The failure mechanism of the 1839 Bindon Landslide, Devon, UK: almost right first time

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The Axmouth to Lyme Regis Undercliffs National Nature Reserve in east Devon includes the most famous mass-movement feature in Britain, the Bindon Landslide of Christmas Day 1839. Tens of millions of tonnes of rock, older landslide debris and beach deposits were pushed forward when a large mass of Cretaceous rocks became detached from the 120 m-high cliffs and slid seaward. Fissures appeared in the cliff top on the 23rd December and culminated in the main movement during the night of the 25-26th December. The event attracted large numbers of sightseers from all over southern England. Fortunately for geology, these included the pioneer geologists the reverends William Buckland and William Conybeare who lived in the area, and a local surveyor William Dawson. They, together with Buckland's artistically gifted wife Mary, produced detailed geological descriptions, plans, views and sections of the landslide within a few weeks of its occurrence. Their published account is commonly quoted as the first detailed description of the mechanism of a large landslide. Later authors have queried their conclusions, but none of these accounts paid such detailed attention to the role of the geology in the failure mechanism. Recent geological surveys have confirmed that the description by the Bucklands, Conybeare and Dawson is an outstanding example of observation and analysis, and that their interpretation of the mechanism, although incomplete, was superior to that of any subsequent account. Recently available aerial photographic and multibeam-sonar data has shown that an important factor missing from all previous interpretations are faults that run beneath and subparallel to the structures in the landslide.

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Introduction

The Axmouth to Lyme Regis Undercliffs National Nature Reserve (NNR) in east Devon comprises a complex of overlapping small (hundreds of tonnes) to large (millions of tonnes) landslides[1] that stretch for a distance of 10 kilometres to form a topographically diverse coastal strip 100 to 800 m wide (Figure 1). At its western end, the Bindon Landslide that commenced on 25th December 1839 was one of the more recent large movements within the reserve. The movements took place over a period of several days and attracted much local attention, one result of which is that there are contemporary accounts of the succession of events. The most detailed and comprehensive of these (Conybeare *et al.*, 1840) is that by the local pioneer geologists the reverends William Buckland and William Conybeare together with a local engineer/surveyor William Dawson and Buckland's artistically talented wife (Figure 2).

[1]Most of the large, complex mass-movement structures in Britain have traditionally been referred to as *landslips* (e.g. on BGS maps).

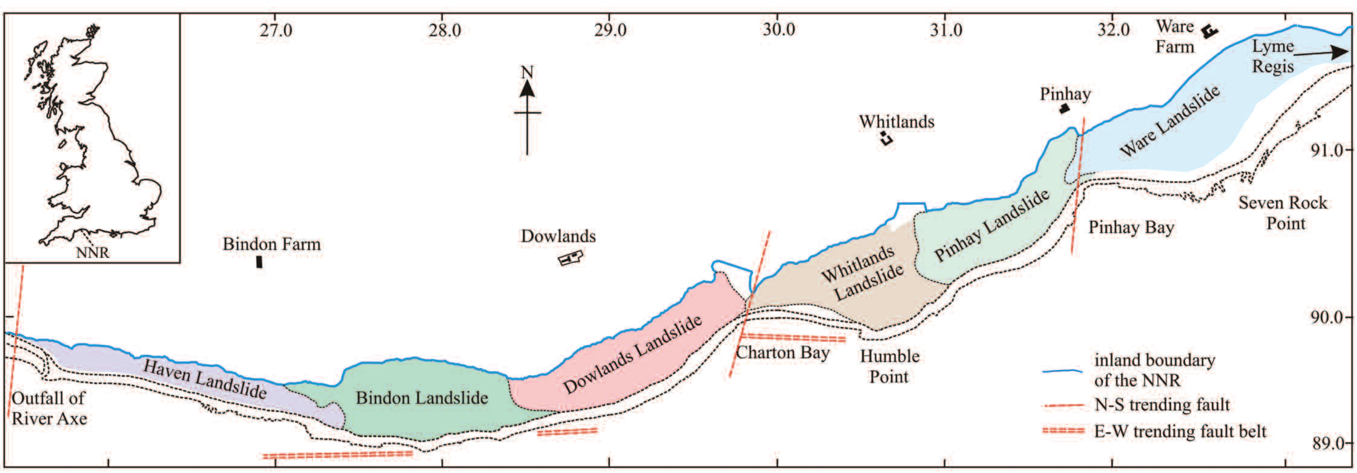

Figure 1. *Geographical sketch map of the Axmouth to Lyme Regis Undercliffs National Nature Reserve (NNR) showing the relationship of the Bindon Landslide complex to the other principal landslide complexes.*

Figure 2. *The Chasm and Goat Island, view west, drawn a few days after the landslide by Mrs Mary Buckland in December 1839 (Plate V in Conybeare et al., 1840).*

On December 23rd, fissures were noted in fields adjacent to the back face of a *c.* 300 m-wide landslide complex, which at that time separated farmed land from the sea. Deeper fissuring in the early hours of the 25th December resulted in the evacuation of two cottages, and culminated in the main movement during the night of the 25-26th December. An intact mass of Cretaceous rocks, Upper Greensand Formation overlain by Chalk Group, up to 150 x 500 m in area and an estimated 70 m thick, continued to move seaward during the 26th December pushing the older landslide debris in front of it. The former cliff line was moved forward, and an extensive new offshore reef of Cretaceous debris was created with a natural harbour on its landward side. The event became nationally famous and attracted large numbers of sightseers, artists and authors. It even inspired the composition of a quadrille (Arber, 1940). The graben that had formed between the *in situ* cliffs and the detached slab (which soon became known as The Chasm and Goat Island respectively) and the slab itself attracted particular attention. The Chasm was especially popular with artists and photographers. Pitts (1974), in a review of historical documents relating to the landslide, reproduced a selection of sketches, watercolours and photographs made between 1840 and 1949. Winter corn that had remained undamaged on Goat Island was ceremonially harvested the following August by local village maidens dressed as attendants of Ceres, the Roman Goddess of the Harvest (Arber, 1940).

Conybeare *et al.* (1840) produced descriptions, plans, views and sections of the landslide within a few weeks of its occurrence. Their descriptive account is more complete and detailed than any contemporary or earlier account of a major landslide and was the first to comprehensively analyse the mechanism. The first part of their account describes the geological and geomorphological setting and includes the important observation that prior to the landslide the sea cliffs were comprised of masses of Cretaceous rocks that had resulted from earlier landslides. The second part provides an hour-by-hour account of the movements based on the first-hand experiences of local farm workers and coastguards who were in the landslide area at the time of the movements. The third and forth parts describe the onshore (The Chasm and Goat Island) and offshore (elevated and submarine reefs) results of the movements respectively. The accompanying "Ten Plates" provide accurate pictures of the principal features, including an oblique aerial view of the whole landslide (Figure 3) and a conjectural geological cross section through the central part. This last includes the principal geological features that contributed to the landslide, including an accurate geological succession and a low seaward dip in the Cretaceous rocks. Few subsequent descriptions of the landslide paid as much attention to the stratigraphy and geological structure, as a result of which some are demonstrably wrong.

