure and weathering profile. This is in accord with the suggestion by Hungr *et al.* (2014) that landslide classifications should be flexible and should focus on the particular mechanism(s) that is (are) of particular interest to the locality being described. It contrasts with that of many published descriptions of landslides which place too much emphasis on the post-landslide geomorphology and materials and not enough on the pre-landslide conditions to enable the mechanism to be understood.

Summary of landslide mechanisms in the NNR

The landslides in the NNR can be divided into three types, primary, secondary and tertiary, on the basis of the materials involved immediately prior to the landslide. This classification can be combined with the type of landslide (fall, slide, etc.) in combination with a knowledge of the geology to identify the position of the initial failure that set the landslide in motion and to determine the probable mechanism(s) involved. The same classification can be applied to similar landslides in Triassic to Quaternary rocks exposed elsewhere on the south coast of England.

Primary landslides are defined here as failures in previously undisturbed strata. They include rotational and translational failures in *in situ* weak or weathered rocks and engineering soils, and rock-block and toppling failures in fractured rocks. *Secondary* landslides are those in all types of material that are no longer *in situ* as a result of earlier landslides and include rock falls, rotational and translational failures, and debris flows that form part of the degradation process of rock faces and steep slopes that have resulted from primary failures. *Tertiary* landslides comprise mud/sand/debris flows and rock falls, mostly during and shortly after prolonged periods of wet weather, that involve mechanically and/or chemically weathered materials within existing landslide complexes, and in the back scarps of the landslides.

All the landslides in the NNR can be assigned to one of these groups. In those cases where a combination of secondary and tertiary mechanisms is involved, the dominant process is used in the descriptions of the individual landslides. All the larger primary landslides in the NNR are translational failures that have involved tens of thousands to millions of tonnes of material. The failure surfaces have all been at or close to the base of the Cretaceous succession: in weak mudstones in the Gault in the eastern part of the NNR (Humble Point to Devonshire Head) and in thin (mostly <0.1 m thick) beds of similar mudstone in the lowest part of the Upper Greensand in the western part of the reserve. The mineralogy of the mudstones, the geological structure (seaward dip), the presence of E-W trending fractures, and prolonged high rainfall that gives rise to high pore-water pressures have all been critical factors that have affected the initiation of this type of landslide. The most recent examples in the NNR are the Bindon (1839) and Dowlands (1840) landslides.

The landslides in the NNR fall into four broad groups on the basis of size. When considered in combination with the pre-failure state of the materials involved they can be used to estimate the frequency of occurrence of the various landslide types (Table 2). The sizes are inevitably rough estimates in almost all cases because there is no published description made at or shortly after a landslide in the NNR that includes an estimate of the dimensions and/or weight of the debris involved. Estimates of the volume of material have commonly been made months or years after the event when much of the debris may have been removed by erosion.

There has been no very-large-scale failure in the NNR or on the adjacent coasts since 1840, and there is no record of any earlier failure that is detailed enough to ascertain whether or not it was of similar size or origin. It is not possible, therefore, to estimate the frequency with which these large primary events occur. The only published records of landslides of comparable size on the Devon and Dorset coasts that involved similar Cretaceous successions and failure mechanisms were those at The Hooken in 1790 (Mortimore *et al.*, 2001) and White Nothe in 1880 (Damon, 1884). The most recent (2001) failure in the upper part of the Black Ven landslide complex (Gallois, 2008) and that at Salcombe Regis in 2006 (Gallois, 2007) involved the same type of failure in Cretaceous rocks, but on a smaller scale.

Details of individual landslides

Haven Landslide complex

The Haven Landslide complex is the most recently active of the NNR landslides, but is the least well documented. Arber (1940) suggested that the Haven Landslide was a relatively recent event, and there is evidence to support this interpretation. A geological sketch section of the cliffs between the River Axe and Lyme Regis made by De la Beche in 1818-19 (published 1822) shows continuous 'Under Cliffs' (=landslides) between Devonshire Head and Culverhole Foreshore, but none westwards from there. Comparison of the positions of the top of the sea cliff and the inland limit of the landslides on a detailed (Six Inches to One Mile scale) pre-1835 tithe map with the earliest available aerial photographs, taken by the RAF in 1947, and modern 1:10,000-scale Ordnance Survey maps suggests that Haven Cliff was an upper sea cliff separated from a lower sea cliff by a relatively narrow terrace of collapsed debris or scree material. Eastwards from there, much of the ground now occupied by the landslide complex consisted of unbroken slopes. This interpretation is supported by a painting of the coast made shortly after the 1839 Bindon Landslide (Figure 3a) that appears to show an Upper Greensand outcrop cloaked by a veneer of either Head and/or shallow-seated landslide deposits. Comparison of the earliest 1:2,500-scale Ordnance Survey map (1895) with the pre-1835 map and a photograph of the eastern end of the cliffs taken by H.T. Wood in 1896 (British Association for the Advancement of Science No. 01243) confirms the presence of these vegetated slopes.

At some time prior to 1914, a mass of Upper Greensand and Chalk up to *c.* 150 m long became detached from the western end of Haven Cliff (Figure 4a) and subsided up to 15 m. This is presumed to have been a primary translational failure in a thin mudstone close above the base of the Upper Greensand (Figure 5a) along one or more joints running parallel to the cliff face. This was followed by major falls in the same area and eastwards from there in the early 1930s, at least one of which was the secondary collapse of the detached mass which gave rise to the rugged topography known locally as the Elephants' Graveyard (Figure 3c). The Ordnance Survey 1:2,500 scale map of 1931 shows *c.* 600 m of the outcrop of the Mercia Mudstone in Haven Sea Cliff obscured by landslide debris. The Geological Survey Photographer was despatched to the site in 1934 and produced a series of pictures that show large areas of relatively fresh debris covering the slopes between Haven Cliff and the sea cliff (Figure 4d). Arber (1940) noted that at the eastern end of Haven Cliff "*great masses of Upper Greensand and Chalk have fallen on to the shore and become banked up against the cliff*". Given the speed at which such debris is removed by the sea, this must have been a relatively recent event at the time of her writing (1938). The most recent documented events have been at the eastern end of the complex where Grainger (2000-2005) recorded the formation of a new back scar at some time between 1957 and 1962. An additional landslide scar was formed inland of the first in 2001 following what was at that time the second wettest year since records began (Table 1). This now forms the inland edge of the Undercliffs over a distance of *c.* 200 m in which the strata on its seaward side have subsided by up to 2.5 m (Figure 4e). A geological section through the eastern part of the complex is shown in Figure 5a. There is no visible seaward dip in the Upper Greensand and Chalk in Haven Cliff that might explain the estimated difference in the height of *c.* 13 m in the estimated positions of the basal Cretaceous unconformity below Haven Cliff and at the top of Haven Sea Cliff. The difference is therefore presumed to be due to faulting.

