

THE RELATIONSHIP OF STRATIGRAPHICALLY CONTROLLED LITHOLOGICAL VARIATIONS IN THE MERCIA MUDSTONE GROUP (TRIASSIC) IN SOUTH-WEST ENGLAND TO WEATHERING PROCESSES AND LANDSLIDE MECHANISMS



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Gallois, R.W. 2013. The relationship of stratigraphically controlled lithological variations in the Mercia Mudstone Group (Triassic) in South-West England to weathering processes and landslide mechanisms. *Geoscience in South-West England*, **13**, 172-182.

The principal exposures of the 350 m to 450 m thick Mercia Mudstone Group in South-West England are cliff sections on the east Devon coast between Sidmouth and Seaton, and on the north Somerset coast between Blue Anchor and St Audrie's Bay. Inland, where the mudstones weather to clays that form slopes that mostly rest at 5° to 10°, there are few exposures. The group is divided on gross lithology into four formations and nine members, each of which influences the shapes of the cliff profiles and the types of landslide mechanism. On the Devon coast, failures in the lower part of the cliffs in the red silty mudstones of the Sidmouth Mudstone and Branscombe Mudstone Formations are initiated by marine erosion acting on joints and bedding planes: in the middle part by joint-bounded rock-block failures; and in the upper part by toppling failures and the failure of weak mudstone soils in the weathered zone. Thin (<10 mm thick) beds of laminated grey mudstone in the Dunscombe Mudstone and Blue Anchor Formations give rise to rotational and translational shear failures on the Devon coast. On the Somerset coast, where there is a large (up to 12 m) tide range and the cliffs are less protected by beach deposits, the principal landslide mechanisms are rock-block and toppling failures that are strongly influenced by faulting and have little relationship to the stratigraphy. Landslides in the Mercia Mudstone Group are rare in inland Devon and Somerset except for shallow-seated failures close to the spring line and unconformity at the base of the Cretaceous Upper Greensand Formation, and in some of the narrow, steep-sided valleys (goyles) on the Upper Greensand outcrop in east Devon.

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Keywords: Mercia Mudstone Group, Triassic, landslides, Devon, Somerset.

INTRODUCTION

An almost complete section through the Mercia Mudstone Group is exposed in the cliffs between High Peak [SY 105 860], Sidmouth and Haven Cliff [SY 270 895], Seaton in east Devon (Figure 1a). There, the group crops out with a low easterly dip in a series of long sections separated by small faults. Much of the outcrop is unconformably overlain by permeable sandstones of the Foxmould Member of the Cretaceous Upper Greensand Formation in cliffs up to 160 m high. Slope angles in the mudstone cliffs mostly range from 30° to 70°. The unconformity surface is marked by seepages and springs that give rise to gullies and secondary landslides in the underlying mudstones.

All except the lowest part of the group is exposed in fault-bounded sections on the Somerset coast between Gray Rock [ST 0385 4370], Blue Anchor and Watchet Harbour [ST 0734 4345], and between there and Blue Ben [ST 1207 4380], St Audrie's Bay (Figure 1b) in cliffs that are mostly 20 m to 40 m high. The faulting brings the Mercia Mudstone into juxtaposition with the predominantly argillaceous Penarth and Lias Groups, both of which contain beds that are prone to landslide.

The Mercia Mudstone is divided on the basis of gross lithology into four formations and nine members (Figure 2) that can be recognised throughout the outcrop and subcrop in southern England. The bulk of the group (Sidmouth Mudstone and Branscombe Mudstone Formations) comprises a rhythmic succession of brownish-red mudstones and silty mudstones in

which slightly darker clay-rich mudstones commonly pass up into paler, orange-brown, more silt-rich mudstones. Each rhythm reflects a change from a wetter to a drier climate. Beds of finely laminated mudstone and partially dolomitised mudstone (commonly green in colour), and brownish red coarse-grained siltstone to fine-grained sandstone occur at a few levels. The most common subsidiary lithology is thin (up to 0.3 m thick), laterally persistent beds of green mudstone, many of which are finely laminated and/or partially dolomitised. Gypsum occurs throughout the succession as nodular geodes and fine-grained cements (gypcretes), and as fibrous satin spa veins along joints and bedding planes. It is rock-forming in the Red Rock Gypsum Member, and is especially common in the Hook Ebb Member and in the Blue Anchor Formation on the Somerset coast. The sedimentology of the mudstones and the presence of gypsum/anhydrite nodules and salt pseudomorphs indicate deposition in playa-lake environments in hot deserts.

The Dunscombe Mudstone and Blue Anchor Formations comprise laminated green, grey and red-brown mudstones with thin limestone interbeds that were deposited in shallow ephemeral lakes in wetter climates. Beds of halite up to 130 m thick are present in graben areas in the Dunscombe Mudstone in the Wessex and Bristol Channel Basins (Gallois, 2003). These are absent from the Devon and Somerset coastal outcrops which were deposited in intergraben areas. Landslides in the Sidmouth and Branscombe Mudstones at outcrop on the Devon

coast are mostly initiated by the failure of deeply weathered material in the upper parts of the cliffs. A few rotational and bedding-plane translational failures occur along thin (a few cm thick) beds of fissile mudstone in the Dunscombe Mudstone and the Blue Anchor Formation. Most of the landslides in the Mercia Mudstone on the Somerset coast are strongly influenced by the proximity of fracture zones associated with faults.

Geotechnical properties of the Mercia Mudstone

The bulk of the Mercia Mudstone comprises mudstones made up of mixtures of clay minerals and quartz silt in varying proportions that were initially deposited in shallow temporary lakes and on damp mudflats in a low-relief landscape. They were subsequently partially redistributed and added to by flash floods and dust storms. The most common sedimentary structures are brecciation due to the repeated precipitation and dissolution of gypsum and salt evaporites, thermal expansion and contraction (insolation), and aggradation of the clay and silt particles to form weakly cemented silt- and sand-grade clusters. As a result, the clay contents of Mercia Mudstone samples

determined by x-ray diffraction are commonly higher than those measured by sedimentation methods (Dumbleton and West, 1966a). The disaggregation of these clusters, either naturally within the weathering profile or by mechanical working, can convert the mudstones from a weak rock to a liquid slurry (Atkinson *et al.*, 2003).