Geological setting

The geology of the Bindon Landslide complex and adjacent areas comprises an almost unbroken succession of late Triassic and early Jurassic rocks with a low (*c.* 03°) easterly dip, overlain with marked unconformity by almost horizontal Cretaceous rocks. The outcrop of the Triassic and Jurassic rocks is cut by numerous small faults (mostly <10 m throw) that trend approximately E-W, most of which do not affect the Cretaceous rocks. Two larger N-S trending faults with westerly downthrows cause the outcrop of the latest Triassic and earliest Jurassic rocks to be repeated at Charton Bay and Pinhay Bay (Figure 1). As a result of the faulting, the exposures in the intertidal area adjacent to the 1839 landslide show marked variations in the beds that underlie the unconformity over a distance of tens of metres, ranging from the Blue Anchor Formation to the Charmouth Mudstone Formation. The geology of the western part of the NNR is summarised in Figure 4 and the susceptibility to landslide of the component formations when weathered is summarised in Table 1.

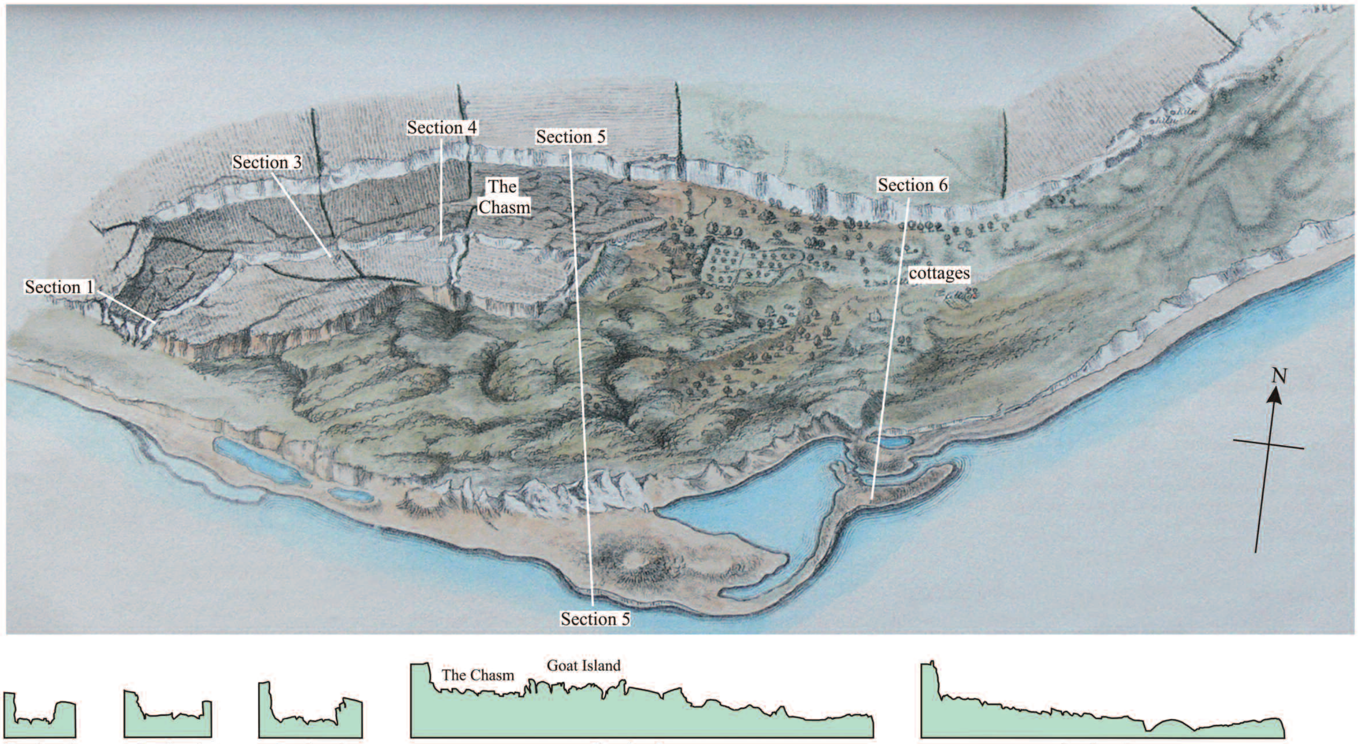

Figure 3. *Artistic oblique aerial view and cross sections (redrawn here) of the 1839 Bindon Landslide made shortly after the failure by William Conybeare (part of Plate II of Conybeare et al., 1840).*