tonnes	**Small** up to *c.* 100	**Medium** *c.* 100 to 5,000	**Large** *c.* 5,000 to 15,000	**Very Large** *c.* 15,000 to >100,000
Primary*	>10 *p.ann.*	up to 5 *p.dec.*	1 *p.dec.* to *p.c.*	<1 *p.c.*
Secondary	>10 *p.ann.*	1 or 2 *p.dec.*	none recorded	none recorded
Tertiary	>10 *p.ann.*	1 or 2 *p.dec.*	<1 *p.dec.*	none recorded

Table 2. *Classification of the landslide types present in the NNR based on size and the pre-landslide state of the materials involved. Estimated frequencies of occurrence (p.c. = per century) based on historical records; (p.ann. = per annum, p.dec. = per decade) based on occurrences between 1990 and 2014. *Excludes frequent (100s per annum) small rock falls <1 tonne.*

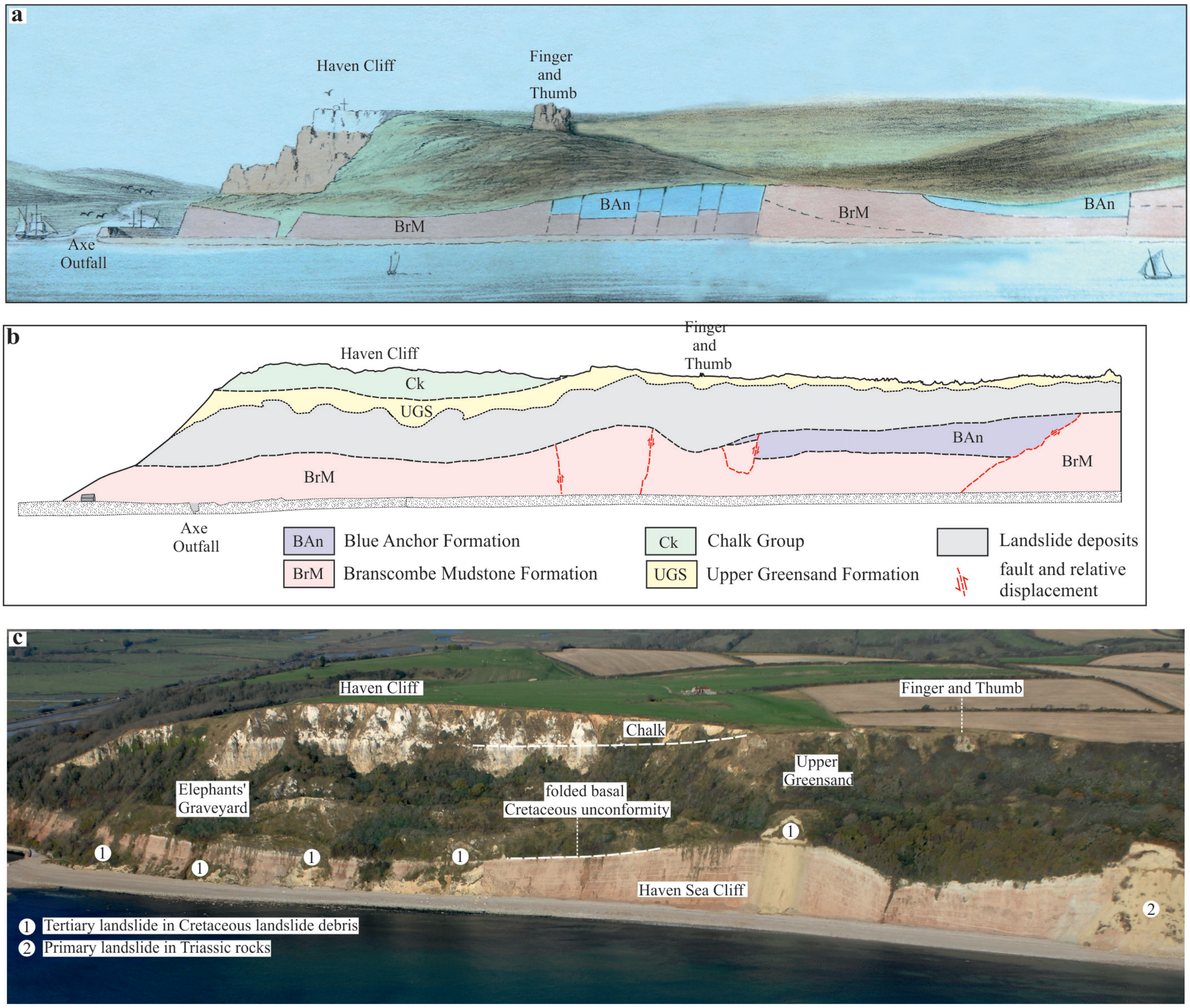

Figure 3. *(**a**) Haven Cliff viewed obliquely from the sea in 1840. Part of Plate II of Conybeare et al. (1840) distorted to match the geological section. Almost all the ground between Haven Cliff and the western end of the Bindon Landslide consists of what appear to be undisturbed slopes. (**b**) Geological sketch map of the area shown in (**a**). (**c**) Oblique air photograph of most of the same area, view N, taken by Paul Witney, BGS in February, 2008. Reproduced with the permission of the British Geological Survey, copyright NERC.*

Bindon Landslide complex

The NNR includes one of the most famous landslides in Britain, the Bindon Landslide of 25-26 December 1839 in which a detached mass of Cretaceous rocks slid seaward and pushed rock and debris from earlier landslides into the sea. A detailed description of the geology and the suggested mechanism of the landslide were published within a few weeks of the event (Conybeare *et al.*, 1840). When comparing the mechanism of the landslide with that of other large landslides on the south coast (Isle of Portland, Isle of Wight, Folkestone, etc.), Conybeare (in Conybeare *et al.*, 1840) concluded that during periods of unusually high rainfall a shear failure occurred close to the base of the Cretaceous succession and that this caused the saturated Foxmould to become liquefied. The mass of Upper Greensand and Chalk which now forms Goat Island became detached from the cliffs and slid forward. Pitts and Brunsden (1987) subsequently concluded that the mechanism proposed by Conybeare placed too much emphasis on the liquefaction of the Foxmould and that the failure surface was in the Westbury Mudstone. Gallois (2010) confirmed that the Conybeare *et al.* (1840) interpretation was essentially geologically correct and that the failure surface was close above the base of the Foxmould. Geological sections through the eastern and central parts of the complex are shown in Figures 5b and c.

