Landslides In The Cretaceous Rocks Of The Devon Coast, UK: A New Explanation For An Old Phenomenon

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Some of the largest landslides in the United Kingdom, such as those on the south coast of England at Folkestone (Kent), Ventnor (Isle of Wight) and Black Ven (Dorset) were initiated by failure surfaces developed in mudstones in the Cretaceous Gault Formation. When traced westwards from Dorset into Devon, the Gault passes laterally into the Upper Greensand Formation, calcareous sandstones and sandy calcarenites, which crop out on steep slopes and in almost continuous cliffs between Sidmouth and Seaton. They form an integral part of the Dorset and East Devon Coast World Heritage Site. Along this stretch of coast, large blocks of Upper Greensand form debris aprons that extend out beyond the low water mark of median tides. These have been presumed to be the result of landslides initiated either by shear failures in the Gault or as joint-bounded toppling failures in oversteepened cliffs. However, the Gault has not been recorded either *in situ* or in landslide deposits west of the Axe Valley at Seaton. Observations of landslide occurrences in the Upper Greensand on this part of the Devon coast over the past 30 years have shown that the larger landslides have been initiated by failures surfaces in thin (mostly <50 mm thick) beds of mudstone in the lowest part of the formation. These have initiated sand flows in the decalcified lower part of the Upper Greensand and toppling failures in strongly cemented sandstones and calcarenites in the middle and upper parts. A similar mechanism involving beds of fluidised sand can be attributed to some of the older landslides: for example, the 1790 Hooken Landslide. It explains how detached masses of Upper Greensand and the overlying Chalk Group were able to run out up to 180 m and downward up to 60 m without disruption of their stratigraphical successions.

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Introduction

Almost continuous cliffs 120 m to 160 m high between Sidmouth and Seaton, Devon (Fig. 1) can be divided into two distinct geological domains. The lower part is composed of well-jointed, moderately strong Triassic mudstones and siltstones of the Mercia Mudstone Group that crop out in steep (mostly 40° to 80°) cliffs. These are overlain with marked unconformity by the Cretaceous Upper Greensand Formation and Chalk Group which form imposing cliffs that are mostly at 75° to vertical. Minor landslides, mostly joint/bedding-bounded toppling failures and shear failures, are locally present in the

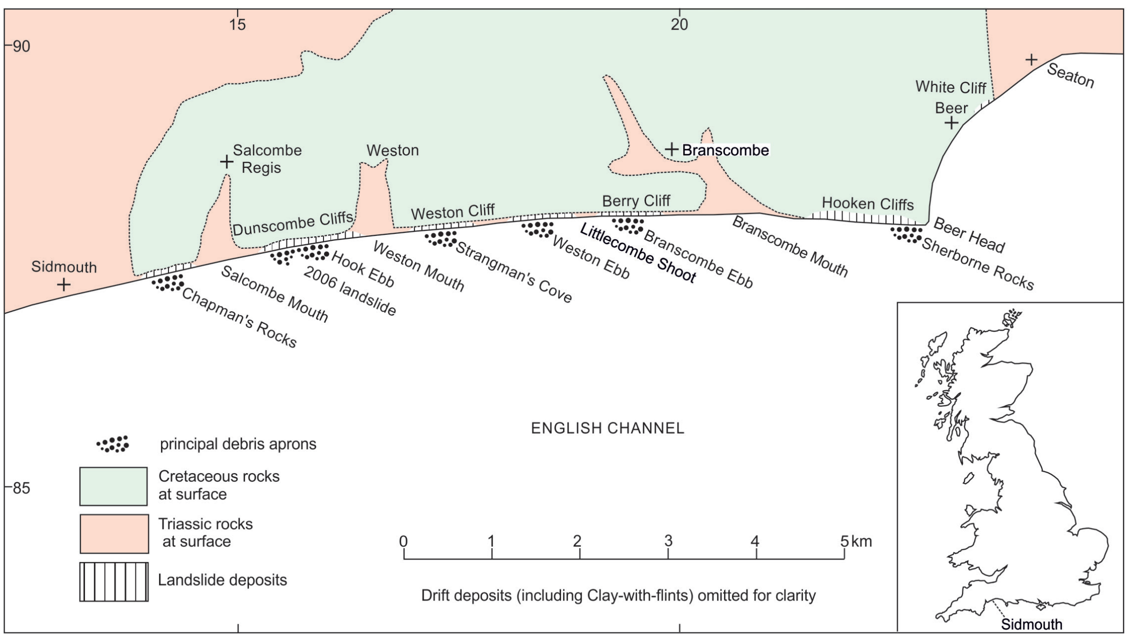


Figure 1. *Geological sketch map of the East Devon and Dorset Coast World Heritage Site between Sidmouth and Seaton, Devon showing the principal landslide debris aprons that extend into the intertidal area (after Gallois, 2007).*