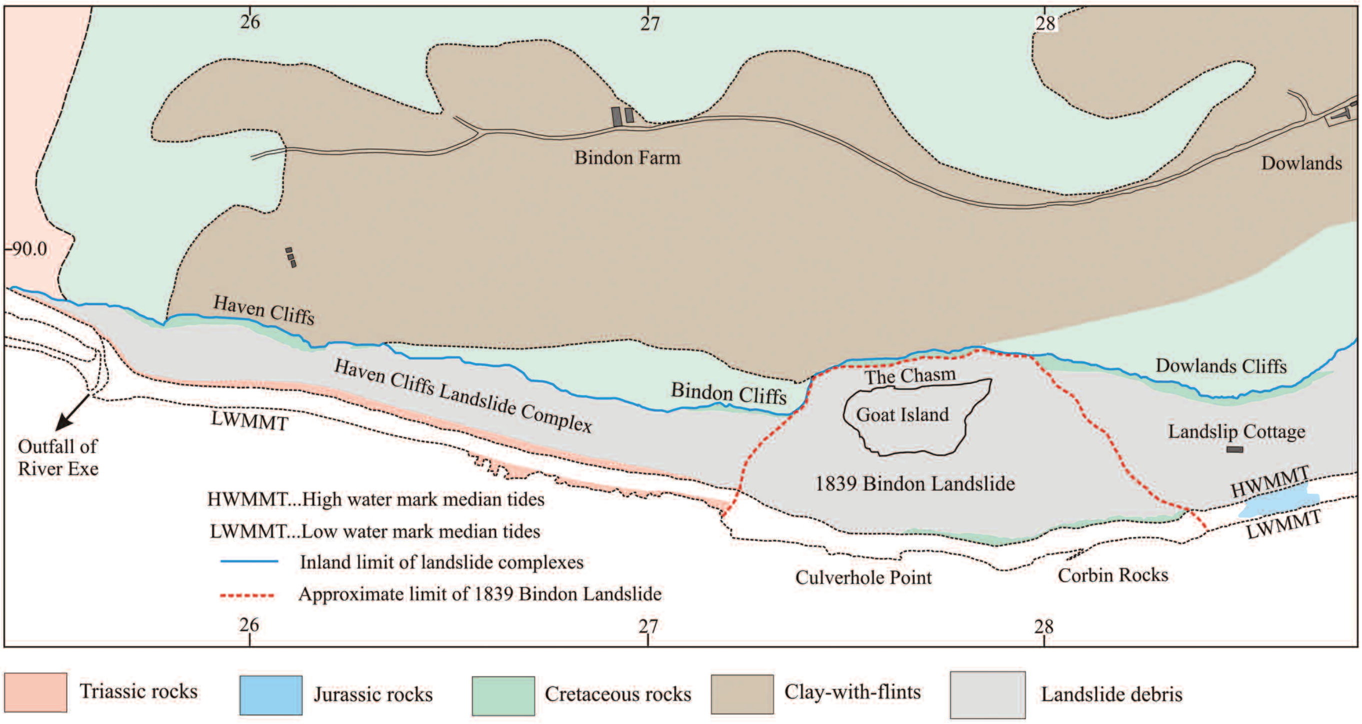

Figure 4. *Geological sketch map of the western part of the NNR and the adjacent inland area showing the positions of localities referred to in the text. See Figure 9 for the geology of the offshore area.*

The Triassic rocks at outcrop in the sea cliffs and in the intertidal area adjacent to the 1839 landslide are largely composed of relatively strong rocks that, even when weathered, do not give rise to shear failures. The principal exception is the pyritic Westbury Mudstone Formation which rapidly weathers to weak clay that gives rise to shallow-seated landslides and mudflows. Jurassic rocks are well exposed in the cliffs and foreshores in, and adjacent to, the NNR where their stratigraphy is well documented (Edwards and Gallois, 2004). At the base of the succession, the Blue Lias Formation forms a stable foundation composed of thinly interbedded mudstones and limestones. Above this, the mudstones of the Charmouth Mudstone Formation can be divided into two main lithological types. Thinly interbedded and interlaminated clay-mineral-rich and organic-rich mudstones that weather to weak fissile mudstones ('paper shales') and clays, and calcareous

System	Group, Formation (Fm.) (thickness m)	Predominant unweathered lithology	Susceptibility to landslide
Quaternary	Clay-with-flints (0 to 15)	clayey, stony sand	low
	Head Deposits (0 to 5)	clayey, stony sand	low
Cretaceous	Chalk Group (0 to 70)	limestone	none
	Upper Greensand Fm. (50 to 55)	sandstone and calcarenite	high at base
	Gault Fm. (0 to 2)	mudstone	ubiquitous
Jurassic	Charmouth Mudstone Fm. (0 to 50)	mudstone with few limestone beds	low to high
	Blue Lias Fm. (0 to 28)	limestone and mudstone	none to low
Triassic	White Lias Fm. (8)	limestone	none
	Cotham Formation Fm. (2.5)	mudstone with thin limestone beds	low
	Westbury Mudstone Fm. (6)	mudstone	high
	Blue Anchor Fm. (30)	mudstone and siltstone	low to moderate
	Sidmouth Mudstone Fm. (40)	mudstone and siltstone	low

Table 1. *Susceptibility to landslide (excluding rock falls and toppling failures) of the deposits that crop out in the Axmouth to Lyme Regis Undercliffs NNR.*

mudstones with widely spaced nodules and beds of muddy limestone. The principal failure surfaces occur in fissile-weathering mudstones a little above each of the more laterally persistent limestone beds in the Shales-with-Beef and Black Ven Marl members (Gallois, 2008).

The Cretaceous succession in the NNR comprises three lithologically distinct parts, mudstones, weak sandstones, and strong sandstones and calcarenites. The Gault thins rapidly westwards from *c.* 2 m thick at Lyme Regis, where it comprises montmorillonite-rich mudstones that readily weather to weak swelling clays. Its distribution in east Devon may be patchy and related to faults that were active at the time of its deposition. The farthest west that it has been observed is in landslide debris at Humble Point [SY 306 899] (Jukes-Browne and Hill, 1900) where it is still visible on the foreshore. The Upper Greensand is divided into the Foxmould comprised of weakly calcareously cemented sandstones that contain one or more thin (mostly <100 mm thick) beds of mudstone in its lowest part. Where unweathered, the overlying Whitecliff Chert and Bindon Sandstone consist of strong calcareous sandstones and calcarenites that give rise to vertical and near-vertical cliffs along much of the east Devon coast where they are mostly capped by the Chalk.

The tectonic history of east Devon is complex, with evidence of repeated fault movements and associated folding that can be traced from the late Carboniferous (*c.* 300 Ma) to the Miocene (*c.* 15 Ma). Seismic-reflection surveys in the inland area have revealed several N-S trending major faults in the pre-Permian basement rocks (Edwards and Gallois, 2004, figure 6). These are represented in the Triassic and Jurassic rocks by belts of faulting 100 m to 500 m wide in which synthetic and antithetic faults are mostly sub-parallel to a basement fracture. A second trend, roughly E-W and parallel to the principal Variscan structural fabric of South West England, is represented by a few fault belts. These are more numerous in the offshore area where they are related to the opening of the English Channel in the Permian. Three of these fault belts in the nearshore area between the Axe Valley and Lyme Regis (Figure 1) have influenced the rates of erosion of the coastline and presumably played an important, but still poorly understood, role in the development of the landslide complexes in the Undercliffs NNR.

1839 Bindon Landslide

Taken together the “Ten Plates” and accompanying script of the Conybeare *et al.* (1840) account provide a comprehensive description of the geomorphology and more notable landscape features a few days after the landslide occurred. They include descriptions of the stratigraphy, the nature and content of the collapsed onshore and offshore materials, the formation and denudation of short-lived rock pillars and lagoons, measured cross sections, estimates of the quantities of material involved, and drawings of the new offshore reefs and The Chasm (e.g. Figure 2). This last was 122 m wide at its widest and up to 64 m deep before it became partially filled with collapsed debris. Plate II of Conybeare *et al.* (1840) comprises geologically annotated ‘before and after’ views of the landslide from the sea. The ‘before’ views conform to what is known about the topography prior to the landslide, but it is not clear to what extent they are conjectural or based on earlier material.