Conybeare *et al.* (1840) noted that an estimated seaward dip of *c.* 3° in the Cretaceous rocks, based on the difference in height of the basal Cretaceous unconformity between its estimated position in the cliffs and that at outcrop at Culverhole foreshore, was an important factor in initiating the 1839 landslide. However, the base of the Chalk in the cliff and 500 m N where it crops out around South Combe [SY 276 905] is at *c.* 85 m above Ordnance Datum. The southerly dip in the Cretaceous rocks may therefore be confined to the area south of the cliffs.

Comparison with the mechanisms by which masses of Cretaceous rocks became detached from the cliffs at Haven Cliff (Figure 4a) and Pinhay Cliff (see below) suggests that the gap between Goat Island and the *in situ* cliff opened up along an E-W trending fracture zone as a result of a translational failure close to the base of the Cretaceous rocks. Pitts (1974) referred to an unpublished report which suggested that the initial fracture might have formed along the line of a fault. There is no published field evidence to support this suggestion, but several E-W trending faults pass beneath the landslides in this part of the NNR (Gallois, 2010, figure 9), and the Chasm is

Figure 4. *(**a**) View E of the western end of Haven Cliff showing the 'cleft' that separated a detached mass of Upper Greensand and Chalk from the in situ cliff. Photographed by T.W. Reader in 1914, British Geological Survey (BGS) No. P252446, copyright NERC. (**b**) Tension crack (arrowed) in Upper Greensand and Holywell Nodular Chalk, western end of Haven Cliff [SY 2585 8983] in 2012, view E. The crest of the cliff A is that shown in (**a**). The crack does not penetrate the partially decalcified chalk at the top of the sections which acts as a weakly consolidated soil. (**c**) Detached pillar of in situ Upper Greensand and Chalk, c. 15 m high, Dowlands Cliff [SY 2846 8961]. (**d**) Haven Cliff photographed by Frank Rhodes in 1934 shortly after a large rock fall in the Upper Greensand and Chalk. View W towards Seaton. The detached mass shown in (**a**) may have collapsed at this time. Reproduced with the permission of BGS, copyright NERC. (**e**) Subsidence of the Coastal Path at the eastern end of the Haven Landslide complex [SY 2663 8973] in the unusually wet winter of 2000-2001. View W from 50 m W of the western entrance to the NNR. (**f**) Back tilted masses of Upper Greensand and Chalk at the seaward edge of the Dowlands Landslide complex [SY 2878 8945] that may have secondarily moved along failure surfaces in seaward dipping Shales-with-Beef. In situ limestone beds in the basal part of the Shales-with-Beef (foreground) are within an E-W trending fault zone. View E from the eastern end of The Slabs. (**g**) View W across Charton Bay from the apron of Upper Greensand blocks at Humble Point towards The Plateau, a large detached mass of Cretaceous rocks in the Dowlands Landslide complex.*