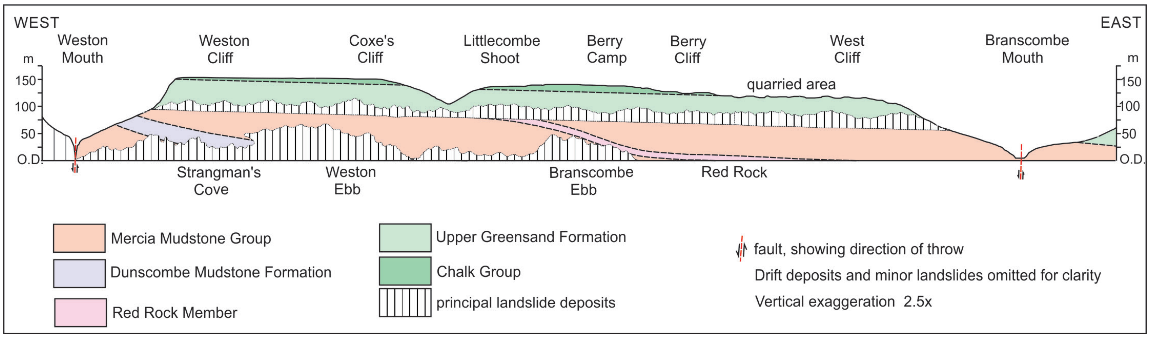


Figure 2. *Geological sketch section of the cliffs between Weston Mouth and Branscombe Mouth showing the relationships of the principal landslide deposits to the stratigraphy.*

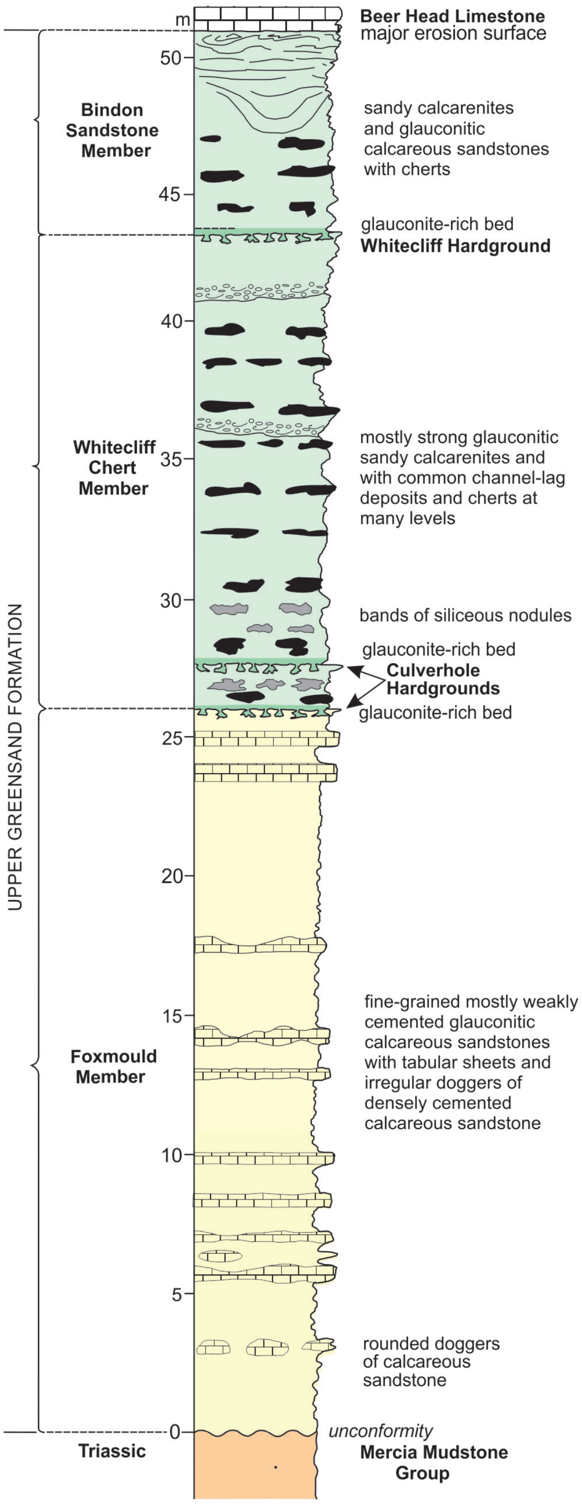


Figure 3. *Generalised vertical section for the Upper Greensand Formation exposed on the east Devon coast (after Gallois, 2004).*

Mercia Mudstone but all the major landslides, those that involve the full height of the cliff, were initiated close to the base of the Upper Greensand. Throughout much of its length the unconformity is obscured by deposits derived from landslides that formed in the lower part of the Upper Greensand. The coarser elements of similar landslides are locally banked up against the Triassic outcrop (Fig. 2).

