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The development of an abandoned cliff in London Clay at Hadleigh, Essex

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[Plates 8–11]

Hadleigh Cliff forms part of a line of abandoned London Clay slopes, rising to a height of generally +40 m O.D. or more, which extends westwards from Southend-on-Sea. The cliff, with its toe level originally at about −19 m O.D., was formed by strong fluvial erosion in the Middle and Late Devensian. By the latter part of the Late Devensian erosion had virtually ceased and since then the cliff has degraded in an episodic manner, largely in response to climatic changes.

Four main stages of degradation, with intermediate periods of relative stability, have been recognized and dated, as follows:

(1) Late-glacial, periglacial mudsliding, associated with a toe level of −19 m O.D.

(2) Early Atlantic, temperate mudsliding, associated with a toe level which was rising with the continuing Flandrian aggradation, but lay on average at about −9 m O.D.

(3) Early Sub-Atlantic, temperate mudsliding, taking place to the present toe level of about +3 m O.D.

(4) A late 19th century, moderately deep-seated landslide in the crest of the slope, possibly caused in part by human interference.

The times at which the first three of these stages of degradation occurred are believed to represent periods of generally increased mass movement activity in much of Britain and Europe.

The present morphology of Hadleigh Cliff comprises a straight 20° scarp at the crest, an irregular and actively unstable 11° degradation zone, fronted by a smoother, quasi-stable accumulation zone inclined at about 8°. From a knowledge of the volumes and dates of the various colluvial units mantling the slope, reconstructions of earlier positions of the cliff profile are made. These indicate that during the last 10000 years the inclination of the combined degradation zone and crest scarp has declined from about 19° to 13°, while that of the accumulation zone has remained relatively constant. The accompanying recession of the cliff crest has been approximately 50 m.

From the pattern and dating of the various stages of colluviation, which increase both in age and in degree of fabric breakdown from crest to toe of the slope, it is clear that the cliff is degrading from the top. This is also reflected in the fact that the zone of weathered, *in situ* London Clay beneath the colluvium diminishes in thickness, in general, from bottom to top of the slope and is entirely absent beneath the late 19th century landslide.

In an average year the potential evaporation at Hadleigh exceeds the rainfall. As a result soil moisture deficits are unusually high and appreciable pore-water tensions in the capillary zone probably exist even at times of maximum seasonal piezometric levels. Account is taken of these in the stability analyses that are carried out, which indicate that the accumulation zone has a factor of safety of around 1.05 in comparison with the value of unity obtaining in the currently unstable degradation zone. A comparison between the values of ϕ'_r indicated by the back analyses and those measured on the Hadleigh colluvium in ring shear shows the latter to be appreciably the lower: the discrepancy is reduced if the effects of pore-water tensions in the capillary zone are allowed for.

INTRODUCTION

Attention has been drawn in an earlier paper (Hutchinson 1967*a*) to the process of free degradation, by which slopes that have been abandoned by the eroding agent which formed them are brought, given sufficient time, to a condition of long-term stability. Such slopes are widespread in the British Isles as a result chiefly of abandonment by the sea, by rivers, by glacial lakes and by melt-water flows. In addition to their scientific interest, abandoned slopes frequently give rise to serious civil engineering problems, particularly where formed in argillaceous strata, as described by Early & Skempton (1972).

In the course of the earlier work, which was essentially morphological and of a reconnaissance nature, a well developed line of abandoned cliffs was noted on the north side of the River Thames in southeast Essex (figure 1), between South Benfleet and Leigh on Sea (Hutchinson 1965). These cliffs are now fronted by the inned marshes of Hadleigh, Leigh and Canvey Island, and their foot is reached by the high tide only very exceptionally, as in the 1953 storm surge (Grieve 1959).

The present paper describes the detailed subsurface investigation of a part of the abandoned cliff line at Hadleigh (figure 2, plate 8), about 3 km west of Leigh on Sea. This slope was chosen for further study because it is geologically simple, consisting virtually entirely of London Clay, is unmodified by stabilization works, has at its foot a Flandrian marsh which seemed likely to yield datable organic material, and has on its crest a mediaeval castle which has been partly encroached upon by the more recent landslides affecting the cliff.