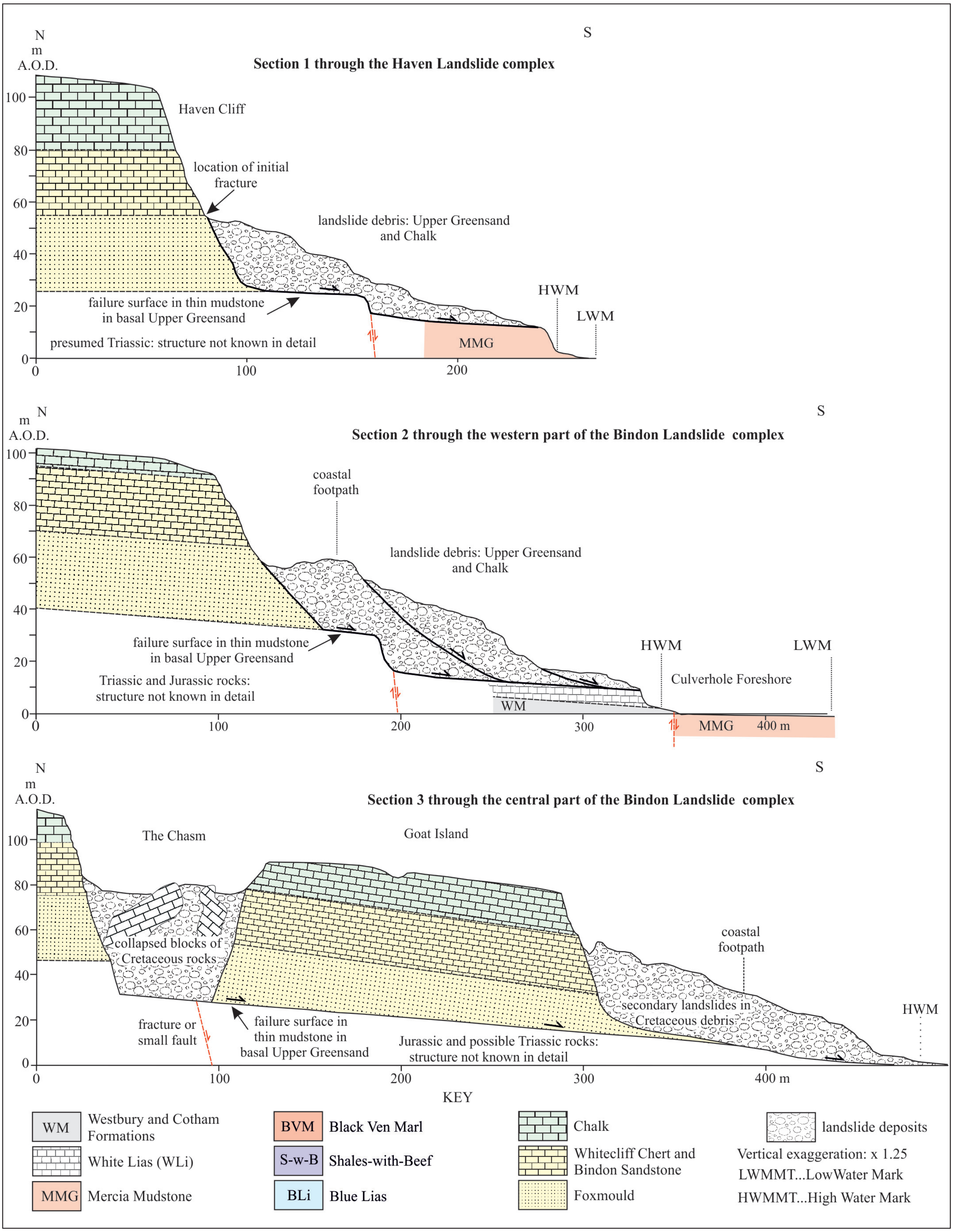

Figure 5. *Geological sketch sections along selected traverses in the Haven and Bindon Landslide complexes. Section 3 after Gallois (2010). See Figure 1 for lines of sections.*

roughly aligned with a dry valley (Figure 1). Goat Island differs from the other examples of this type of failure in the NNR in that the movement continued over a period of two days during which time the detached mass became separated from the cliff by up to 100 m, parts of the north face of the 'island' collapsed into The Chasm, and additional masses became detached from the cliff to form back-tilted blocks and pillars within The Chasm.

The second most prominent feature in the Bindon Landslide complex after Goat Island is a detached mass of Upper Greensand and Chalk at and adjacent to Culverhole Point in which beds ranging from the Foxmould to the New Pit Chalk Formation have retained their stratigraphical integrity. A westerly dip suggests that the mass was rotated sinistrally when it was pushed forward during the 1839 landslide. When allowance is made for the pillars of Cretaceous rocks that collapsed within a few weeks of the 1839 landslide (Conybeare *et al.*, 1840, plates VII and VIII) the mass was probably as long as Goat Island (*c.* 350 m) and at least 50 m thick. Along much of its length the foot of the south face is within the intertidal zone and subject to marine erosion. This washes away the more weathered parts of the Foxmould and contributes to rock falls in the stronger upper part of the Upper Greensand and in the Chalk, mostly by hydraulically opening up the joints and bedding discontinuities.

Small and medium sized landslides in the complex in the past 15 years have included the collapse of a 1 to 2 m thick layer of Chalk in part of the south face [SY 276 894] of Goat Island. The debris fell into a 15 m deep 'chasm' at the foot of the cliff. Shallow-seated tertiary landslides in weathered landslide debris between Goat Island and Culverhole Point that were initiated during a period of unusually high rainfall in January 2012 have continued to move sporadically and have breached *c.* 100 m of the coastal path.

Dowlands Landslide complex

The western boundary of the complex is overlapped by the debris from the 1839 Bindon Landslide. The most prominent feature in the complex is a large, fractured but otherwise intact mass of Upper Greensand and Chalk *c.* 600 m long, up to 150 m wide and originally at least 70 m thick on the basis of the stratigraphical succession preserved within it that forms the Plateau and Dowlands Sea Cliff (Figure 4g). When compared with the south faces of Goat Island and the detached Cretaceous mass at Culverhole Point, that part of Dowlands Sea Cliff which is above the level of active marine erosion is more deeply weathered. This suggests that it is an older feature, which is in accord with the absence of any record of a major landslide within the Dowlands Landslide complex in the past 200 years. A painting made in 1784 by Copplestone Bampfyld (reproduced in Campbell, 2006) shows Dowlands Cliffs fronted by what appears to be undercliffs with, at their seaward edge, a cliff in much the same position as the present-day Cretaceous mass that forms the eastern part of Dowlands Sea Cliff. Dawson's paintings of the pre- and post-1839 topography at the junction of the Bindon and Dowlands complexes (in Conybeare *et al.*, 1840) show the western part of the Dowlands Landslide unchanged.

The most recent large movement in the complex was at the eastern end of Dowlands Cliffs in the unusually wet period of 2000-2001 when part of the Chalk face collapsed to produce a debris cone that reached as far as the Coastal Path. At the seaward edge of the complex, a back tilted mass of Upper Greensand and Chalk which may have originally been part of the Plateau mass, appears to have experienced secondary movements along one or more failure surfaces in the Shales-with-Beef (Figure 4f). However, the detached mass overlies and is fronted by a complex E-W trending fault belt. In the intertidal area, steeply dipping Foxmould resting unconformably on Shales-with-Beef is patchily exposed beneath an extensive cover of beach boulders. Many of the exposures contain or are separated by fractures that may be tectonic in origin, landslide shear planes, or a combination of the two.

Whitlands Landslide complex

At its western end, the landslide complex is separated from the Dowlands Landslide complex by Rousdon Goyle. There, Cretaceous landslide debris rests on *in situ* Blue Lias that crops out along parts of the former cart track that ran from Rousdon to Humble Point (Figures 6b and 9a). Beneath this, the Blue Lias outcrop is separated from the outcrop of the Blue Anchor Formation in Charton Sea Cliff by a narrow zone of disturbed White Lias and Cotham Formation that are founded on shallow-seated (1 to 3 m deep) failure surfaces in weathered Westbury Mudstone (Figure 6b). A back-tilted block of White Lias limestone (Figure 9b) within these landslides was likened by Arber (1940) to the rock face on the south side of Goat Island and incorrectly assumed to be part of one of the much larger landslides in the Cretaceous rocks.

The principal movements in the Whitlands Landslide for which there are records appear to have occurred in the central part of the complex. According to Roberts (1840) there was extensive subsidence in 1765 following the "*memorable wet season of 1764*". A similar wet period in 1839 continued until 10 February 1840 towards the end of which more subsidence occurred at Whitlands on the 3 February 1840. A new face of Chalk a quarter mile long and up to 18 m (60 ft high) was formed, the lower part of the Undercliffs moved forward, and cottages were damaged. Humble Point was forced so far out into the sea that it became visible from The Cobb at Lyme Regis (Arber, 1940). A double reef more than half a mile long composed of shingle, Cowstones and Chalk derived from earlier landslides that had been pushed forward, was formed in the subtidal area. Observers who walked on the reef saw "*semi-fluid Foxmould being squirted up through rifts in harder rocks*" (Arber, 1940 based on contemporary accounts).