The features recorded by Conybeare *et al.* (1840) which they considered were important to an understanding of the mechanism of the failure were:

(i) An upper layer of porous rock. They identified this as the highly permeable upper part of the Upper Greensand (now Whitecliff Chert and Bindon Sand members) and the Chalk with numerous open joints and gravel-filled solution pipes that allowed rapid access to rainwater.

(ii) An intermediate layer of loose sand. This is the weakly calcareously cemented Foxmould Member which becomes decalcified at outcrop and beneath the Whitecliff Chert in the zone of past and present-day water-table fluctuation.

(iii) An argillaceous bed impervious to water. They presumed this to be the mudstones of the Lias Group: the Gault Formation had not at that time been recognised west of Lyme Regis.

(iv) A seaward dip in the Cretaceous rocks. This is most pronounced in the central part of the landslide where Conybeare *et al.* (1840) estimated the base of the Cretaceous to dip south at *c.* 03° (Figure 6). Comparison of the calculated in situ position of the unconformity in Bindon to Dowlands Cliffs

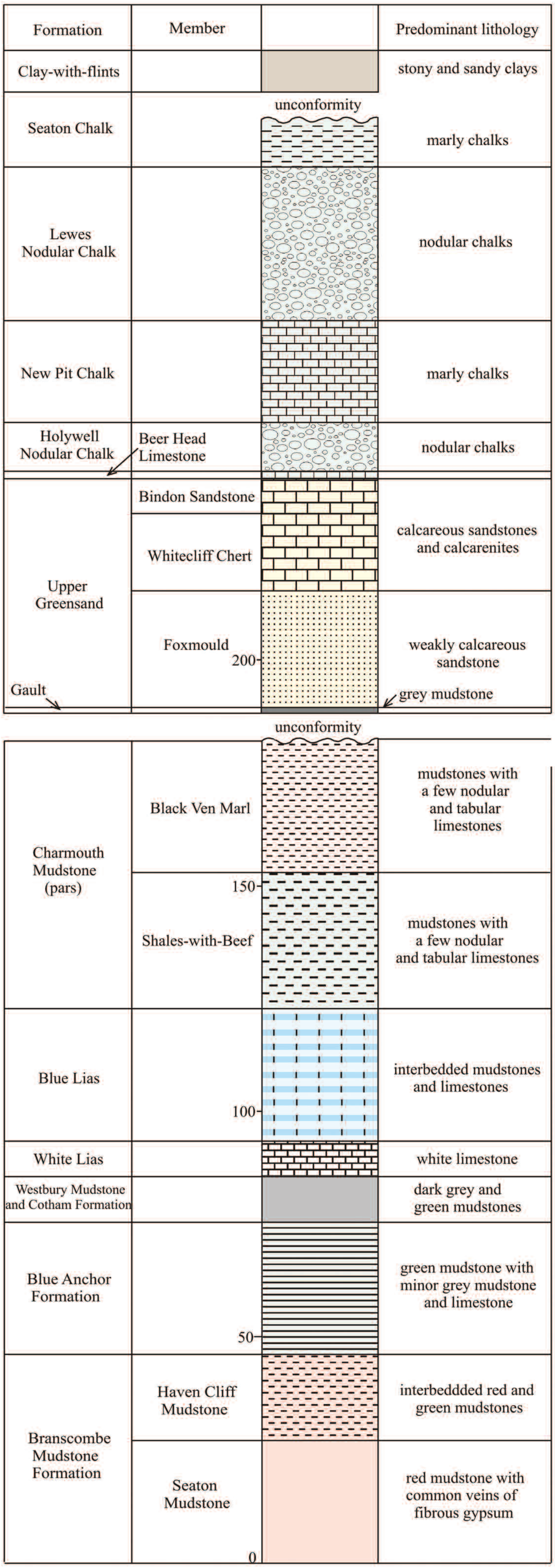

Figure 5. *Generalised vertical section for the strata that crop out in and adjacent to the 1839 Bindon Landslide.*

with its observed position in the sea cliffs between Haven Cliff and The Slabs, shows a maximum height difference of 45 to 50 m along a N-S section across Goat Island. Conybeare *et al.* (1840) interpreted this as a steady seaward dip, but suggested that part of the difference might be due to a fault with a seaward downthrow of up to 15 m that was concealed beneath the landslide debris.

(v) With two minor exceptions, the landslide only involved Cretaceous rocks. Goat Island, the landslide debris between the 'island' and the coast, and the newly formed cliffs, pinnacles and offshore reefs were all composed of Upper Greensand and Chalk. The exceptions that they recorded were two small outcrops (tens of metres across) of Lias in the intertidal area near Culverhole Point that appeared to have been disturbed by the landslide. The beds in the larger of these [SY 275 893] had post-landslide dips of 40° to 70° close to the cliff, but were horizontal at low-water mark. Recent surveys have shown that these beds (Shales-with-Beef) crop out in a narrow (up to 20 m wide) E-W trending fault zone with variable dips. The disturbance could be related to the bulldozer effect of a large mass of landslide debris being pushed forward over, and into, the weak Jurassic mudstones. Alternatively, the anomalous dips may be tectonic or tectonic dips that were modified by the landslide.

(vi) A period of high rainfall in the latter part of the year. Arber (1940), quoting contemporary sources, stated that the rainfall between June 1839 and the time of the landslide the rain had been *"almost continuous and twice as heavy as usual"*, and Roberts (1840) noted an *"abnormally"* high rainfall of 15.59 inches (396 mm) during the same period. The Meteorological Office database holds continuous instrumented precipitation records for England and Wales from 1766 to the present day (245 years), but only from 1873 to the present day for SW England. The England and Wales rainfall figures for the second half of 1839 confirm that it was an unusually wet period. The 'summer' (June to August) rainfall (351 mm) was the eighth highest on record and the 'autumn' (September to November) rainfall (358 mm) was the 27th highest. This suggests that Roberts (1840) may have been quoting the England and Wales data, but only for a three-month period. A major landslide occurred at the western end of the Whitlands Landslide complex, *c.* 2 km east of the Bindon Landslide, in February 1840 during the same wet period. Conybeare *et al.* (1840) described the mechanism as a repetition of the Bindon phenomenon, but on a smaller scale.

Prior to 1839, the coastal strip between Lyme Regis and The River Axe outfall except for *c.* 300 m at the western end, consisted of landslide complexes composed of Upper Greensand and Chalk (De la Beche, 1822, plate VIII). The area that was to become Goat Island is shown as part of a promontory on the First Series Ordnance Survey map (1835) and on a contemporary estate map as a promontory flanked by the back scars of earlier landslides. Comparison of the rates of retreat of the back faces of the landslides in the western part of the NNR, based on maps and air photographs, shows little change in the Bindon to Dowlands area since the time of the 1839 failure (Figure 7). Later failures larger than a few thousand tonnes have been confined to the Haven Landslide complex. The best documented of these was the collapse of a 250 m-long section of Haven Cliff in 1932 that extended the Haven Landslide complex to the Axe outfall (Figure 1).