The main aims of the investigation were to elucidate the nature and mechanics of the processes whereby Hadleigh Cliff has developed to its present morphology and condition, and to date these.

GEOLOGY OF THE SITE

Solid geology

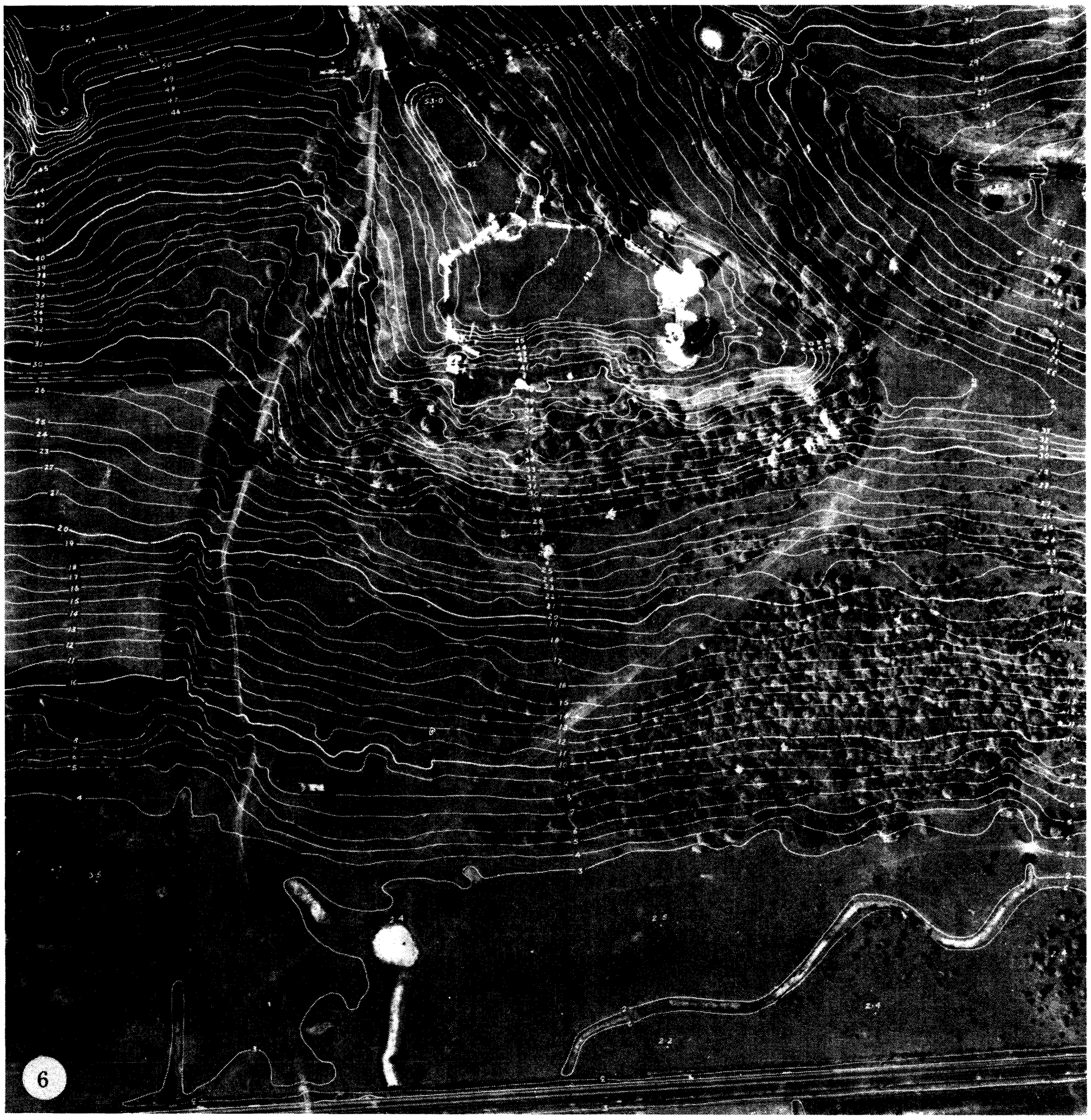
The abandoned cliff line between South Benfleet and Leigh on Sea forms the southern edge of the high ground of the Rayleigh Hills, which rises to a maximum elevation of about + 85 m O.D. and consists of outliers of Bagshot Sands, capped in places by high level Pleistocene gravels, and everywhere underlain by the Claygate Beds and the London Clay. The geological map of the area (figure 1) shows that the western part of the abandoned cliff line consists of London Clay capped with Claygate Beds and Bagshot Sands, whereas in the eastern part, where Hadleigh Cliff is situated, these cappings have been removed by past erosion, leaving the cliffs composed almost entirely of London Clay.