The clay mineralogy of the group at all stratigraphical levels is dominated by the detrital mineral mica (illite of some authors) with lesser amounts of chlorite (Dumbleton and West, 1966b). As a result, the Mercia Mudstone is considered to have a low shrink-swell potential. However, Atkinson *et al.* (2003) recorded appreciable contents (16-31%) of smectite in four samples from the Edwalton Formation (the correlative of part of the Sidmouth Mudstone) in the Midlands. In South-West England Jeans (1978) recorded a similar clay-mineral suite in the red silty mudstones from the Devon coast to that of Dumbleton and West (1966b). This assemblage is not conducive to the type of bedding-plane shear failure that is common in the Jurassic Charmouth Mudstone Formation (e.g. Gallois, 2008) and the Cretaceous Gault Formation (e.g. Hutchinson, 1969) in southern England. Jeans (2006)

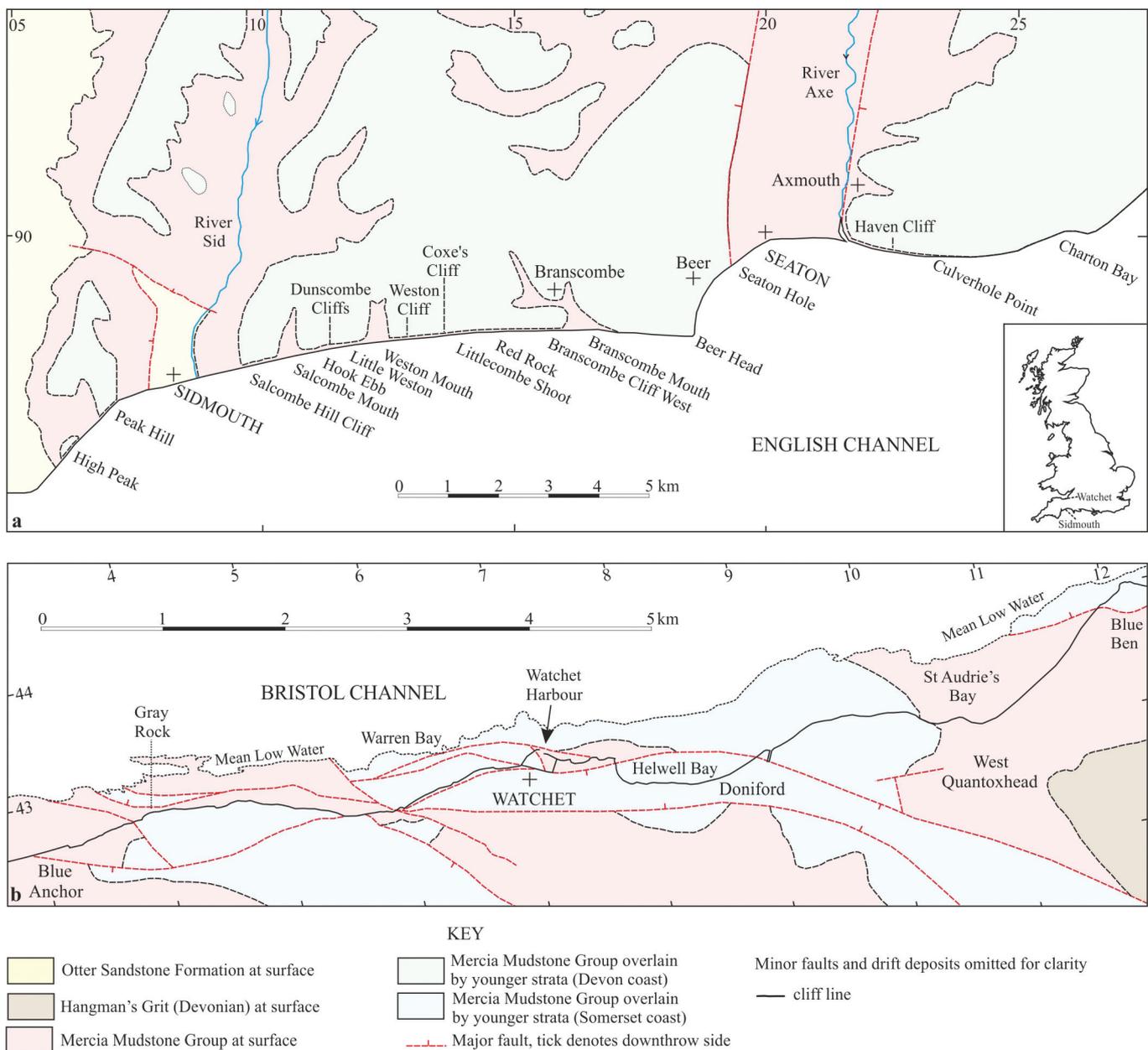


Figure 1. Geological sketch maps of the areas adjacent to (a) the east Devon coast and (b) the Somerset coast showing the positions of localities referred to in the text. Based on BGS 1:50,000 Geological Sheets 278 (Minehead), 279 (Weston-super-Mare) and 326 (Sidmouth).

Penarth Group			
Member	Mercia Mudstone Group	Predominant lithology metres	
Blue Anchor Formation	30	green mudstone with minor grey mudstone and limestone	
	Haven Cliff Mudstone	20 -400	interbedded red and green mudstones
Branscombe Mudstone Formation	Seaton Mudstone	120 -350 -300	red mudstone with common veins of fibrous gypsum
	Red Rock Gypsum	10	muddy gypsum/anhydrite
	Littlecombe Shoot Mudstone	75 -250 -200	red mudstone with minor sandstones
	Dunscombe Mudstone Formation	Lincombe Member	40
Sidmouth Mudstone Formation	Little Weston Mudstone	40 -150	interbedded red and purplish red mudstones and breccias with common gypsum
	Hook Ebb Mudstone	40 -100	red mudstone with much fibrous gypsum
	Salcombe Mouth	11	interbedded coarse siltstone and laminated mudstone
	Salcombe Hill Mudstone	60 -50	red mudstones with common nodular gypsum
	Sid Mudstone	15 0	red and green mudstones with dolomitic hardgrounds
	Sherwood Sandstone Group		

Figure 2. Generalised vertical section for the Mercia Mudstone Group succession exposed on the Devon and Somerset coasts (after Gallois, 2001). Generalised thicknesses are for the east Devon coast.

subsequently noted that the authigenic minerals smectite-mica, smectite-chlorite, sepiolite and palygorskite are present in significant quantities in laminated and/or carbonate-rich beds where they are largely confined to the Dunscombe Mudstone and Blue Anchor Formations. The Dunscombe Mudstone and Blue Anchor Formation in the Midlands are more silty and arenaceous proximal deposits than their correlatives in South-West England. Bedding-plane failures in laminated mudstones of the type that occur on the Devon coast have not been reported from that region.

Geotechnical classifications of the Mercia Mudstone are mostly based on the recognition of weathering zones in order to focus on the reduction in strength that can give rise to failures in engineering works. Chandler and Davies (1973) proposed a simple visual classification for which they defined four zones. Zone 1 comprises unweathered, jointed mudstone that is classified as a weak rock or highly consolidated soil. This passes up into fully weathered clays (Zone 4) by the progressive breakdown of mudstone lithorelics in a clay matrix. A more comprehensive classification which includes lithological variations and chemical properties was proposed by the British Standards Institution (1999).

The scarcity of substantial civil engineering projects founded on the Mercia Mudstone in South-West England means that there is little geotechnical data available for the group locally. Hobbs *et al.* (2002) compiled geotechnical data collected from site-investigation reports, mostly from shallow depths (<30 m below ground level), from road schemes in the Midlands and northern England. The compilation was extended to depths down to 50 m and the whole of England by Hobbs and Reeves (2009) who included all the data available at that time in the British Geological Survey's National Geotechnical Properties Database. Much of the data reported are restricted to the 'red' mudstones composed almost entirely of mica and chlorite. As one would expect, they exhibit a wide range of physical and mechanical properties depending on their weathering state: much of the material tested could be more accurately described as 'soil derived from the Mercia Mudstone' rather than Mercia Mudstone. Typical values for bulk density reported by Hobbs *et al.* (2002) range from 2.48 Mg/m³ for unweathered mudstones to 1.84 Mg/m³ for clays derived by weathering from the Mercia Mudstone. Reported unconfined compressive strengths and effective shear strengths vary by factors of 100 or more (Hobbs and Reeves, 2009) and confirm the observation of Chandler (1969) that the deformation behaviour of the mudstones in the Mercia Mudstone changes from brittle to plastic as weathering progresses.