Some of the larger clasts, angular blocks of Upper Greensand sandstone and calcarenite up to several metres across, form debris aprons in the intertidal and adjacent subtidal area at regular intervals along the coast between Sidmouth and Beer (Fig. 1). These are assumed to be the residues of former large landslides that involved the whole of the Upper Greensand and, locally, the Chalk. They appear to have been so infrequent that they have not been geologically described.

The Upper Greensand can be divided on gross lithology into three stratigraphically controlled units (Fig. 3) that give rise to characteristic cliff profiles. In the lowest part, weakly calcareously cemented permeable sandstones are prone to dissolution by groundwater seepages for a few metres above the sharp unconformable junction with the impermeable Mercia Mudstone. The lowest 1–2 m contain thin (mostly < 50 mm thick), laterally impersistent beds of mudstone in which the clay content is largely comprised of collapsible smectite minerals (Jeans, 2006). The higher parts consist of weakly cemented glauconitic sandstones with doggers (the 'Cowstones' of De la Beche, 1826) and lenticular beds of well-cemented calcareous sandstone at several levels. The overlying Whitecliff Chert and Bindon Sandstone Members (Gallois, 2004), collectively referred to as the 'Chert Beds' by Jukes Browne and Hill (1900), consist of strong, mostly massive calcareous sandstones and sandy calcarenites with a laterally variable number of chert beds. They form vertical and near-vertical cliffs with well-defined bedding and joining that locally gives rise to toppling failures.

In January 2006, a large landslide in Higher Dunscombe Cliff that was initiated in the Upper Greensand enabled the distribution of the lithologies in the landslide and their subsequent marine dispersal to be studied (Gallois, 2007). This showed that the landslide mechanism for this, and probably for similar landslides on this part of the Devon coast, was more complex than had previously been assumed.

Sidmouth To Weston Mouth

Prior to 2011 there were two debris aprons between Sidmouth and Weston Mouth, Chapman's Rocks [SY 141 875] below the highest part of Salcombe Hill (160 m O.D.) and Hook Ebb [SY 154 877] below Higher Dunscombe Cliff (160 m O.D.). Chapman's Rocks comprise a scattering of Whitecliff Chert/Bindon Sandstone blocks up to 5 m across (Fig. 4a). These lie directly below an arcuate landslide embayment in the Upper Greensand that is occupied by mature vegetation. The lower and middle parts of the underlying Mercia Mudstone cliff are clean and without landside deposits which suggests, by comparison with more recent landslides on this part of the coast, that the landslide occurred over 140 years ago. The debris apron is shown on Ordnance Survey Six Inch to One Mile Sheet Devonshire 94 NE (1889). The Hook Ebb debris is