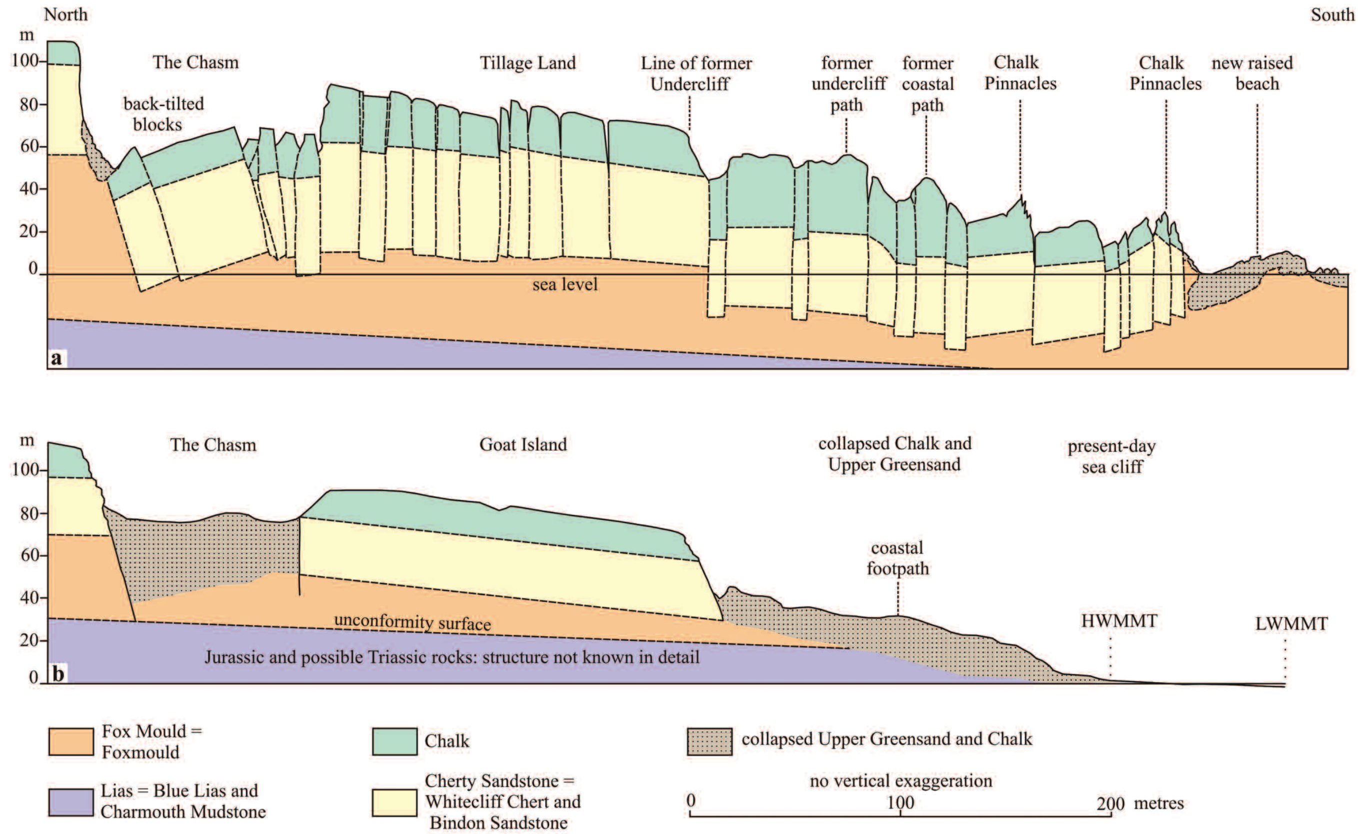

Figure 6. *Geological sketch section through the central part of the 1839 landslide approximately along the line of Section 5 in Figure 4. (**a**) A few weeks after the landslide: redrawn from Conybeare et al., 1840, Plate II. (**b**) Based on present-day exposures.*

1839 Bindon Landslide mechanism

Conybeare et al. (1840) proposed mechanism

When comparing the mechanism of the 1839 Bindon Landslide to that of other large landslides on the south coast (Isle of Portland, Isle of Wight, Folkestone etc), Conybeare *et al.* (1840) identified three geological factors as affording *"the most favourable circumstances"* for foundering. These were (in modern terminology) an upper layer comprised of a highly porous reservoir rock, a middle layer of loose sand, and an argillaceous lower layer that would act as an aquiclude. It was already known from De la Beche (1839) that the principal failure surfaces in the major landslides on the Dorset coast were in the Gault. However, Conybeare *et al.* (1840) observed that the formation was absent at Bindon and that the basal bed of the Cretaceous, at outcrop [SY 273 894] 500 m W of Culverhole Point, consisted of argillaceous sandstone. They therefore proposed a mechanism in which, during prolonged periods of unusually high rainfall, water ponded up in the lower part of the Foxmould and caused it to turn into a *"mass of quicksand"*. They envisaged that this was leached away by springs at outcrop with the result that the superincumbent rock was undermined. The whole mass (Goat Island) then moved seaward over the fluidised sand and pushed the terraces of Cretaceous debris that had been formed by earlier landslides forward to create a new cliff line. At the seaward edge, the Cretaceous debris that had formed the old sea cliff was pushed across the underlying Triassic and Jurassic rocks to form offshore reefs.

Subsequent proposed mechanisms

Some of the more important alternative explanations of the mechanism, those that appear to have been based on additional field observations, were summarised by Pitts (1981). Most subsequent authors have accepted parts of the Conybeare *et al.* (1840) explanation, but have rejected liquefaction of the Foxmould as the principal cause. Several of these accounts cite evidence in support of their suggested hypothesis that is based on events that were near contemporaneous with, but not part of the main failure, and some that occurred many years after the failure. The problem of combining evidence from different events that may have different mechanisms is not confined to the Bindon Landslide, but is widespread in landslide studies. It results from the failure of current landslide classifications to differentiate primary and secondary processes in what are usually complex interactions that take place over periods of time that can vary from minutes to hundreds of years.