Conybeare (in Conybeare *et al.*, 1840) concluded that the mechanism was the same as for the 1839 Bindon Landslide, namely a shear failure in the lowest part of the Cretaceous succession that caused liquefaction of the Foxmould and the collapse of the overlying beds. The presence of softened dark grey clay that is lithologically distinctively different from the Lias mudstones on the foreshore at Humble Point [SY 306 899], confirms that the landslide was initiated by a failure in Gault mudstone. The most recent large movement for which there is a record is that in 1961 when "*Lias Clay* [almost certainly Gault] *squeezed under the foreshore for 500 m east of Humble Point…and the beach was pushed up by some 4-5 metres*" (Campbell, 2006).

Pinhay Landslide complex

The landslide complex is bounded by the valleys that run down from Whitlands and Pinhay. To the west, the lower landslide ridges of the 1840 Whitlands Landslide overlap onto or have pushed aside the older landslides at the seaward edge of the Pinhay complex. The Chalk succession exposed in Pinhay Cliffs is the thickest and most complete preserved in the NNR, and this has had a marked effect on the nature of the landslides and the topography of this part of the Undercliffs. The thickness of the stable Chalk and post-Foxmould Upper Greensand is such that repeated shear failures at the base of the Cretaceous succession have resulted in large rock masses, up to 300 m long and 100 m thick, becoming detached from the cliffs and remaining more or less intact when they moved downslope. A view of the area from the sea by Conybeare (in Conybeare *et al.*, 1840, plate II) suggests that the 'steps' of Cretaceous rocks between Pinhay Cliffs and the sea were already in place and extensively vegetated at the time when he painted them (Figure 7).

The Great Cleft (Rowe, 1903, plate II, reproduced in Campbell, 2006) at the western end of Pinhay Cliffs opened in 1886 along a major joint or a fracture zone, and a mass of

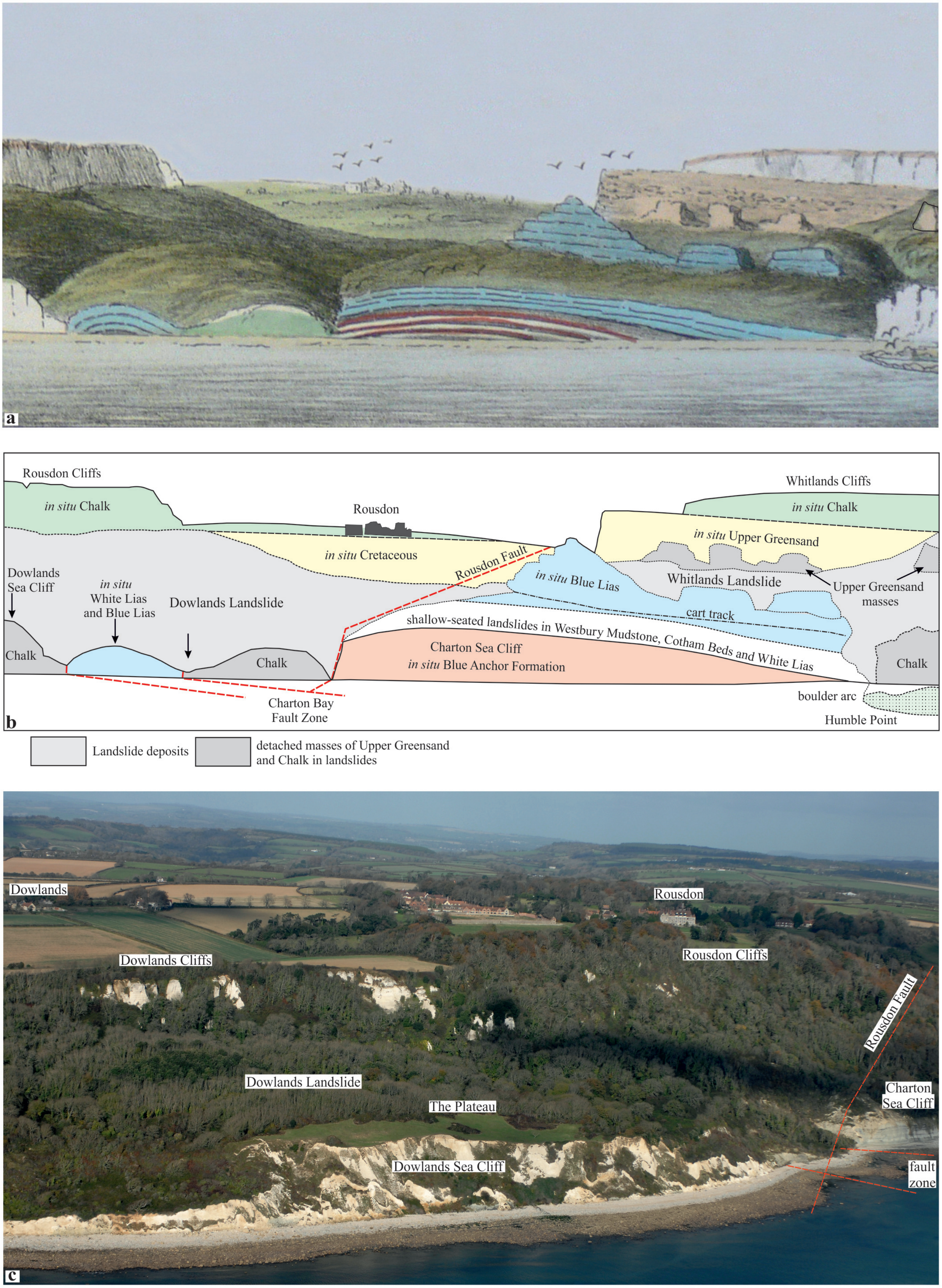

Figure 6. *(**a**) Charton Bay viewed from the sea in 1840 (part of Plate II of Conybeare et al. (1840)). (**b**) Geological interpretation of (**a**). (**c**) Oblique air photograph of eastern part of the Dowlands Landslide complex taken by Paul Witney, BGS in February, 2008. Reproduced with the permission of BGS, copyright NERC.*