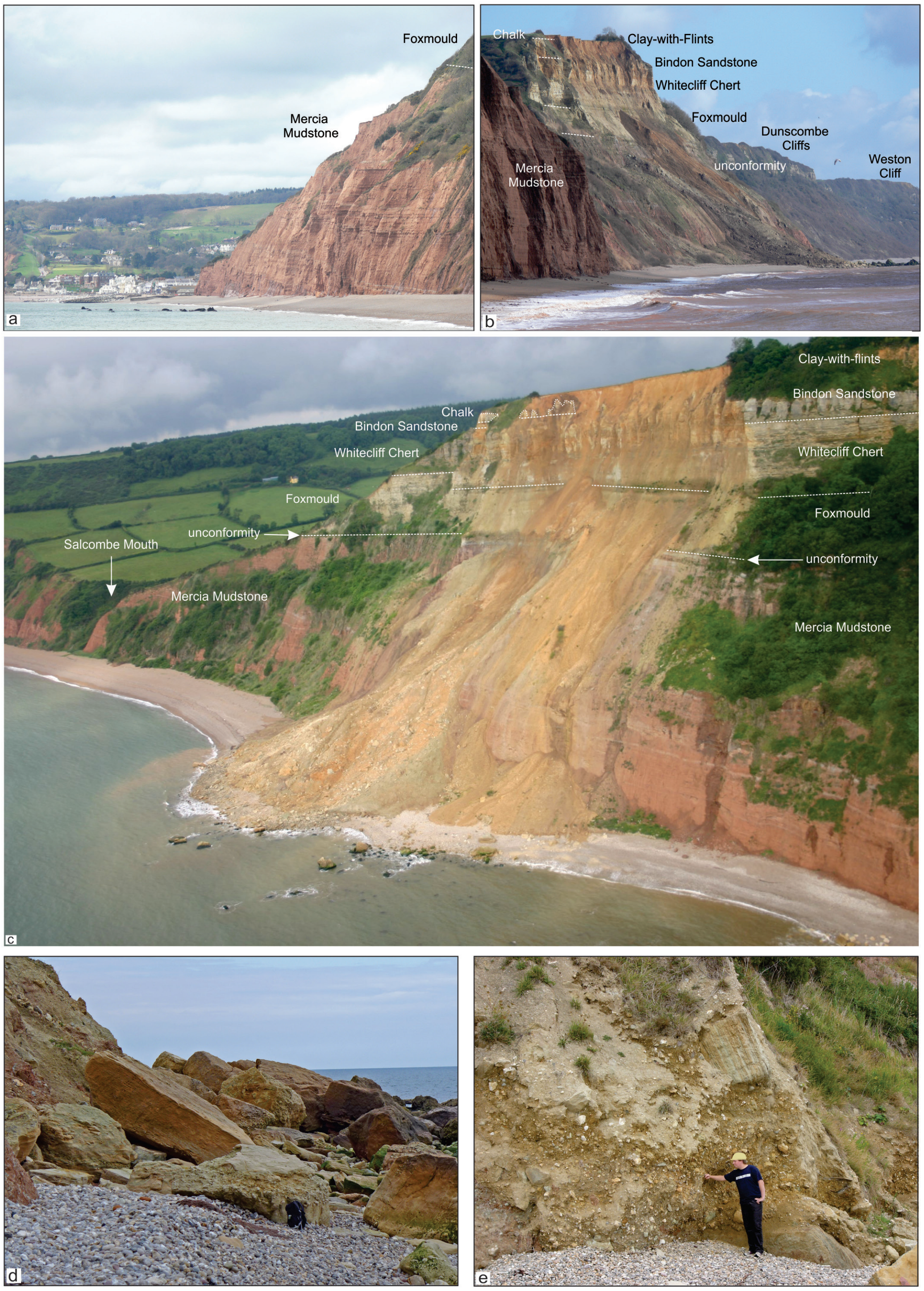


Figure 4. *Landslides between Sidmouth and Weston Mouth. (a) Chapman's Rocks debris apron at the foot of Salcombe Hill Cliff. View west from Salcombe Mouth towards Sidmouth. (b) The Salcombe Landslide of January 2006 viewed in March 2007 by which time all of the finer grained materials in the intertidal zone had been removed by the sea. View E from Salcombe Mouth. (c) The 2006 landslide viewed in July 2007 after several rock falls and secondary sand and debris flows had added to the deposit. View W towards Salcombe Mouth. Photograph courtesy Maritime and Coastguard Agency (MCA), copyright MCA. (d) Part of the remains of the 2006 landslide in May 2021 showing exhumed angular blocks of calcareous sandstone and calcarenite up to 4m across derived from the Whitecliff Chert and Bindon Sandstone Members. (e) Debris flow composed of angular clasts of Upper Greensand chert and sandstone and calcarenite blocks up to several tonnes in weight supported by a matrix of fine-grained sand derived from the decalcified Foxmould. Hook Ebb 1968 landslide.*

shown on the same map. The cliffs above the eastern part of Hook Ebb are free of landslide deposits but the remainder are plastered with Upper Greensand debris from a landslide that occurred, according to local residents, in 1968.

A large landslide that gave rise to a new debris apron [SY 150 878] occurred after a period of wet weather in January 2006 when several thousand tons of Upper Greensand fell from the western end of Higher Dunscombe Cliff (Fig. 4b, c) adjacent to the most westerly of the Hook Ebb landslides. The distribution of the materials in the landslide deposits showed

Figure 5. *Sand flows between Weston Mouth and Branscombe Mouth. (a) A succession of sand flows in the lowest part of the Foxmould and toppling failures in the higher parts in February and March 2020 resulted in a composite landside of several thousand tonnes. 500 m E of Weston Mouth [SY 169 879]. Image copyright Google 2021. (b) The upper part of the landslide viewed from the east in June 2020. The seepage line at the junction of the Mercia Mudstone and Upper Greensand is overlain by a 2m-thick bed of modern tufa along much of this part of the coast. (c) Flow in loose Foxmould-derived sand overlain by toppling failures in deeply weathered, highly fractured Foxmould sandstones following heavy rain in May 2002. Between Strangman's Cove and Littlecombe Shoot [SY 174 879]. Photograph courtesy Chris Pamplin. (d) minor sand flow [SY176 880] initiated in the lowest part of the Foxmould. Coxe's Cliff, 200 m W of Littlecombe Shoot, early 2002. (e) In October 2001, a sand flow derived from the lower Foxmould poured over the unconformity, down a shallow gully, around and through a scout hut and across the beach to beyond low tide mark. West side of Littlecombe Shoot [SY 178 880].*

that they were deposited in roughly the same stratigraphical order as they occur in the cliffs (Gallois, 2007). The deeper parts of the landslide deposit comprise loose sand and weakly cemented sandstone with thin lenses and burrowfills of dark grey mudstone derived from the lowest part of the Foxmould. This was overlain by small blocks of weakly cemented glauconitic sandstones with a few calcareous doggers ('Cowstones') and slabs of sandy cementstone derived from higher parts of the Foxmould. Large cuboidal blocks (up to 9 x 5 x 2 m) of joint/bedding-bounded Whitecliff Chert/ Bindon Sandstone occurred in the upper part of the landslide deposit which stretched out across and beyond the intertidal area. Their unabraded condition and right-way-up distribution suggested that they were carried to their present positions within a matrix-supported debris flow rather than had rolled down the debris cone.