Recently a large number of boreholes have been put down in the alluvial marshes at the foot of the abandoned cliff, largely in connection with the Thames flood prevention scheme (Essex River Authority 1972). The locations of the more relevant of these, together with boreholes made by the Institute of Geological Sciences and by the Essex Water Company, are also shown

DESCRIPTION OF PLATE 8

FIGURE 2. Oblique aerial photograph of Hadleigh Castle looking southeast, taken 30 March 1954. The abandoned coastal cliff is encroaching on to the castle from the right and the River Thames is seen in the background (with acknowledgements to Aerofilms Ltd).

FIGURE 6. Orthophoto map of Hadleigh Cliff, with contours at 1 m vertical intervals (with acknowledgements to Fairey Surveys Ltd).



FIGURES 2 AND 6. For description see opposite.

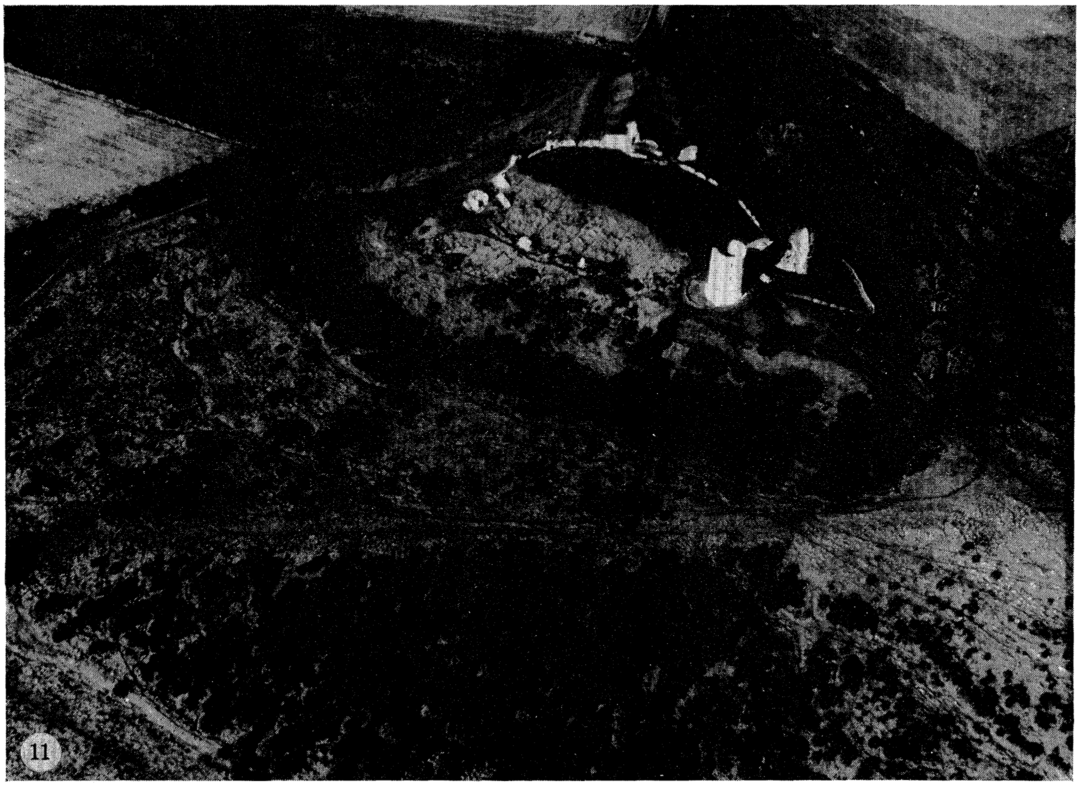


FIGURE 10. Oblique aerial photograph of Hadleigh Cliff, looking NW, taken 6 October 1928 (with acknowledgements to Aerofilms Ltd).

FIGURE 11. Oblique aerial photograph of Hadleigh Cliff, looking NW, taken 7 November 1967 (with acknowledgements to Aerofilms Ltd).