RELATIONSHIP OF LITHOSTRATIGRAPHY TO LANDSLIDE MECHANISMS

Landslide mechanisms

Most of the landslides in the Sidmouth and Branscombe Mudstones in the lower and middle parts of the cliffs on the Devon and Somerset coasts are rock-block failures that range from small (up to a few kg) frequent falls to infrequent cliff collapses involving tens of thousands of tonnes of mudstone. These failures can be initiated by a wide range of factors or combinations of factors that make them unpredictable even in the most general terms. They include unusually wet weather (when pore pressures are higher and joint surfaces become lubricated), shrinkage on drying during hot dry spells, thermal expansion/contraction mostly after hard frosts, and dissolution in the more gypsum-rich parts of the succession. On the Devon coast, where almost all the cliffs are fronted by shingle beaches up to 6 m high, marine erosion at the foot of the cliffs in the form of undercutting and hydraulic stoping along joints is restricted to those areas where the beach is temporarily depleted or removed by erosion. This has most commonly happened in recent years at Pennington Point [SY 130 873], below Salcombe Hill [SY 140 875], at Hook Ebb [SY 155 878]

and at Seaton [SY 237 897]. Similarly on the Somerset coast, marine erosion is most pronounced in those areas that are commonly swept clear of beach deposits, notably at Gray Rock [ST 043 438], locally between there and Watchet [e.g. ST 046 437 and 065 435] and at Helwell Bay [ST 077 434].

In the upper parts of the cliffs the principal landslide mechanism is the failure of weak material in the weathering profile. In Devon where the mudstones are locally overlain by permeable decalcified Foxmould sands, springs at the base of the sands produce gullies and small landslides in the saturated mudstones below the junction. Seepages also occur within the mudstones at minor lithological changes, many of which are picked out by bedding-plane joints. Shear failures occur along a few of the thin (a few mm thick) laminated dark grey mudstones in the Dunscombe Mudstone and the Blue Anchor Formation.

Sidmouth Mudstone Formation

The Sidmouth Mudstone crops out in the cliffs between High Peak and Weston Mouth (Figure 3) where the shape of the cliff profile is markedly influenced by relatively minor variations in lithology (Figures 4a and b; 5a and b). The formation is divided into 4 members (Figure 2). At the base, the Sid Mudstone consists of silty mudstones with calcitised and/or dolomitised hardground surfaces and associated gypsum nodules. The Salcombe Hill Mudstone consists of mudstones and silty mudstones that show little lateral or vertical variation. Thin beds of siltstone, mostly <0.1 m thick, and partially dolomitised beds occur at several levels, the latter mostly in association with gypsum. In the middle part of the member, a bed of laminated, green mudstone forms a fissile harder unit and a break in slope in the cliffs (Figures 4a and b). The Salcombe Mouth Member comprises four fining-upward rhythms in which very fine-grained sandstones pass up into laminated mudstones. These are more resistant to weathering than the underlying and overlying mudstones and form a prominent rib that separates

the gullies in the Hook Ebb Mudstone from joint-bounded failures in the Salcombe Hill Mudstone (Figure 5b).

In the upper part of the Sidmouth Mudstone the Hook Ebb Mudstone and Little Weston Mudstones contain progressively higher concentrations of laminated green mudstones and gypsum veins and nodules than the older members. The highest 20 m of the Little Weston Mudstone is especially gypsum rich when fresh, but almost all of this has been removed by pervasive solution at outcrop on the coast and in inland exposures. This has given rise to friable mudstone with obscure deformed bedding and largely vegetated outcrops in the cliffs (Figure 5f).

Small lithological variations and jointing (Figures 5c and d) play important parts in delimiting the boundaries between the various types of landslide in the Sidmouth Mudstone. Weathering also has a significant role. In the highest parts of the cliffs the mudstones degrade to weak clay-rich soils that become fissured down to depths of several metres during dry periods. They commonly fail after prolonged periods of rain, at times as sufficiently large masses to cause secondary failures in the underlying mudstones. Recent examples have occurred at Pennington Point, Sidmouth (Gallois, 2011, fig. 6) and between there and Salcombe Hill. A landslide of several thousand tonnes 350 m ENE of the Sid outfall [SY 133 874] in October 2001 generated a debris cone that ran from the foot of the cliff to beyond low water mark (Figure 6). There is no published eye-witness account of the landslide, other than descriptions of the size, noise and clouds of dust that were reported in the local press. Examination of the debris cone shortly after the fall showed a crude reversed stratigraphy in which many of the larger blocks of stronger mudstone derived from the lower part of the cliff rested on the finer-grained, friable, more weathered material derived from the middle and upper parts of the cliff. It was assumed from this and observations of the landslide mechanisms in the adjacent cliffs that the following sequence of events had occurred:

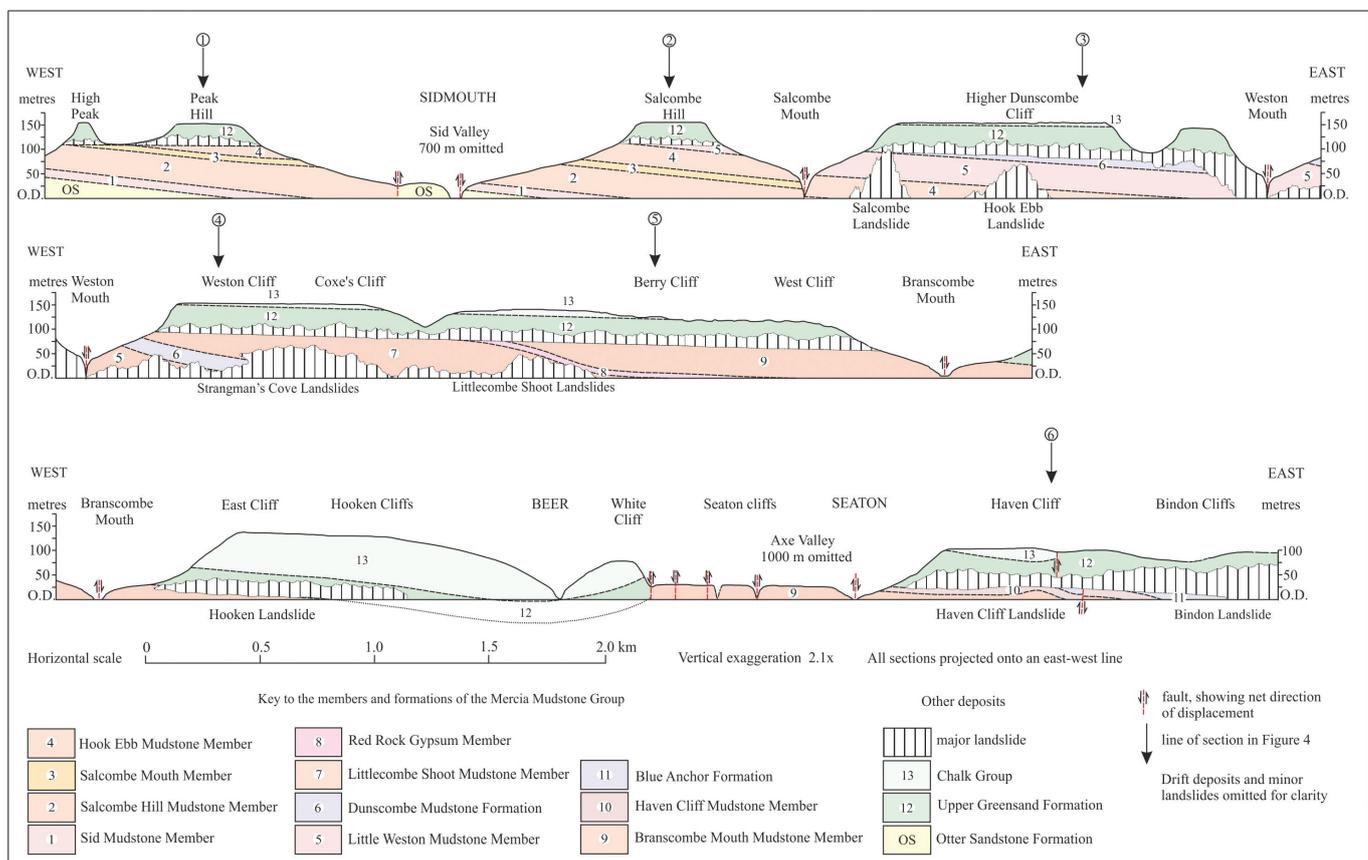


Figure 3. Geological sketch sections of the successions exposed in the east Devon cliffs between Peak Hill, Sidmouth and Haven Cliff, Seaton.

- 1) Failure of the top few metres of cliff formed of up to 5 m of deeply weathered (including the soil and subsoil profile) and partially remobilised mudstone, locally combined with sand or stony sand derived as hill wash from the Cretaceous Upper Greensand. Slope angles in these materials in the adjacent parts of the cliff varied between *c.* 40° and 70°.
- 2) Collapse of deeply weathered, friable mudstones in the

upper part of the cliff (initial slopes 50° to 80°).

- 3) Failure of middle part of cliff (slope angles mostly at 50° to vertical) where partially weathered and fractured mudstones were already locally undermined by small rock-block and toppling failures. This was especially so in the lowest part of the cliff where marine erosion had caused undercutting and hydraulic stoping along joints at times when the level of beach shingle had been low.

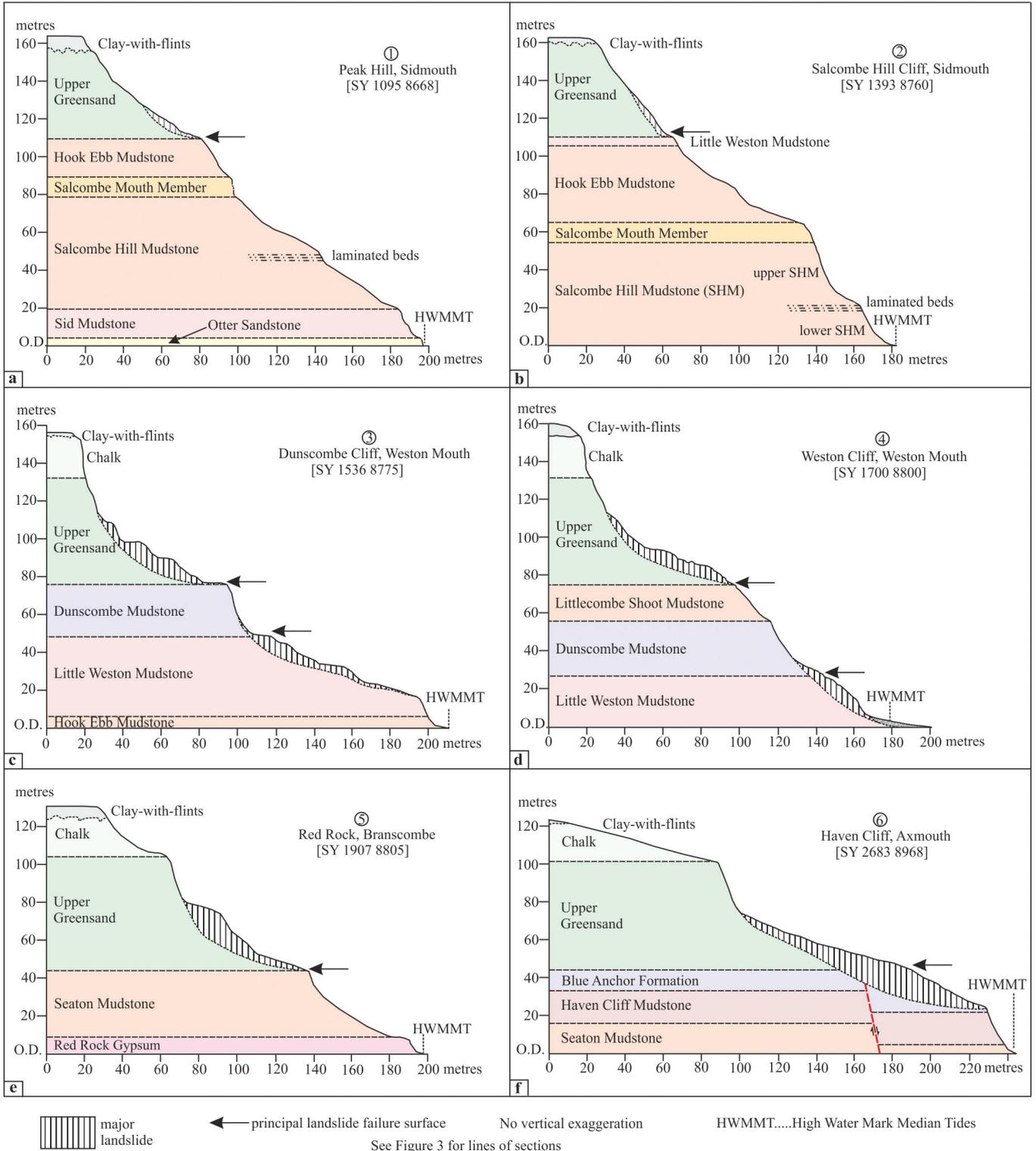


Figure 4. Selected geological sketch sections through the cliffs of the east Devon coast between Peak Hill, Sidmouth and Haven Cliff, Seaton. See Figure 3 for lines of sections. (a) Peak Hill [SY 1095 8668], Sidmouth. See also Figure 5a. (b) Salcombe Hill Cliff [SY 1393 8760], Sidmouth. See also Figure 5b. (c) Dunscombe Cliff [SY 1536 8775], Weston Mouth. See also Figure 5f. (d) Weston Cliff [SY 1700 8800], Weston Mouth. See also Figures 5e and g. (e) Red Rock [SY 1907 8805], Branscombe Mouth. See also Figure 7e. (f) Haven Cliff [SY 2683 8968], Axmouth. See also Figure 7f.