Most of the fines from the landslide deposit in the intertidal area were removed by the sea within a few tidal cycles. Four weeks after the landslide, the less well-cemented lithologies had been reduced to rounded cobbles and boulders but the larger blocks of Whitecliff Chert and Bindon Sandstone had retained their angular shapes.

Similar blocks in the residual debris from the adjacent Hook Ebb landslide suggest that they become encrusted by *Mytilus* and other organisms within 1 to 2 years and suffer little further erosion. The matrix-supported nature of the larger blocks within the landslide deposits can be observed in cliff sections at the foot of the 2006 (Fig. 4d) and 1968 (Fig. 4e) landslides.

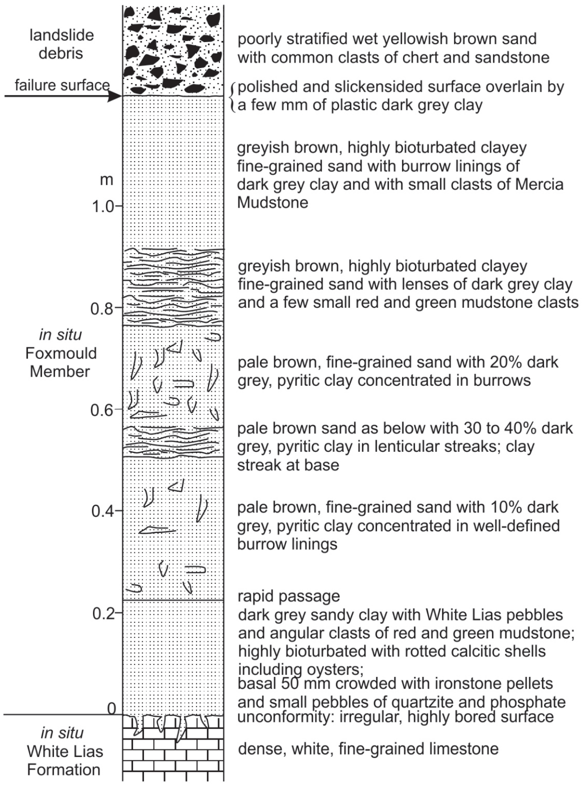
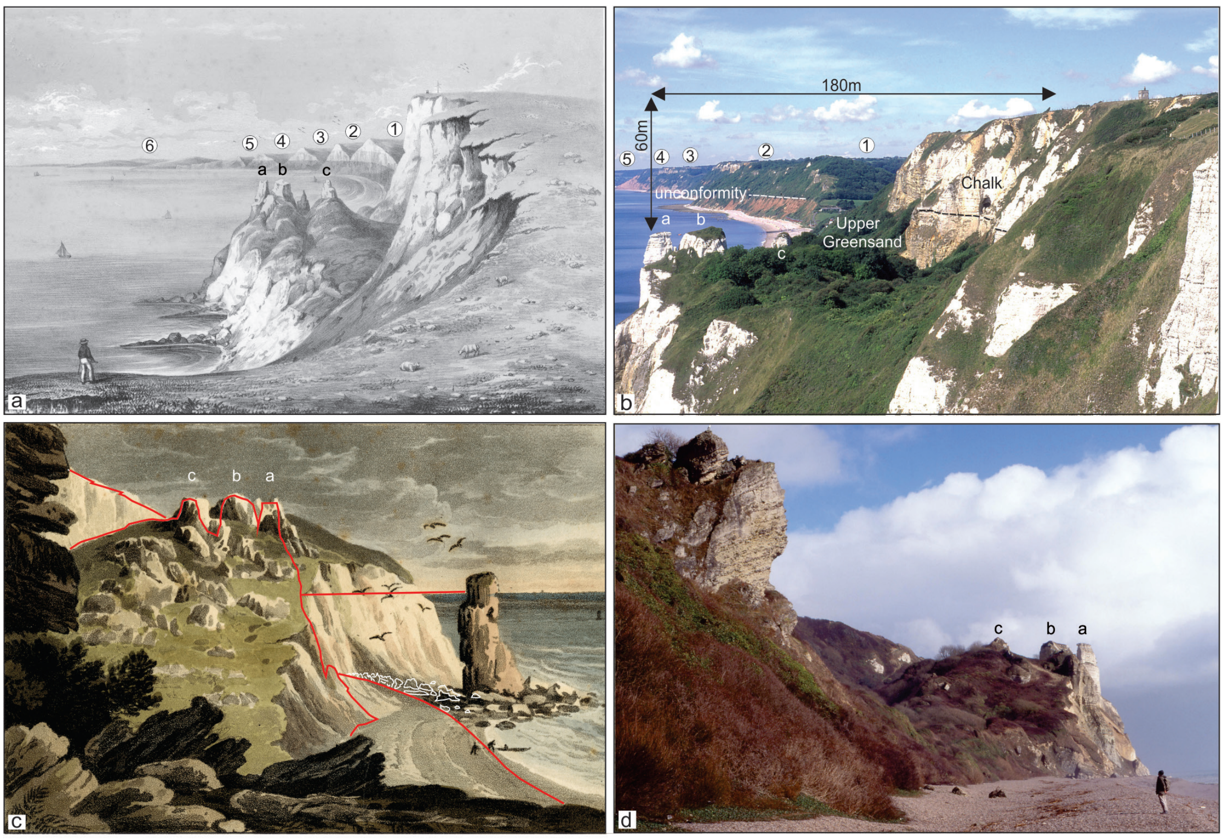