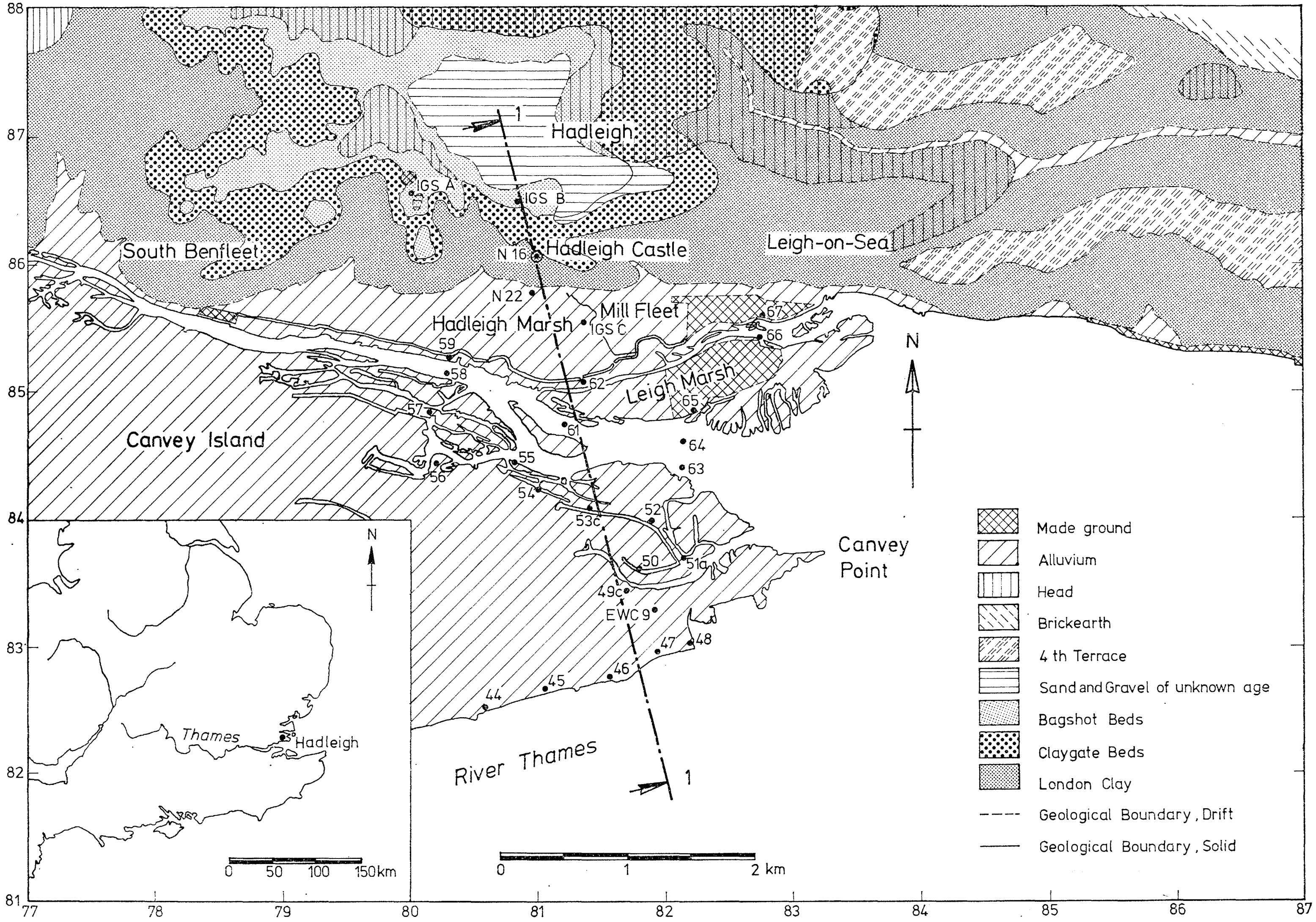


FIGURE 1. Geological map (based on Lake *et al.* 1975). (The '4th Terrace' may be equivalent to the 'Asheldham surface' of Gruhn *et al.* 1974.)