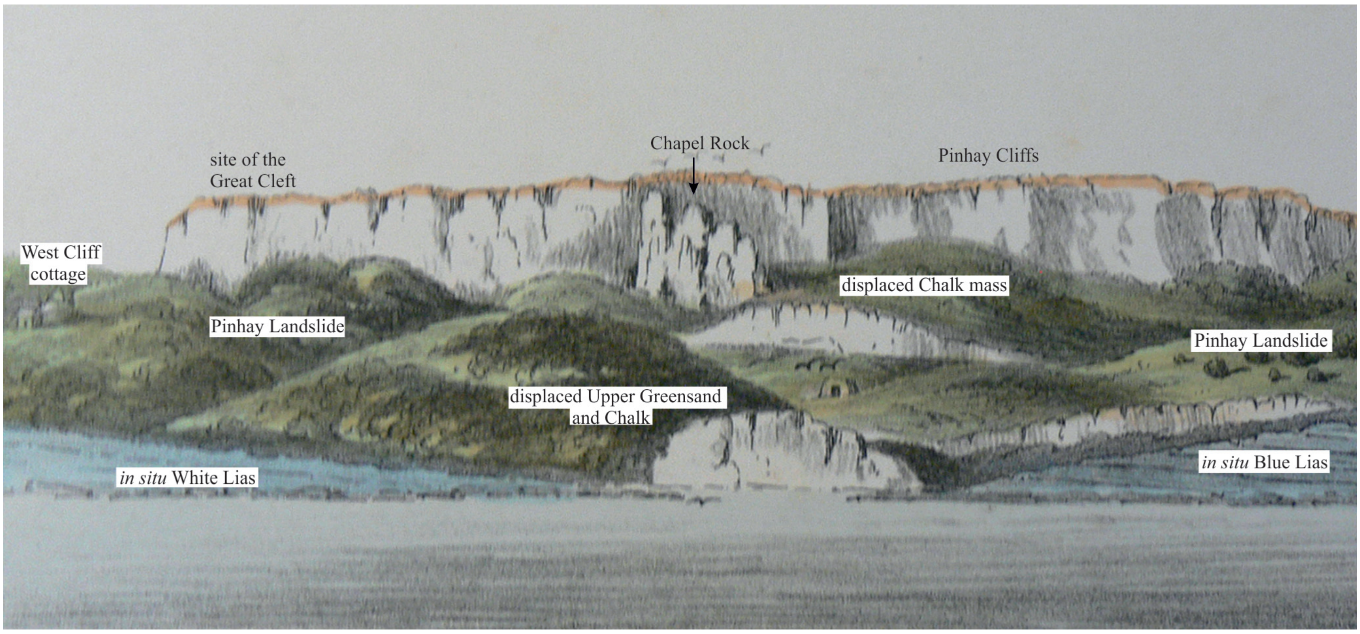

Figure 7. *Humble Point and Chapel Rock viewed from the sea in 1840 by Wm Conybeare (part of Plate II in Conybeare et al. (1840)).*

Cretaceous rocks up to 80 m long slid forward. The crack became steadily wider and enabled Rowe (1903) to examine the geological succession in what had previously been an inaccessible cliff face. The detached mass collapsed in *c.* 1910. Chapel Rock, one of the most distinctive landforms in the NNR, is a similar joint-bounded mass of Cretaceous rocks that has moved forward and subsided. It reputedly takes its name from its clandestine use by Protestant worshippers during the reign of Mary Tudor (1553-1558) (Woodward and Ussher, 1911). Comparison of the succession exposed in the adjacent cliff and in Chapel Rock show that the mass has moved forward *c.* 20 m and has subsided *c.* 25 m. The failure mechanism for the Great Cleft and Chapel Rock are presumed to be similar to those at Haven Cliff and Goat Island where the forward movement was initiated by a translational failure in mudstone close to the base of the Cretaceous succession, and the subsidence by the loss of liquefied Foxmould Sand in the lower part of the succession.

There is no published description of a major failure in the Pinhay complex comparable to those of the 1839 Bindon Landslide and 1840 Dowlands Landslide, but there are records of a large number of small- to medium-sized movements for nearly 200 years. The earliest geological description of a landslide and its mechanism in the NNR is that by De la Beche (1830) who drew a geological section through a large collapse in the Chapel Rock area "*four days after the catastrophe*". In the accompanying explanation he described the Cretaceous succession as "*chalk and green sand, both porous rocks through which the water percolates to the clay bed composed of the lower part of the green sand*". The name Gault, which was not in wide use at that time, later came to be applied to the basal clay which De la Beche had shown to rest unconformably on Lias mudstones. He envisaged that water percolated down through the porous beds, was held up by the clay and then moved sideways to emerge as springs, softening the clay as it did so. This caused the higher beds to become undermined and collapse. This explanation is similar to that of Conybeare *et al.* (1840) for the 1839 Bindon Landslide. In both cases the authors recognised that the landslides were confined to Cretaceous strata.

Small failures in the Pinhay Landslide complex include the frequent flows of mud-sand mixtures derived from the Lias and Upper Greensand in the area around the former Pinhay Pumping Station (Figure 9a). Similar small movements have occurred in all the landslide complexes in the NNR. Those in the Pinhay complex have been better documented because springs that emerge from displaced Cretaceous rocks in the lower part of the Undercliffs were the principal water supply for Lyme Regis from 1935 until 2001. The electricity supply and water pipes to the pumping station were frequently disrupted by small landslides and the facility was abandoned in 2001 following a succession of movements during the unusually wet autumn and winter of 2000-2001 (Campbell, 2006). Detailed accounts of the movements and an interpretation of the landslide mechanism were given by Grainger *et al.* (1986) who concurred with earlier conclusions that all the major landslides had been initiated by failures in the Gault. A typical cross section through the complex is shown in Figure 8b. A similar section through an adjacent part of the complex is given in Grainger *et al.* (1986, figure 3). As with all the other landslide complexes in the NNR, the geological succession and structure beneath the landslide complex is not known.