The most commonly used landslide classification world-wide is that of Varnes (1978; modified by Cruden and Varnes, 1996) in which the materials involved are classified as *rock, debris* or *earth*, and the landslide mechanisms are divided into *falls, slides, flows* and *complex*. It is of little practical use for analytical or risk-assessment purposes when applied to landslides in the Undercliffs NNR, for two principal reasons. First, it places too much emphasis on post-landslide landforms at the expense of the pre-landslide condition and the geological stratigraphy and structure. Second, it does not differentiate between *in situ* and *ex situ* materials, nor between unweathered, partially weathered and deeply weathered materials. The definition of *rock* includes *in situ* and *ex situ* materials that are classified as rocks or soils in the geotechnical sense, and their weathered *ex situ* derivatives. *Debris* includes a wide range of *in situ* and *ex situ* materials including weakly consolidated primary materials such as glacial tills (diamictites), and accumulations of weathered materials. The term *earth* has no geologically or geotechnically defined meaning in the UK. Its principal component seems, from its usage in published descriptions of landslides, to be a fine-grained variety of 'debris'.

A more practical classification is to divide landslides into three types, primary, secondary and tertiary, based on the

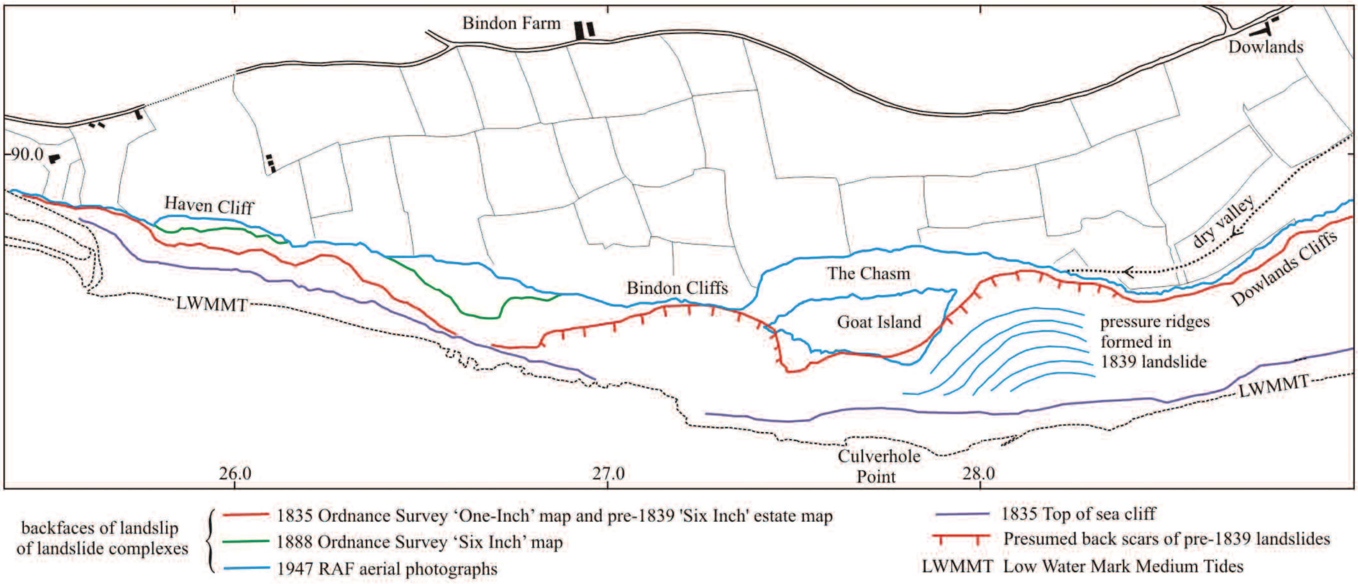

Figure 7. *Geographical changes in the extents of the Haven and Bindon Landslide complexes between 1835 and 1947.*

nature and geotechnical properties of the unweathered and weathered materials involved in the landslide. Primary landslides are defined here as failures in previously undisturbed strata. They include rotational and translational failures in weak or weathered rocks, and rock-block and toppling failures in fractured rocks. In the Undercliffs NNR, primary failures range in size from large, infrequent (<1 per century) events such as the 1839 Bindon Landslide to small (a few kg), frequent (several per week) rock falls from the sea cliffs. Secondary landslides include rock falls, rotational and translational failures, and debris flows that form part of the degradation process of potentially unstable rock faces and slopes that have resulted from primary failures. Examples in the 1839 Bindon Landslide include the collapse of the rock pillars into The Chasm and rotational failures along its back face. Tertiary landslides comprise mud/sand/debris flows and rock falls that involve mechanically and/or chemically weathered materials within the landslide complex and in the back faces of the landslides. The largest of this type in recent years was a collapse of part of the surface layers of the Chalk face on the south side of Goat Island in 2001 shortly after the wettest winter on record. At the eastern end of the NNR, they include active mudflows in the Ware Landslide complex that are derived from deeply weathered Charmouth Mudstone Formation.

One of the earliest alternative explanations for the mechanism of the 1839 landslide was that by Jukes-Browne and Hill (1900, figure 62) who suggested that the seaward dipping Cretaceous rocks might have slid forward across the Rhaetic Beds. They presumably envisaged a planar failure surface in the Westbury Mudstone Formation beneath the strong limestones of the White Lias Formation. Arber (1940) reiterated the Conybeare *et al.* (1840) explanation and suggested that all the major landslides on the Devon-Dorset coast between Beer and Charmouth were connected with the unconformity at the base of the Cretaceous succession, as originally envisaged by De la Beche (1822), without identifying a specific failure surface.

Ward (1945) was the first to suggest, by analogy with the Folkestone Warren Landslide in Kent, that the principal mechanism for the 1839 Bindon Landslide was a rotational failure in the Gault. This was modified by MacFadyen (1971) who proposed a deep (up to 100 m below sea level) semicircular failure surface in the Mercia Mudstone Group, notwithstanding the absence of any rotational failures in the Mercia Mudstone Group in the 8 km of almost continuous Mercia Mudstone cliffs between Beer and Sidmouth. Arber (1973) subsequently accepted Ward's (1945) interpretation after noting the presence of several rotational landslides in the NNR, notably at Charton Bay. They and McFadyen (1971) cited as evidence the back-tilted masses of Cretaceous rocks on the north side of The Chasm (figures 2 and 6). These are interpreted here as secondary landslides that occurred as a consequence of the primary failure. They could not have formed until The Chasm was sufficiently open to accommodate them. Their depiction in Mary Buckland's drawing, completed within a few days of the initial failure, suggests that they may have formed whilst Goat Island was still moving. Examples of back-tilted blocks quoted by Arber (1973) in the Whitlands Landslide complex resulted from minor failures that occurred over 100 years after the primary landslide with which they are associated.