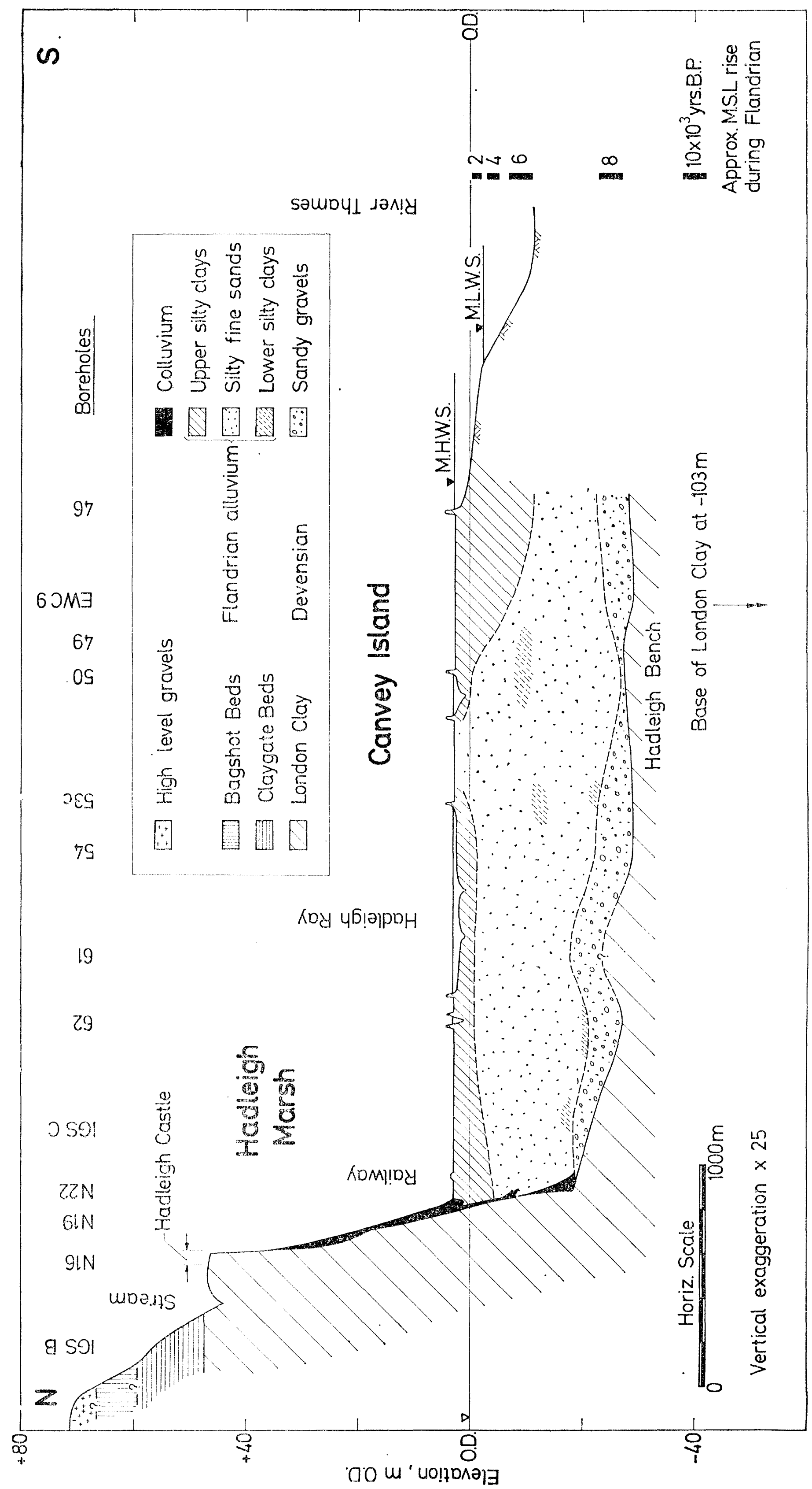


FIGURE 3. General cross section 1–1.

in figure 1. From this information it has been possible to draw a section (1–1, figures 1 and 3) defining the shape of the buried part of Hadleigh Cliff and details of the submarsh geology.

In this vicinity, the full thickness of the London Clay is between 130 and 140 m. As shown by figure 3, the crest of Hadleigh Cliff is virtually coincident with the junction between the London Clay and the Claygate Beds. This probably reflects the greater ease with which the latter stratum, with its frequent sand layers, could be eroded. The whole cliff is therefore composed of approximately the upper half of the London Clay stratum, or lithological units F, E, D and part of C as recognized by Lake, Ellison, Hanson & Conway (1975).

The area lies within the London Basin and is structurally simple. A minor fold, the Thundersley anticline, crosses the Rayleigh Hills from WNW to ESE, its axis passing through North Benfleet and Thundersley and north of Hadleigh Cliff (Wooldridge 1923). The London Clay in the abandoned cliffs is thus dipping in a southerly direction and Wooldridge suggested that the widespread landslipping on these is a reflexion of this structure. As the maximum dip attained is only of the order of 1°, however, the influence of structure on the landslides can be discounted.

Quaternary geology

Although the site has never been glaciated, it will have been subjected to periglacial conditions on a number of occasions during the Pleistocene. Also, in common with the lower Thames area generally, the present morphology and superficial geology of the site result from other important extra-glacial events associated with the Pleistocene glaciations, particularly the modification of the pre-existing drainage and vegetation patterns, the occurrence of high-energy, fluvial and niveo-fluvial flows and major, glacio-eustatic fluctuations of sea level.