Figure 6. *The* in situ *succession at the base of the Upper Greensand Formation exposed at beach level below the 1839 Bindon Sandstone c. 3.5 km E of Seaton (after Gallois, 2010).*

Weston Mouth To Branscombe Mouth

Between Weston Mouth and Branscombe Mouth, debris aprons are shown on Ordnance Survey Six Inch to One Mile Sheet Devonshire 95 W and NE (1889) at Strangman's Cove, Weston Ebb and Branscombe Ebb (Fig.1). None of these can be related to landslide scars in the cliffs that might have involved the full thickness of the Upper Greensand. These aprons are therefore also presumed to more than 140 years old. The only observed moderately large landslide in this area in recent years has been that 500 m E of Weston Mouth [SY168 879] in February and March 2020. Several failures, which were initiated close to the base of the Foxmould, resulted in sand flows that undermined beds of sandstone in the higher parts of the Foxmould and carried them down the cliff (Fig. 5a, b). The Whitecliff Chert and Bindon Sandstone appear to have been unaffected.

Throughout this section of the cliffs the sharp, unconformable junction of the Upper Greensand aquifer with the Mercia Mudstone Group aquitard is marked by a seepage line and an almost continuous bed of modern tufa up to 2 m thick (Fig. 5b) which is presumed to have largely formed from calcium carbonate cement leached from the lower part of the Foxmould. Minor sand flows that were initiated in the lowest part of the Foxmould occur every few years on this part of the coast. Some of these have extended up into the higher parts of the member (Fig. 5c), others have only involved the lowest beds (Fig. 5d, e). All these minor, sand-dominated landslides occurred within days or weeks of periods of wet weather. In the Scout Hut example, the *in situ* Foxmould 1–2 m above the unconformity contained a 50 mm thick dark grey mudstone which was shown by Dr C. V. Jeans *(pers comm.)* to be largely composed of the expansible clay mineral montmorillonite.



1.Branscombe Mouth 2. Littlecombe Shoot 3.Weston Mouth 4. Salcombe Mouth 5. Sidmouth 6. Exe Estuary a..b..c pinnacles

Figure 7. *The Hooken Landslide of March 1790. (a) The landslide viewed from the east in a drawing by William Dawson (plate X in Conybeare* et al.*, 1840). The overhanging nature of the in-situ cliffs and their foreground extension are artistic additions. (b) An attempt to recreate the same view in May 2021 taken from the cliff edge. (c) Painting of the landslide by H. Haseler as viewed from the top of Martin's Rock in 1819. (d) View of the landslide from the west taken from the beach below Martin's Rock [SY 2163 8047]. Comparison with a photograph taken from the same place in 2010 has allowed the approximate present-day positions (red lines) of the coastline, pinnacles and in-situ cliff to be shown.*

Elsewhere on the Devon coast, lithologically similar thin beds of mudstone in similar stratigraphical positions close to the base of the Foxmould form the basal shear surfaces of landslides, for example below Hooken Cliffs (see below) and beneath a reactivated part of the 1839 Bindon Landslide (Fig. 6 after, Gallois 2010).

Branscombe Mouth To Beer

Hooken Cliffs, between Branscombe Mouth and Beer Head are up to 130 m high. They expose the whole of the Upper Greensand Formation and the most complete succession of the Chalk Group in Devon (Mortimore *et al.*, 2001). According to contemporary accounts recorded by Conybeare et al. (1840), a landslide mass of seven to ten acres on the west side of Beer Head suddenly sank down 200 to 260 feet (61 to 79 m) during the night in March 1790. In the subsided area there were pinnacles of chalk and sunken fragments of fields that were still traversed by hedgerows including an undisturbed stile. Fishermen reported that crab-pots laid on the adjacent sea-bed were raised on a reef that was 15 ft (4.5 m) above sea level (Conybeare et al., 1840). Part of the reef has survived as the debris apron known as Sherborne Rocks. Ordnance Survey Six Inch to One Mile Sheet Devonshire 95 NE (1889) on which the subsided area is referred to as Under Hooken, shows a lozenge-shaped area c. 460 m long and 240 m wide. Immediately west of this, older landslide deposits, parts of which had been reclaimed as cultivated land, stretched 550 m to the foot of the western end of Hooken Cliffs.