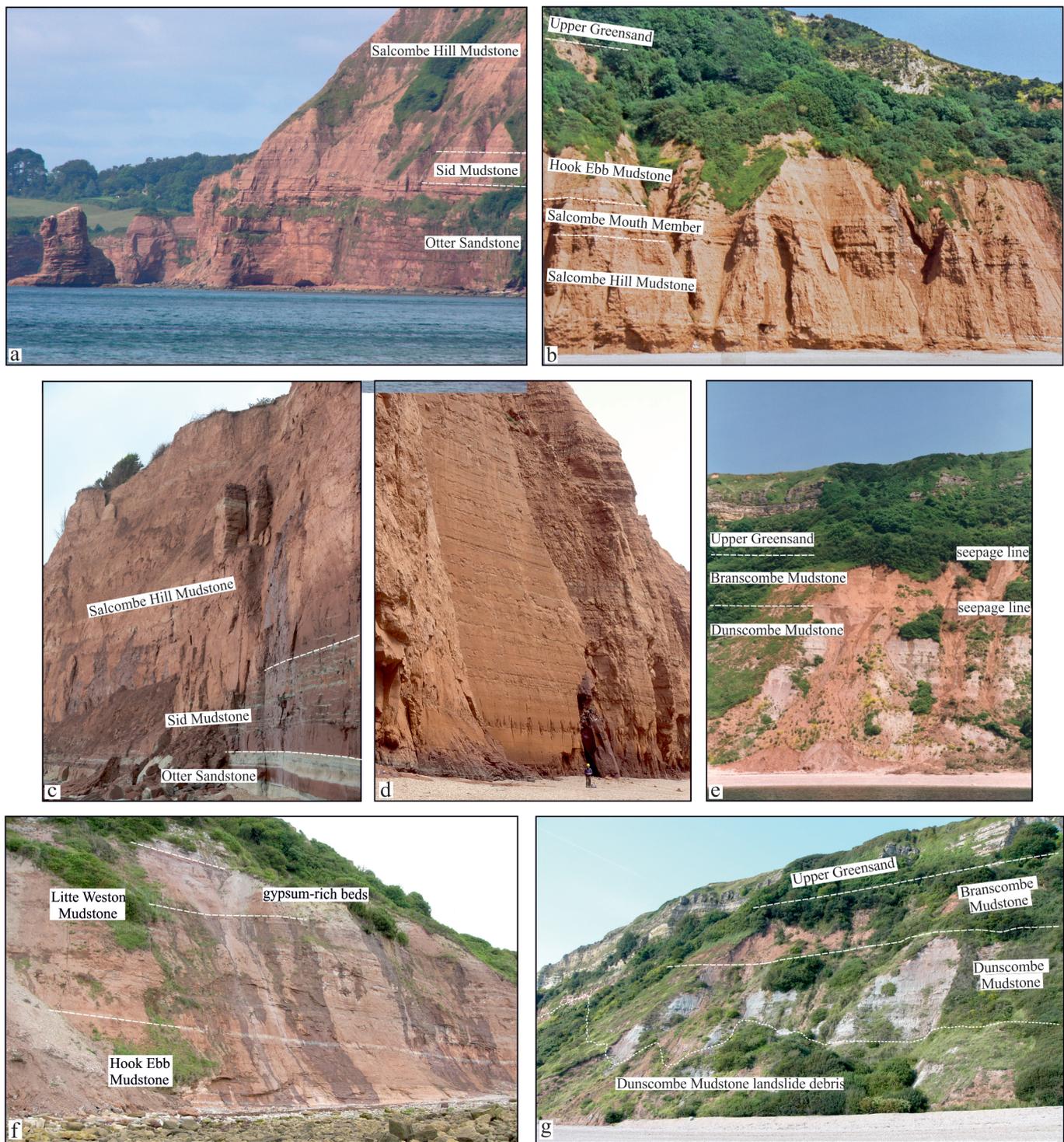


Figure 5. Landslides in the Mercia Mudstone Group on the Devon coast between Sidmouth and Branscombe. **(a)** View W from Jacob's Ladder, Sidmouth to High Peak [SY 105 855]. The cliff profile in the Sidmouth Mudstone reflects variations in the silt content, being steeper in the silt-rich Sid Mudstone and in laminated beds in the Salcombe Hill Mudstone. **(b)** Cliff [SY 1359 8747] below Salcombe Hill, Sidmouth in which the silt-rich Salcombe Mouth Member weathers out as strong ribs that separate predominantly joint-bounded failures in the Sid Mudstone from gully erosion in the overlying softer, more deeply weathered Hook Ebb Mudstone. As elsewhere on the east Devon coast the principal landslide failure surface is in a thin (5-10 mm thick) montmorillonite-rich mudstone close above the base of the Foxmould Member of the Upper Greensand Formation. Cliff c. 150 m high: photo uncorrected for parallax. **(c)** Toppling and rock-block failures occur as 1-2 m thick exfoliation sheets adjacent to major joints that run sub-parallel to the cliff face in the Salcombe Hill Mudstone. Pennington Point [SY 1310 8738], Sidmouth. Cliff 50 m high: photo uncorrected for parallax. **(d)** Major joint face in the Salcombe Hill Mudstone exposed by a recent rock-block failure. View N of cliff below Salcombe Hill, Sidmouth [SY 1380 8750]. **(e)** Mudflows in the Dunscombe Mudstone initiated by springs at the base of the Branscombe Mudstone and in permeable autobreccias in the highest part of the Dunscombe Mudstone after a period of heavy rain in September 2004. View N of 160 m high Weston Cliff [SY 1701 8795]: photo uncorrected for parallax. **(f)** View N of cliff above Hook Ebb [SY 1549 8774] where the upper part of the Little Weston Mudstone forms degraded, largely vegetated slopes due to the dissolution of a high gypsum content. **(g)** Landslides formed on failure surfaces in thin beds of dark grey mudstone in the Dunscombe Mudstone and close above the base of the Upper Greensand. View NW of slopes [SY 1692 8792] below Weston Cliff: photo uncorrected for parallax.