In pre-Anglian times a forerunner of the River Thames flowed north of the present river, through Hertfordshire and Essex, possibly reaching the sea in the area now occupied by the estuaries of the Rivers Crouch and Blackwater (Wooldridge 1938; Wooldridge & Linton 1955; Wooldridge 1960; Kellaway *et al.* 1973). At this stage an ancestor of the River Medway, in flowing northwards to the original line of the Thames, is thought to have deposited the high level gravels of the Rayleigh Hills (figures 1 and 3). The Thames drainage then appears to have been forced southward by ice, probably during the Anglian, into essentially the route followed by the present river.

The situation at Hadleigh itself is summarized in figure 3. Beneath the alluvium lies a wide bench cut in the London Clay, referred to here as the 'Hadleigh bench', which has a general level of between –27 and –30 m O.D. but rises to –19 m O.D. at its northern limit, formed by the buried toe of Hadleigh Cliff. No subsurface data are available for the area to the south, beneath the present channel of the River Thames. The bench is largely covered by the 'Hadleigh gravels', an uneven spread of dense, sandy, subangular to rounded flint gravel, commonly between 4 and 6 m in thickness.† This, in turn, is overlain by 20–30 m of fine sands, silts, soft clays and peats. No other benches and terrace deposits are present, apart from those represented by the high level gravels (figures 1 and 3), any intermediate ones presumably having been removed by the erosion which formed Hadleigh Cliff. The knoll upon which Hadleigh Castle stands appears to be a purely local erosion remnant left by the adjacent streams to the W and NE (figure 1).

† An unworn mammoth tooth (*Mammuthus primigenius*), dredged up off Canvey Point (figure 1) in 1935 and held in the Prittlewell Priory Museum (D. G. Macleod, personal communication), may have come from an extension of this deposit.