The most detailed 20th Century analysis of the mechanism of the 1839 landslide was that of Pitts and Brunsden (1987). They recorded a shear surface in the Westbury Mudstone Formation at beach level 500 m W of Culverhole Point [SY 273 894] (referred to as Culverhole Point in their account) and concluded that the principal failure surface in the 1839 landslide was in the Westbury Mudstone Formation. They also noted shear failures in the same formation at Charton Bay [SY 273 894]. At both localities these are small (tens of metres across), shallow-seated, secondary failures that cause back-tilting in the overlying White Lias, but do not affect younger strata. With the exception of the small area of disturbed Shales-with-Beef in the intertidal area near Culverhole Point referred to above, all the onshore and offshore debris produced in the 1839 landslide was derived from the Upper Greensand and Chalk. It does not include the limestones of the White Lias and Blue Lias that would have been present in large quantities if the failure surface had been in the Westbury Mudstone Formation.

In recent years the Westbury Mudstone outcrop recorded by Pitts and Brunsden (1987) has been concealed beneath beach gravels. At the top of the beach, a northward dipping (at 20°) block of White Lias rests against *in situ* White Lias that is unconformably overlain by the basal argillaceous sandstone (decalcified here) of the Foxmould (Gallois, 2007a, figure 8). The sandstone is separated from landslide material composed of Upper Greensand debris by a polished and slickensided shear surface coated with plastic clay (Figure 8). The field evidence suggests that the failure surface is at the base of a post-1839 secondary landslide that formed seaward of Goat Island. The sheared clay is at a similar stratigraphical level to thin (<100 mm thick) beds of smectite-rich mudstone (Jeans, 2006) in the lowest 1 to 2 m of the Foxmould Member. These have been the principal failure surfaces in large coastal landslides between Beer and Sidmouth where the Upper Greensand rests unconformably on stable Mercia Mudstone

Group. In each case, a shear failure in a mudstone during or shortly after a prolonged period of wet weather caused waterlogged sands in the partially decalcified lower Foxmould to collapse and undermine the overlying beds. These combined with the sand to produce a matrix-supported debris flow. Where the failure surface was high in the cliffs, as in the 2006 landslide at Salcombe Regis (Gallois, 2007b), the flows descended rapidly and transported large blocks (>50 tonnes) of Upper Greensand up to 150 m into the sea. Where the failure surface was close to sea level, as in the 1795 Hooken Landslide (Mortimore *et al.*, 2001), large intact masses of Upper Greensand and Chalk moved seaward over a period of several days. Fodal (1994) has shown that in this type of flow slide the development of pressure waves at the base of the flow reduces the basal drag and allows long run-out landslides to develop.

A possible contributing factor to the 1839 failure that was not considered by Conybeare *et al.* (1840) was coastal erosion. Arber (1940) noted that there had been large storms in the months before the 1839 landslide and Pitts and Brunsden (1987) suggested that a contributing factor to the failure was high tides (culminating in a spring tide on December 23rd) that removed beach material which had acted as a toe weight that stabilised earlier landslides. It is difficult to confirm or disprove this suggestion. Prior to the landslide, the southern edge of the stable land was separated from high-water mark by a *c.* 150 m-wide strip of landslide debris (Figure 7). De la Beche (1822) depicted this section of the coast as a line of cliffs that Conybeare *et al.* (1840) described as wall-like and 15 m to over 30 m high. The comparable present-day cliffs at Culverhole Point are fronted by a wide apron of boulders, 'cowstones' derived from the Foxmould and large blocks of calcarenite

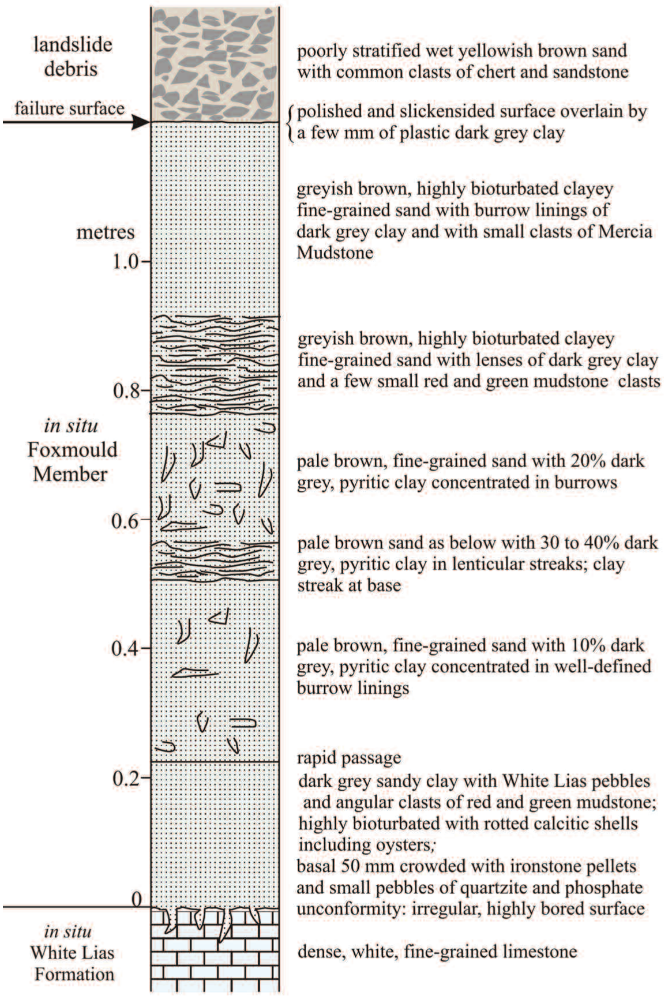

Figure 8. *Detail of the in situ Upper Greensand succession, the basal Cretaceous unconformity, and the failure surface at the base of a post-1839 landslide exposed 500 m west of Culverhole Point.*

derived from the Whitecliff Chert and Bindon Sandstone. At the present time the principal failures in these cliffs are infrequent small rock falls (mostly <100 tonnes), and the rate of retreat of the cliff line is low in comparison with other parts of the east Devon coast. Pitts (1983) recorded rates of retreat of 1.0 m to 1.5 m per annum for this part of the coast during the period 1905 to 1958. It is unlikely, therefore, that sufficient material would have been removed by one or more storms to destabilise the large volume of debris between the cliff line and the stable land.

Although there are first-hand accounts of 'liquefied' Foxmould sand squirting out of the ground in active landslides in the Undercliffs NNR (e.g. Arber, 1940), Pitts and Brunsden (1987) doubted that such a dense material as unweathered Foxmould of the type that crops out in the cliffs at Culverhole Point could be liquefied. Brunsden (2002) subsequently concluded that although liquefaction of the Foxmould occurred in the 1839 Bindon Landslide, it was not the primary cause of the failure. This conclusion has been confirmed by more recent observations which have shown that all the major failures on the east Devon coast that involved large quantities of Foxmould-derived sand were initiated by a shear failure in a mudstone.