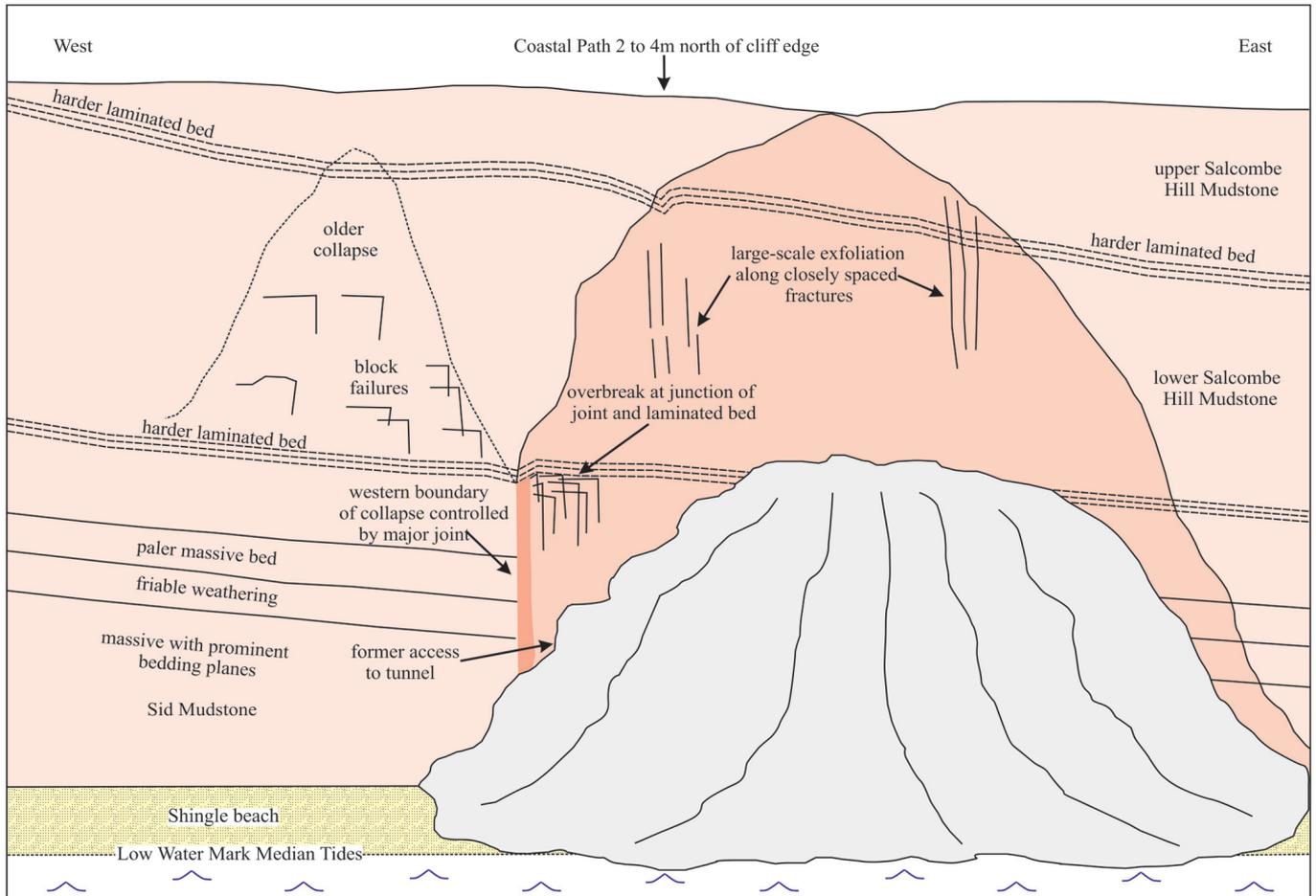
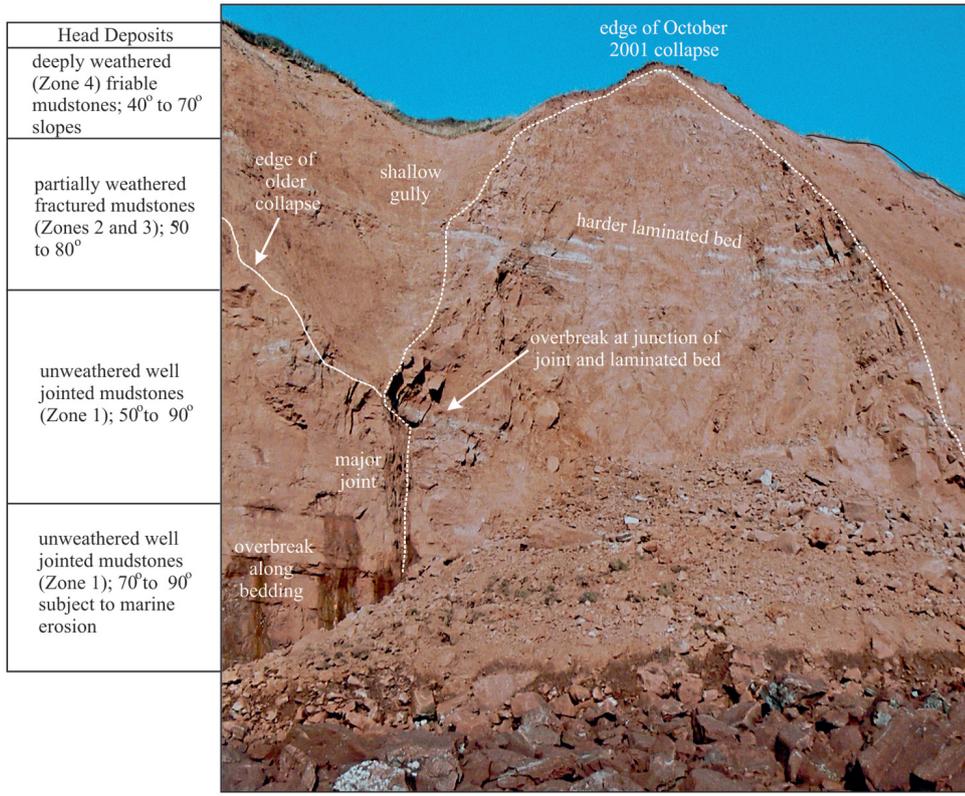


Figure 6. Landslide [SY 1388 8744] in the Salcombe Hill Mudstone 300m ENE of the River Sid, Sidmouth in October 2001. View N from low tide mark: cliff 50 m high, photo uncorrected for parallax. See text for details.

Dunscombe Mudstone Formation

The Dunscombe Mudstone consists at outcrop of 35–40 m of thinly interbedded green, purple and orange-brown mudstones with thin beds of dolomite, dark grey mudstone and mudstone autobreccias that were formed by the growth and dissolution of gypsum and halite (Gallois and Porter, 2006). Lenticular beds of fine-grained sandstone are locally present in the lower part of the formation, notably on the Devon coast and in the Taunton, North Curry and Sutton Mallet areas in Somerset. Much of the succession is well laminated, in marked contrast to the generally structureless mudstones of the Sidmouth and Branscombe Formations. The sedimentology and ichnology of the formation indicates that it was deposited in shallow, oxygenated freshwater lakes in a low-relief topography that was at times crossed by broad distributary channels (Porter and Gallois, 2008). The formation is poorly exposed inland, but the striking colour difference from that of the adjacent formations enables its outcrop to be traced more or less continuously from the Devon to Somerset coasts. At outcrop at Weston Mouth, laminated dark grey mudstones in the lowest part of the formation give rise to small bedding-plane failures (Figures 4c and d, 5g). On the Somerset coast the Dunscombe Mudstone only crops out at St Audrie's Bay [ST 1127 4320] where it is largely cut out by a fault.