Along the present course of the middle and lower Thames are developed the classical bench and terrace sequences, reviewed by Wooldridge & Linton (1955) and by Zeuner (1959), which have probably been formed at various times from the Hoxnian to the Devensian. As indicated by figure 4, however, these are poorly developed downstream of the Chalk belt associated with the Purfleet anticline, and are absent, above sea level, from about Fobbing through Hadleigh to Southend-on-Sea. In the latter area Gruhn, Bryan & Moss (1974) have mapped a sequence of benches and terraces which commence in Southend-on-Sea and trend NNE across Foulness Island, Wallasea Island and the Dengie peninsula to the River Blackwater (figure 4). Correlation of these benches and terraces with the classical sequence upstream of Hadleigh is rendered difficult, however, by the break in continuity noted above, by down-warping of this area towards the southern North Sea basin (West 1972) and by uncertainty as to the date and indeed the reality of some of the classical features. Nevertheless this altimetric approach does point to a Devensian age for the Hadleigh bench.

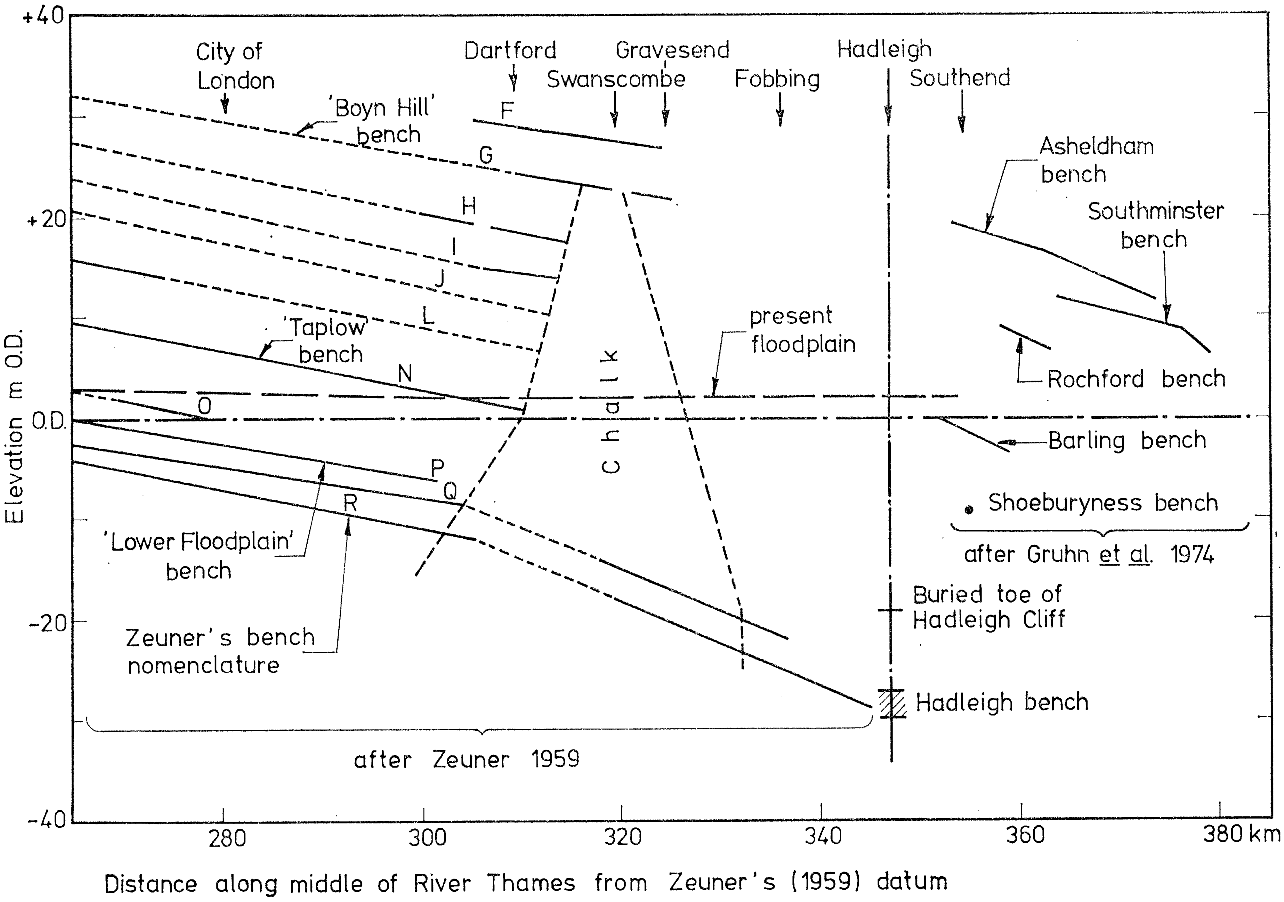


FIGURE 4. Longitudinal profile of the supposed benches of the lower Thames.

A detailed study of the Quaternary geology of this part of the lower Thames has been made by Lake *et al.* (1975). In the Canvey area they distinguish two 'buried channels'; the first cut in the London Clay and infilled with fluviatile sands and gravels, the second cut in the gravel filling of the first and infilled with fluviatile and estuarine clays, silts, fine sands and peats. In the estuary, these channels are reported to extend deeper than −40 m and −30 m O.D.

respectively. A tentative chronology of these events is summarized in table 1. In terms of the section of figure 3, the cutting of the first buried channel is represented by the erosion of the Hadleigh bench, and the gravels lying on this form part of the infilling of that channel. The cutting of the second buried channel is represented by the erosion surface at the level of the top of the Hadleigh gravels, and the overlying estuarine clays and silts constitute the infilling of that channel.

Table 1. Tentative chronology of Late Quaternary events in the Canvey area (after Lake *et al.* 1975)