The pinnacles referred to in contemporary accounts are still largely intact (Fig. 7a –d). The undisturbed Chalk stratigraphy in them can be matched in detail with that in the nearest *in situ* cliffs. This shows that the outer pinnacle has moved forward c. 180 m and subsided c. 60 m. The lower parts of the pinnacles expose an undisturbed succession in the Bindon Sandstone and Whitecliff Chert Members, and the Foxmould down to a level in the lower part of the member. Comparison with the nearest complete sections in the Foxmould, at Weston Cliff and White Cliff, suggests that the lowest *c.* 10 m of the member is now either below sea level or is missing through erosion, ground away during the forward movement of the landslide.

The *in situ* unconformable junction of the Foxmould with the Mercia Mudstone has been exposed from time to time at beach level below the western part of Hooken Cliffs [SY 210 881] where the bored top of the Mercia Mudstone Group is overlain by up to 1m of highly bioturbated clayey fine-grained sand at the base of the Foxmould.

This is overlain by a few millimeter-thick bed of dark grey plastic clay that marks the failure surface at the base of one of the older Hooken landslides (Gallois and Goldring, 2007). The lowest part of the landside deposit is a loose sand with angular clasts of sandstone and chert. The nearby Michell's Stile Rock [SY 2137 8091] and Martin's Rock [SY 2163 8047] expose the highest part of Upper Greensand and the junction with the Chalk: the same succession is exposed *in situ* c. 60m higher in the adjacent cliffs. Comparison of a drawing of the landslide (Fig. 7a) by William Dawson (plate X in Conybeare *et al.*, 1840, probably made in 1839 or 1840 at the time when the paper was being prepared) with a 2020 photograph (Fig. 7b) taken from roughly the same viewpoint shows that the three principal pillars in the landslide are still in place. The unrealistic overhanging nature of the *in situ* chalk cliffs in the drawing, reminiscent of Hokusai's (*c.* 1831) woodblock print The Wave, is presumed to be an artistic enhancement.

Comparison of a recent photograph (Fig. 7c) taken from the beach below Martin's Rock [SY 2163 8047], 200 m W of the pinnacles, with a painting of the landslide viewed from the top of Martin's Rock by H. Haseler in 1819 allows an estimate to be made of how much of the landslide deposit has been lost to erosion during the past 200 years (Fig. 7d). Haseler's painting also shows that there had been considerable erosion of the seaward part of the landslide prior to Dawson's (1840) drawing, including the loss of a former pillar. Contemporary paintings of Branscombe and coastal towns by the Haseler are accurately representational so there is no reason to believe that his depiction of the landslide is unduly distorted. The intact nature of the bedding/jointing and stratigraphy in the three remaining pillars suggest that they were supported during their downward and forward movement from their *in-situ* to present positions. This is confirmed by Haseler's painting which shows them enclosed and supported within a mass of landslide debris. As with the well-documented 1839 Bindon Landslide (Conybeare *et al.*, 1840; Pitts and Brunsden, 1987; Gallois, 2010) 3.5 km E of Seaton which involved the same Cretaceous succession, the Hooken Landslide probably took place over a period of days.

Failure Mechanisms

A common factor observed in the more recent (1990 to present) landslides in Cretaceous rocks on this part of the Devon coast is the fluidisation of sands in the lowest part of the Foxmould shortly after a period of wet weather. None of the available local rainfall records are sufficiently localised to identify higher-than-average periods of rainfall in the vicinity of a particular landslide. The build-up of water in decalcified sands is sufficient to explain minor sand flows such as those adjacent to Weston Mouth (Fig. 5a, b) and Littlecombe Shoot (Fig. 5c, d), but large landslides including those at Salcombe Mouth (Fig. 4c), the Hooken (Fig. 7b) and the 1839 Bindon Landslide [SY 277 895] that involve the full thickness of the Cretaceous succession require a basal shear failure to mobilise such large amounts of material. Shear surfaces have been recorded in (<50 mm thick) mudstones in the lowest 1 to 2m of the Foxmould, for example below the Hooken Landslide and the Bindon Landslide (Fig. 6), although these were not the primary failure surfaces of these events. The Bindon Landslide, of comparable size to the Hooken Landslide and involving similar large masses of Upper Greensand and Chalk, was attributed by Conybeare *et al.* (1840) to an initial failure in a bed of Gault clay following a prolonged period of unusually high rainfall. This, they surmised, turned the saturated lower part of the Foxmould into a "mass of quicksand" over which the Cretaceous rocks moved seaward. This explanation is supported by the present study in which it is suggested that sand-and-debris flows enable large masses of Cretaceous rocks to be displaced in an intact condition. Subsequent authors (*e.g.*, Pitts and Brunsden, 1987) rejected liquefaction of the Foxmould as a major contributing factor because they doubted that such a well-cemented material as the unweathered Foxmould seen at outcrop in the cliffs below the Bindon Landslide could be fluidised However, these cliff outcrops are restricted to the middle and upper parts of the member to lithologies that are more glauconitic, less prone to decalcification and contain common cemented tabular sandstones and 'Cowstones'. The basal, partially or wholly decalcified sandstones, are rarely seen at outcrop east of Seaton being everywhere obscured by landslide deposits, by vegetation or washed away during the formation of landslides.