Branscombe Mudstone Formation

The Branscombe Mudstone crops out in the cliffs between Weston Mouth and Branscombe where the unconformity at the base of the Cretaceous comes down to sea level, at Seaton in a fault zone on the west side of the Axe Valley, and east of the outfall of the river in Haven Sea Cliff (Figure 3). The formation is well exposed on the Somerset coast at St Audrie's Bay and partially exposed in fault zones between Watchet and Blue Anchor. It consists of up to 220 m of relatively uniform red-brown mudstones and orange-brown muddy siltstones with gypsum and thin beds of green laminated mudstone. The formation is poorly exposed inland where it mostly occupies low ground with few exposures: it underlies much of the Somerset Levels. In the middle part of the formation the 10 m-thick Red Rock Gypsum Member forms a prominent cliff on the Devon coast where it consists of anastomosing veins of gypsum and anhydrite separated by partings of red mudstone. It has not been recorded at outcrop inland and is poorly represented on the Somerset coast, in both cases due to dissolution. Secondary veins of fibrous gypsum are common throughout the Branscombe Mudstone in borehole cores, but at outcrop many of these are only represented by thin (a few mm thick) white flexible sheets composed of a mixture of palygorskite, sepiolite and celestite (Jeans, 1978).

The highest part of the formation, the Haven Cliff Mudstone, is well exposed at Haven Sea Cliff on the Devon coast and at St Audrie's Bay on the Somerset coast. It consists of up to 20 m of interbedded red (c. 60%) and green mudstones in beds 0.2 to 0.4 m thick that were referred to as the "*Variiegated Marls*" by earlier authors. On the Devon coast small-scale failures similar to those in the Sidmouth Mudstone are relatively frequent in the deeply weathered (Zone 4) soils in the highest few metres of the cliffs. At Seaton (Figure 7b) these are associated with more friable zones adjacent to faults. A succession of failures in the highest part of the cliffs in recent years has resulted in the retreat of the cliff top and the closure of the old coast road (Figures 7c and d).

Blue Anchor Formation

The Blue Anchor Formation is wholly exposed on the Devon coast at Haven Cliff and Charton Bay and on the Somerset coast at St Audrie's Bay and Blue Anchor (Figure 1). The succession, 30 m in Devon and up to 40 m in Somerset, consists of thinly interbedded grey and grey-green siltstones, muddy siltstones and silty mudstones with a few thin beds of dark grey

mudstone and relatively common beds of pale grey, finely laminated dolomitic limestone. The lithologies, and possibly some of the individual thin beds, are laterally persistent throughout the region. Much of the succession is finely laminated and was deposited subaqueously, probably in large, shallow, interconnected lakes that periodically dried up. Desiccation cracks are common at some levels, nodular and fibrous gypsum is common to abundant throughout the formation on the Somerset coast (Figure 8d), but confined to a few horizons in Devon.

On the Devon coast the formation forms relatively stable near-vertical cliffs in which the dip of the beds is normal to the cliff line. Joint-bounded, rock-block failures occur infrequently (Figure 7f). On the Somerset coast where the mudstones are more indurated than their correlatives in Devon, the Blue Anchor Formation forms stable cliffs in which most of the landslides are joint- and/or fault-bounded rock-block failures that are triggered by marine erosion at the foot of the cliffs.

SUMMARY AND CONCLUSIONS

The mudstones of the Mercia Mudstone Group, up to 450 m thick at outcrop on the Devon and Somerset coasts, appear at first sight to be lithologically relatively uniform. The group is divided into four formations, the predominantly red mudstones of the Sidmouth Mudstone and Branscombe Mudstone (c. 380 m thick in Devon) and the more variegated green, grey and red mudstones of the Dunscombe Mudstone and the Blue Anchor Formation (40 m and 30 m thick respectively in Devon). Where unweathered in the lower parts of the cliffs, the red mudstones form stable faces in which the predominant landslide mechanisms are infrequent toppling and rock-block failures as a result of marine erosion acting on combinations of vertical joints and bedding-plane joints. In the highest parts of the cliffs, where the mudstones weather to a weak clay soil by the mechanical effects of wetting and drying and freeze-thaw action, and the dissolution of weak carbonate and/or gypsum cements the surface layers become unstable when saturated. The resulting landslides commonly cause secondary rock-block falls in the underlying mudstones. Minor lithological variations in the mudstones, mostly related to silt content, that are laterally persistent over distances of tens of kilometres give rise to stratigraphically related variations in the cliff profiles and the types and rates of erosion.

Inland, where the red mudstones are deeply weathered to depths of several metres, they mostly form stable slopes of 2° to 7°. Slopes of up to 25° are present where the mudstones are overlain by the Upper Greensand (Slope Behaviour Unit A of Freeborough *et al.*, 2005). There is commonly a seepage line at the base of the sands which contributes to the tendency of the weathered mudstones to form shallow-seated landslides during periods of wet weather. The resulting deposits mostly contain a high proportion of sand derived from the decalcified Upper Greensand. In the absence of topographical evidence of recent movement, these deposits are difficult to differentiate from periglacial solifluction deposits that cover much of the Mercia Mudstone outcrop below the Upper Greensand outcrop.

The Mercia Mudstone outcrop on the Somerset coast is much affected by faulting (Figure 8a) which in places brings the red mudstones into juxtaposition with dark grey pyritic mudstones in the Penarth and Lias Groups that are prone to bedding-plane shear failure (Figures 8e and f). As a result of this and a more active marine erosion regime and greater tidal range than those of the Devon coast, minor stratigraphical variations in the Mercia Mudstone make little contribution to the landslide mechanisms or the shapes of the cliff profiles.

The Dunscombe Mudstone contains thin (5–10 mm thick) beds of dark grey mudstone that give rise to bedding-plane failures on the Devon coast and in some of the deeply incised valleys (goyles) inland in Devon. The Dunscombe Mudstone is largely cut out by faulting in its sole outcrop on the Somerset coast at St Audrie's Bay. The dips in lithologically similar beds