Ware Landslide complex

In reviews of the movements in the Ware Landslide complex Arber (1940, 1973) and Pitts (1981a) noted that there had been minor failures that had damaged a cottage, part of Underhill Farm and the Coastal Path between 1969 and 1981. The most recent failures were in loose Clay-with-flints (Figure 9a) and the underlying deeply weathered Chalk at the western end of Ware Cliffs in 2000-2001, a similar failure in the outer, deeply weathered part of the Upper Greensand in the middle part of Ware Cliffs in 2013, and tertiary failures in weathered Charmouth Mudstone and Head Deposits near Underhill Farm in 2000-2001 and 2012-2013. Much of the Undercliffs between Ware Cliffs and the coastline are underlain by Jurassic mudstones that give rise to mudflows during prolonged periods of wet weather (Figure 9c). These are shallow-seated and confined to the more deeply weathered mudstones that crop out between Grey Ledge at the top of the Blue Lias and the Birchi Tabular Stone Band at the top of the Shales-with-Beef. The larger of these mudflows and part of the underlying weakened mudstones occasionally overtop the cliffs of Blue Lias and Shales-with-Beef adjacent to Devonshire Head. Unusually large (>10,000 tonnes) landslides of this type occurred after prolonged periods of heavy rain in July 2012 and January 2013 and caused the temporary closure of the beach. Relatively small (mostly tens of tonnes) joint-bedding-bounded rock falls occur from time to time in the Blue Lias cliffs in Pinhay Bay and below Devonshire Head.

The Jurassic rocks in this area have a low seaward dip, but no major bedding-plane failure in the Shales-with-Beef of the

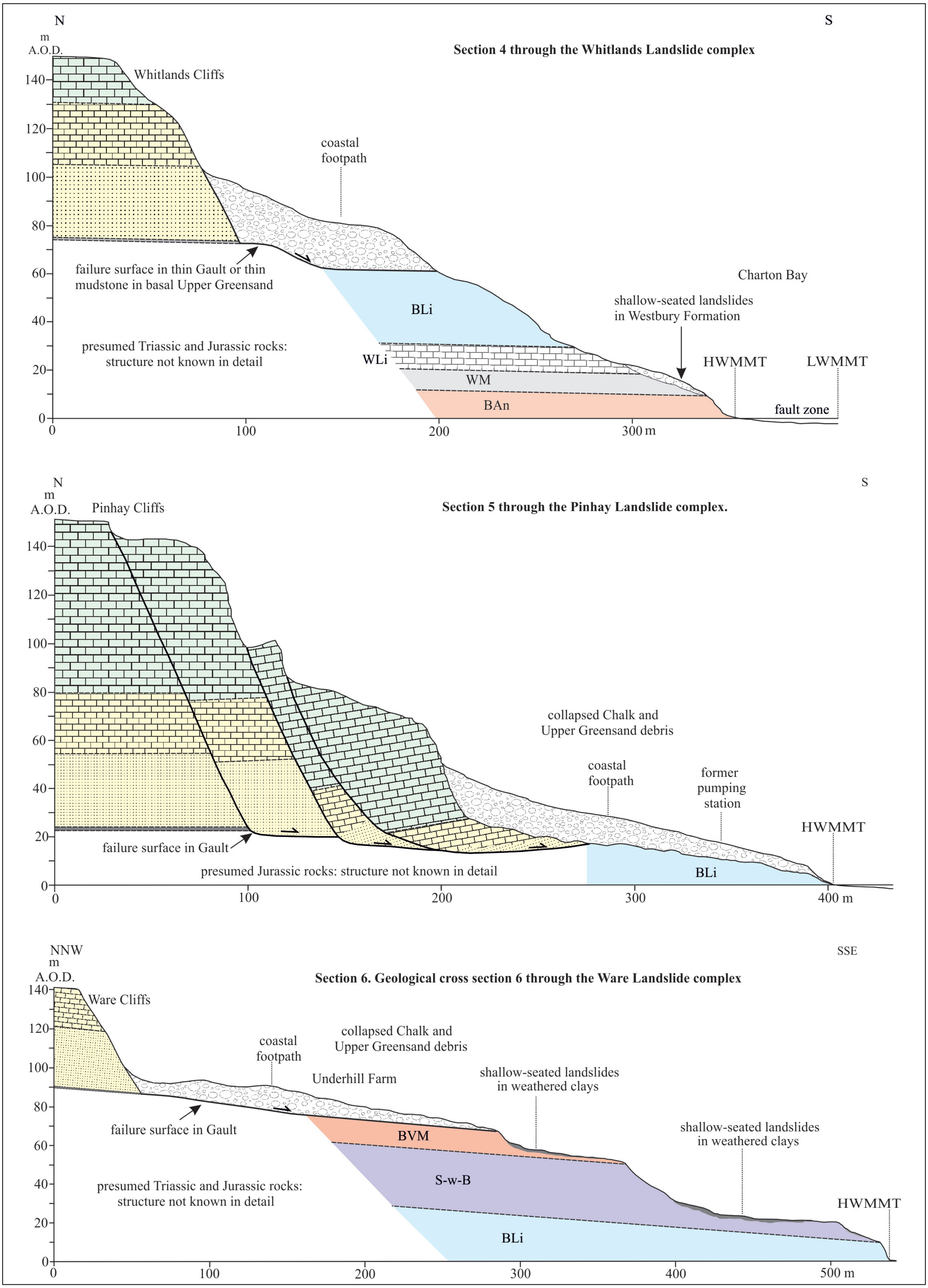

Figure 8. *Geological sketch sections along selected traverses in the Whitlands, Pinhay and Ware Landslide complexes. See Figure 1 for lines of sections.*