Summary

There are extensive debris deposits derived from large landslides on the Devon coast between the county boundary at Lyme Regis and Sidmouth. All of these landslides were initiated close to the base of the Cretaceous deposits, in the Gault in much of the area east of Seaton and in the Upper Greensand west of there. Between Sidmouth and Seaton, the sandstones and calcarenites of the Upper Greensand rest unconformably and with sharp lithological contrast on the mudstones of the Mercia Mudstone Group. The limited historical and map evidence suggests that large landslides that involve the whole of the Cretaceous succession have been rare on this part of the coast, probably not more than one per 40 years. The area

Figure 8. *Comparison of the positions of the cliff tops and field boundaries (red lines) shown on Ordnance Survey Sheets Devonshire Sheets XCIV3 and XCIV4 25-inches-to-1 mile scale, surveyed 1888 and Channel Coast Observatory ortho-corrected photographs SY 14 87 and SY 15 87 (2017). (a) Dunscombe Cliff and (b) adjacent to Salcombe Mouth. See text for comments on accuracy of comparisons.*

is sparsely populated with the result that there are few, if any, descriptions of the historical landslides.

Hutchinson (1885) estimated that the average rate of retreat of the cliffs between Sidmouth and Branscombe Mouth was 8 ft (2.4 m) per century but did not describe the mechanisms involved. Comparison of the earliest large-scale Ordnance Survey maps (Devonshire Sheets XCIV3 to XCV2 25-inches-to-1 mile scale, surveyed 1888) with the most recent Channel Coast Observatory ortho-rectified air photographs (2017) enables estimates to be made of inland retreat of the cliff top. However, the difference between the Cassini Projection used on the maps and ortho-correction used for the photographs is such that the comparison accuracy is probably nowhere better than ±5 m. This is outwith the amount of retreat of the cliff top over almost all of the cliffs between Sidmouth and Seaton. An exception to this is the 2006 Salcombe Landslide where the retreat may be as much as 30 m (Fig. 8a). In contrast, the adjacent cliff line at Salcombe Mouth does not appear to show any significant retreat (Fig. 8b).

In those areas where the unconformity and the overlying failure surface are above sea level, the landslide debris comprises sand with sandstone and calcarenite clasts up to several metres across as at Dunscombe Cliffs (Fig. 4 a–c) and Weston Cliff (Fig. 5b). Where the failure surface is at or below sea level the debris includes intact masses on Upper Greensand and Chalk in which the stratigraphical succession remains intact as in the Hooken Landslide (Fig. 7) and the Bindon Landslide (Conybeare *et al*., 1840).

The landslides observed between Sidmouth and Seaton during the past 30 years can be divided into four types: (i) sand flows derived from the lowest, decalcified part of the Foxmould (Fig. 5d, e); (ii) sand flows from the same source accompanied by collapsed sandstones from the middle and upper parts of the Foxmould (Fig 5b, c); (iii) as (ii) but with debris derived from the Whitecliff Chert and Bindon Sandstone (Fig. 4c); and- (iv) as (iii) with the addition of stratigraphically intact masses of Upper Greensand and Chalk up to 160 m thick (Fig. 7). In those examples where the lowest few metres of the Foxmould have been observed *in situ* the larger failures appear to have been initiated in a thin (mostly <50 mm thick) bed of mudstone rich in expansible clay minerals shortly after a period of wet weather. This failure appears to have triggered the fluidisation of decalcified sandstones in the lowest part of the Foxmould which, in turn, caused the overlying beds to collapse. The combined materials resulted in a heterogeneous, mostly fine-grained debris flow which allowed blocks of sandstone and calcarenite up to several meters across to be carried downslope and into the sea. In the case of the Hooken Landslide, pillars of stratigraphically intact Upper Greensand and Chalk within the landslide debris moved forward up to 180 m and downward up to 60 m.

Acknowledgements

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