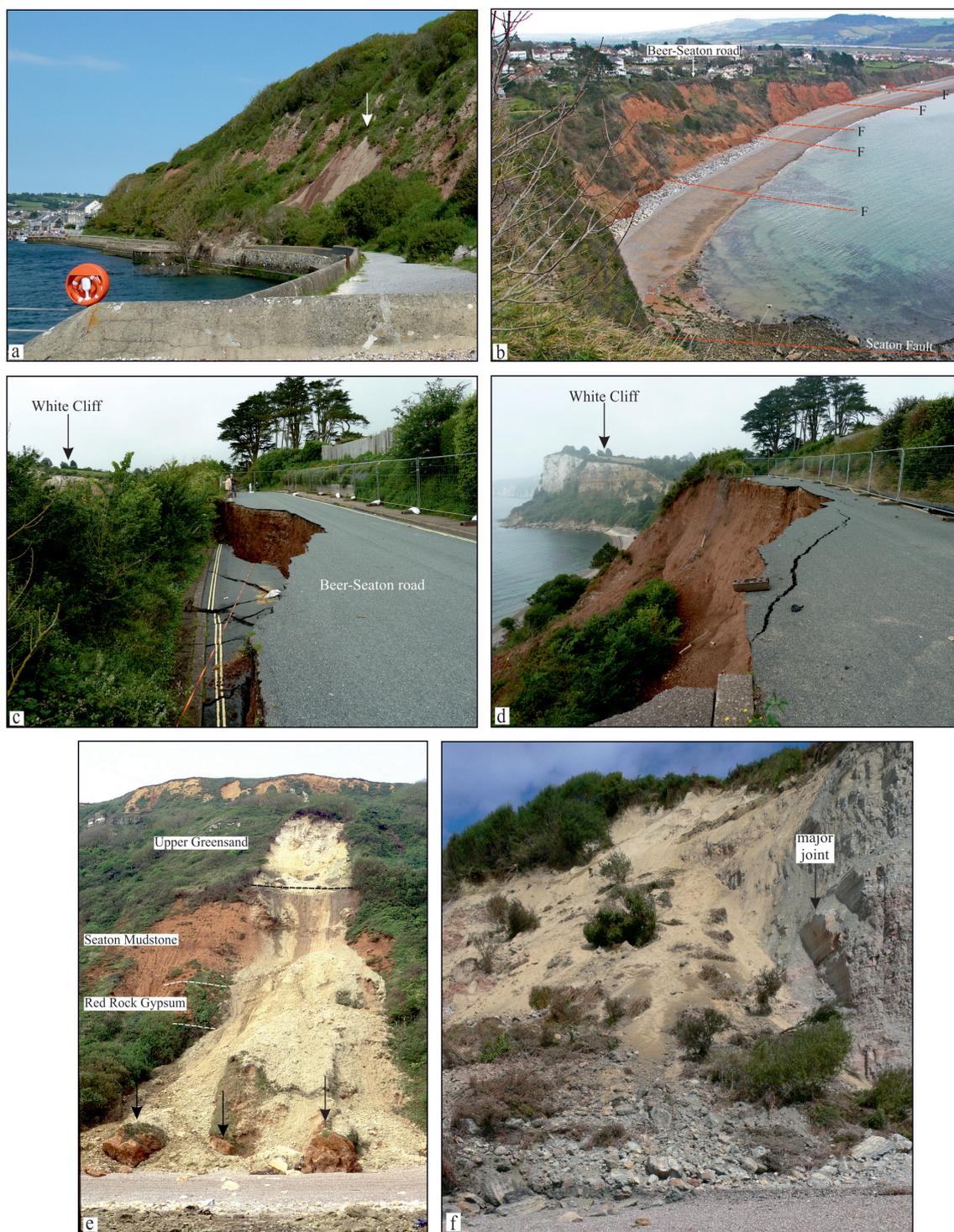


Figure 7. Landslides in the Mercia Mudstone Group on the Devon coast between Branscombe and Seaton. **(a)** A veneer of sandy clay up to 1 m thick, comprising deeply weathered Branscombe Mudstone and decalcified Upper Greensand from the higher slopes, became detached from a joint face in the Branscombe Mudstone (arrowed) following heavy rain in July 2012. The landslide debris pushed a mature tree into the river and blocked the access road [SY 256 897] to the outfall of the River Axe at Seaton. **(b)** View NW to Seaton and the Axe Valley from the Chalk outcrop that caps White Cliff [SY 1233 894]. The Seaton Mudstone outcrop is cut by N-S trending faults with displacements of 25 to 30 m that are sub-parallel to the major Seaton Fault (foreground). Small landslide movements occur in the weathered near-surface layers and in friable zones adjacent to the faults whenever the mudstones become saturated. Cliffs 25-35 m high: photo uncorrected for parallax. **(c)** An 80-m long section of the seaward side of the old Beer to Seaton road subsided up to 4 m in July 2012 following renewed movements of the landslides seen in Figure 7b after the wettest June on record (www.metoffice.gov.uk/badobs). The back scarp of the landslide exposes the road sub-base resting directly on deeply weathered (Zone 4) Seaton Mudstone. **(d)** Further subsidence in January 2013 following the fourth wettest December on record resulted in the loss of the remainder of the road. **(e)** Landslide [SY 1905 8796] in June 2001 in waterlogged decalcified Foxmould sand that resulted in the collapse of the remainder of the overlying Upper Greensand and Chalk and in secondary rock-block failures of the massive Red Rock Gypsum. Arrows indicate intact masses of the full 10 m thickness of the gypsum bed. Branscombe Ebb, Branscombe. Cliff 160 m high: photo uncorrected for parallax. **(f)** Rock-block failure [SY 2700 8946] in the Blue Anchor Formation at Haven Sea Cliff, Axmouth in 2008. The initial failure was at the intersection of a major joint (arrowed) and a thin (10 mm thick) bed of laminated dark grey mudstone. Secondary failures caused part of the underlying Haven Cliff Mudstone and loose sand derived from the overlying decalcified Foxmould to collapse. Cliff 50 m high: photo uncorrected for parallax.



Figure 8. Landslides in the Mercia Mudstone Group on the Somerset coast. **(a)** Vegetated landslide [ST 1104 4309] in highly fractured Branscombe Mudstone adjacent to a major fault, St Audrie's Bay. Cliff 30 m high: photo uncorrected for parallax. **(b)** Debris cones of mudstone and siltstone formed by the failure of deeply weathered (Zone 4) Branscombe Mudstone [ST 0353 4358], Blue Anchor, Somerset. Cliff 20 m high: photo uncorrected for parallax. **(c)** A large (several thousand tonnes) failure along a seaward-dipping fault plane in the Blue Anchor Formation at Grey Rock [ST 4371 0392], Blue Anchor gave rise to cuboidal joint- and bedding-bounded blocks of up to 200 m³. Cliff 50 m high: photo uncorrected for parallax. **(d)** Two-metre thick, upside-down block of gypsum-rich Blue Anchor Formation mudstone: Bed A in Figure 8c. **(e)** On the north side of Watchet Harbour a major fault that runs sub-parallel to and a few metres north of the cliff [ST 0768 4338] brings Blue Lias into contact with Branscombe Mudstone. Failures in the deeply weathered highest part of the Branscombe Mudstone have exposed weak Blue Lias mudstones and resulted in the rapid retreat of the cliff top. View N, cliff 20 m high: photo uncorrected for parallax. **(f)** Part of an extensive landslide complex [ST 0477 4364] up to 100 m wide and 900 m long parallel to the coast in a fault zone that juxtaposes Branscombe Mudstone, Penarth Group mudstones and Lias Group mudstones. View S from Warren Bay, Watchet. Cliff 50 m high: photo uncorrected for parallax.

of dark grey mudstone in the Blue Anchor Formation on both coasts are normal to the cliff lines and have not been observed to give rise to bedding-plane failures. Large rock-block failures in the Blue Anchor Formation on the Somerset coast may in part have resulted from the dissolution of gypsum which comprises up to 50% of the volume of some beds (Figure 8d).

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ACKNOWLEDGEMENTS

I am most grateful to Katy Freeborough and Peter Hobbs whose helpful comments on the first draft of this account resulted in many improvements.

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