A geological factor which is absent from all previous accounts of the 1839 landslide, but which may have made an important contribution to the failure mechanism, is faulting. This omission was partly due to the scarcity of field evidence, and partly to the common assumption that disturbances in strata exposed in the cliffs and intertidal areas adjacent to the NNR resulted from landslide activity (e.g. Page, 2002, figure3). Aerial photographs commissioned by Natural England and taken at times when the sea was calm and clear combined with a multibeam-sonar survey commissioned by the Channel Coast Observatory have revealed complex geological structures in the shallow subtidal area. They include E-W trending fault belts between the Axe Valley and Lyme Regis that are sub-parallel to the coastline and to the principal landslide structures in the NNR (Figure 1). The offshore area adjacent to the 1839 Bindon Landslide contains numerous faults that separate zones of fractured and folded Triassic and Jurassic rocks (Figure 9). One of these faults (A in Figure 9) is exposed [SY 265 896] in the sea cliff where it runs almost parallel to the face. A second fault (B in Figure 9), which cuts out part of the Blue Anchor Formation, was formerly exposed 550 m W of Culverhole Point (H. B. Woodward MS, 1884). Most of the E-W trending faults in this and other offshore fault belts on the east Devon coast are normal and related to the post Variscan opening of the English Channel and Western Approaches.

SUMMARY AND CONCLUSIONS

The Conybeare *et al.* (1840) description of the 1839 landslide is an accurate and comprehensive account based on detailed cartographic and geological field surveys, and a knowledge of the local geology. All except one of their conclusions with respect to the mechanism of the landslide failure have been proved by subsequent research to be correct. They concluded that the initial failure was at or close above the base of the Cretaceous Upper Greensand, and that it resulted in a translational slab slide (Goat Island) that pushed Cretaceous debris from older landslides forward and into the sea. Later interpretations which concluded that the principal failure occurred along a rotational shear surface in the Mercia Mudstone Group or Gault, or along a translational shear in the Westbury Mudstone are not supported by the field evidence. The rotational failures quoted as evidence of these alternative mechanisms are interpreted here as secondary failures that were consequential upon, not precursors of, the initial failure.

The Conybeare *et al.* (1840) conclusions that the seaward dip of the basal Cretaceous unconformity and a prolonged period of unusually heavy rain that resulted in high pore pressures in the permeable Upper Greensand and Chalk were important contributing factors have been confirmed by later authors.

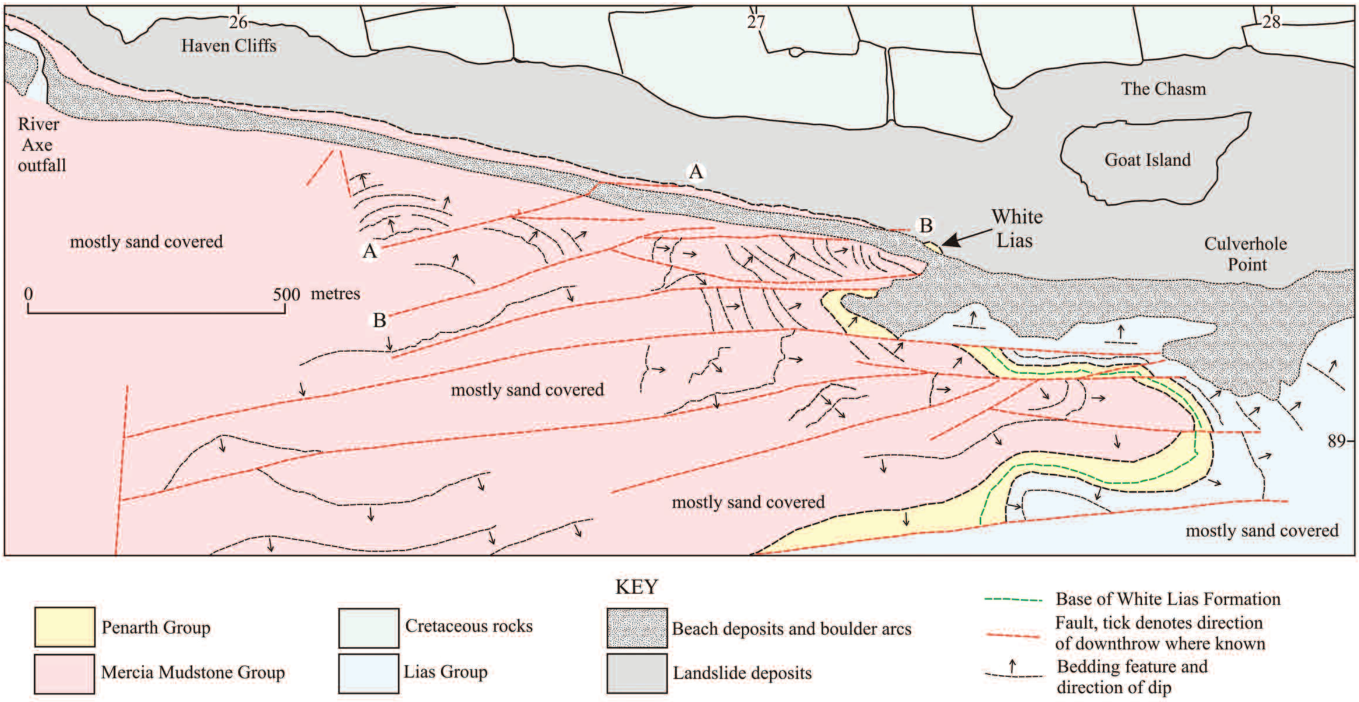

Figure 9. *Geological sketch map of the intertidal and shallow subtidal areas between the outfall of the River Axe and Culverhole Point based on orthographically rectified air photographs commissioned by Natural England and multibeam-sonar images commissioned by the Channel Coast Observatory (www.channelcoast.org).*

However, their conclusion that the principal failure resulted from liquefaction of the lower part of the Foxmould has not been confirmed. More recent landslides on the east Devon coast that have involved the collapse of a similar Cretaceous succession to that at Bindon have been shown to have failed on thin (<100 mm thick) beds of montmorillonite-rich mudstone in the lowest 1 m to 2 m of the Foxmould.

The possible role of faulting in the1859 Bindon Landslide mechanism has not previously been considered in detail. Conybeare *et al.* (1840) suggested that part of the apparent seaward dip and stepped nature of the outcrop of the Cretaceous beds (Figure 6) might, in part, be explained by faulting. Pitts (1974) referred to an unpublished report which suggested that The Chasm might have formed along the line of a fault. There is no published field evidence to support these suggestions, but it is now known that several E-W trending faults pass beneath the landslides in the NNR. These juxtapose weaker and stronger, and more and less permeable strata, and are likely to have contributed to local failures within individual landslides.

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