Figure 9. *(**a**) Rousdon cart road [SY 2998 9020] cut in undisturbed Blue Lias. The unconformity at the base of the Cretaceous is probably marked by the seepage line at the top of the cutting. Photographed by S. H. Reynolds in 1912; BGS No. P238889, copyright NERC. (**b**) Intact block of back tilted White Lias [SY 2997 9014] which has moved downslope c. 1-2 m as the result of shallow-seated landslides in the underlying Westbury Mudstone. Western end on the Whitlands Landslide above Charton Bay. (**c**) Chapel Rock [SY 3117 9063], a detached mass of Chalk that separated from Pinhay Cliffs at some time prior to the mid 16th Century. Photographed by T.W. Reader in 1914, BGS P252433, copyright NERC. (**d**) View NE across the Blue Lias beach outcrop at the seaward edge of the Pinhay Landslide complex towards the active landslides in Cretaceous debris below the former Pinhay Pumping Station, October 2009. Large movements during unusually wet weather in 2001 over-rode a low cliff in Blue Lias and covered the upper part of the intertidal area. (**e**) View W of shallow-seated, collapse of Clay-with-flints debris at the western end of Ware Cliffs [SY 3203 9120]. (**f**) Oblique air photograph, view across Pinhay Bay and the Ware Landslide complex taken by Paul Witney, BGS in February, 2008. Reproduced with the permission of BGS, copyright NERC.*

type described by Jukes-Browne (1908) and Gallois (2009) at the Spittles (east of Lyme Regis) has been recorded in the Devonshire Head area. However, De la Beche (1822) recorded blocks of Chalk seven miles south of Lyme Regis in water depths of *c.* 15 m, and presumed these to be debris from old landslides from a time when the coast lay in that area. This observation has not been confirmed by offshore surveys (Hamblin *et al.*, 1992), but there is an extensive area of landslide debris beneath the sea floor 400 to 800 m south of the present-day low water mark. This has been interpreted as the result of bedding-plane failures in the Shales-with-Beef at a time when the member cropped out at the foot of a former sea cliff (Gallois, 2011).

SUMMARY AND CONCLUSIONS

The Axmouth to Lyme Regis Undercliffs National Nature Reserve includes some of the largest active overlapping and coalescing landslides of their type in Europe. Taken together they include examples of all the more common type of landslide ranging from rock falls in Triassic, Jurassic and Cretaceous in the cliffs to mud flows in deeply weathered clays derived from Jurassic mudstones. The most spectacular are infrequent (<1 per century) large translational failures that include detached masses of Cretaceous rocks of up to millions of tonnes which have been displaced seawards by up to 500 m. When regarded as an evolutionary whole, the various types of mass-movement deposit in the NNR can be divided into three broad categories based on the pre-failure state of the materials involved. Primary landslides occur in *in situ* largely unweathered materials, secondary landslides in relatively unweathered materials that have been displaced by earlier landslides, and tertiary landslides in deeply weathered *in situ* (e.g. mudstones that have weathered to clays) and *ex situ* (e.g. heterogeneous landslide debris) materials. The landslide mechanisms exhibited by the materials exposed in the NNR vary from simple, in the case of the smaller landslides, to complex in the case of the landslides that involve huge masses of foundered strata. They can be grouped into three broad types:

1) the collapse of relatively strong, fractured rocks; falls and toppling failures,
2) shear failures along bedding-planes, usually a mudstone layer: translational and rotational landslides, block slides, flow slides,
3) liquefaction or partial liquefaction of mechanically and/or chemically weathered materials: mud/sand/debris flows, sludges of heterogeneous mixtures of clay, sand and gravel/boulders.

All the larger landslides in the NNR for which there is sufficiently good field or historical evidence for the mechanism to be understood were initiated as primary translational failures in mudstones close above the base of the Cretaceous succession. Examples include the detachment of joint-bounded large relatively intact masses of Upper Greensand and Chalk at Haven Cliff (Figure 4a), Goat Island and Pinhay Cliffs (Figure 9c) and accompanying subsidence as the result of the loss of fluidised Foxmould Sand. In some examples the detached masses subsequently collapsed, as at Haven Cliff, in others they remained intact and slid forward, as at Goat Island and Chapel Rock. In the larger landslides on the east Devon coast, notably at The Hooken [SY 220 880], Bindon and Pinhay, blocks of competent Upper Greensand and Chalk up to 70 m thick have moved vertically and laterally without disrupting their bedding and sedimentary features by being supported within a mobile matrix of waterlogged sand and debris. One commonly reported factor in large-scale slow (creeping) landslides of the type that have occurred in the NNR is that their slip surfaces are in beds only 0.1 m to 0.2 m thick in which the strength behaviour is greatly affected by the expansive-clay-mineral (e.g. smectite/montmorillonite) content. In one set of laboratory tests, an increase in the smectite-chlorite ratio from 5% to 70% in weathered volcanic rocks resulted in a decrease in the residual angle of shearing resistance (ϕ_r) from >30° to <15° (Yatabe *et al.*, 2000).

Brunsden (1996) highlighted five factors that influence the formation of landslides in the Jurassic and Cretaceous rocks on the Dorset coast. These are the geological succession, geological structure, climate (mostly rainfall), sea-level rise, and Man's activities. The first three of these have been of fundamental importance to the development of the landslides in the NNR; the last two of much less importance.

Many of the larger landslide complexes in southern England were probably initiated in periglacial climates in the late Pleistocene when the region was subject to successive periods of freezing and thawing of a deep permafrost layer (Lee and Jones, 2004; Gallois, 2008). There is no recorded evidence of periglacial activity in the NNR except for drift-filled solution pipes in the Chalk in Ware Cliffs and elsewhere. All traces within the landslide complexes have been removed by later landslides or buried beneath them. Along parts of the south coast of England the Holocene rise in sea level of *c.* 30 m consequent on the retreat of the Pleistocene ice sheets, has been identified as a significant factor in the initiation of major landslides. At those localities where the sea is currently eroding potentially unstable cliffs, such as Barton-on-Sea (Fort *et al.*, 2000) and Folkestone Warren (Hutchinson, 2001), the removal of material from landslide toes has resulted in new failures. This process has not contributed to any large-scale failures in Haven, Charton and Ware Sea Cliffs which are formed of relatively strong *in situ* mudstones with limestone interbeds. In the intervening areas, marine erosion is continuously removing landslide debris from the toes of the Bindon, Dowlands and Whitlands and Pinhay landslide complexes and giving rise to renewed coastal and inland failures. The most prominent of these in recent years have been rock falls in the seaward-facing faces of the Culverhole and Whitlands detached Cretaceous masses. There is no published record of a landslide in the NNR that has been attributed to the influence of Man's activities. These have been limited to small amount of quarrying of the Upper Greensand and Chalk, and the construction of a few cottages, cart tracks and footpaths. Drainage into the Undercliffs from the adjacent farmland, much of which is sited on free-draining Chalk, has probably been minimal. This has been offset by the natural colonisation of the under cliffs by indigenous and imported (mostly via arboreta) vegetation during the past 150 years.

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