event	approximate date in years B.P.†	stage‡
infilling of second buried channel	9000 to 500	Flandrian
		—10000—
erosion of second buried channel	17000	Late Devensian
infilling of first buried channel	25000	
		—26000—
cutting of first buried channel	27000	Middle Devensian

† Largely after Evans (1971). ‡ After Shotton (1973).

The erosion and partial removal of the Hadleigh gravels, is believed to have occurred in response to the Late Devensian maximum (*ca.* 18000–16000 B.P.), when sea level was depressed to about -100 m O.D. (Flint 1971). The subsequent climatic amelioration of the Late- and Postglacial brought about the decay of the Late Devensian ice sheets and a corresponding glacio-eustatic rise in sea level to about that of today. This Flandrian transgression is well documented and, although there is disagreement as to detail, the general trend is clear. It is illustrated, for the last 9000 years, in figure 5. The curves shown are the eustatic mean sea level curve of Mörner (1969, 1971) and the relative mean sea level curve of Greensmith & Tucker (1973). At Southend at the present day, mean sea level is $+0.2$ m O.D. and mean high water springs is $+2.8$ m. To each curve, therefore, 2.6 m has been added to yield an estimate of changes in high tide levels in the Thames Estuary during the Flandrian.

As the sea level rose, aggradation of estuarine and fluviatile sands, silts and clays took place. As D'Olier (1972) has shown, the shoreline in 9600 B.P. lay well to the east of the line Margate–Harwich, but by about 8000 B.P. practically the whole of the present Thames Estuary was submerged; figures 3 and 5 show that around 8000 B.P. the sea would be transgressing over the surface of the gravels lying on the Hadleigh bench, and reaching the foot of Hadleigh Cliff itself. The sea continued to rise rapidly until about 5000 B.P., almost to its present elevation, since when there has been a more gentle rise, with superimposed fluctuations (figure 5): deposition of sediments on the marshes would have continued until they were inned, probably between the 12th and 15th centuries (Evans 1953; Akeroyd 1972).

The aggradation of alluvium which accompanied the above transgression extends from the surface of the Hadleigh bench, or of the overlying gravels where they are present, up to present marsh level (figure 3). In their detailed study of this alluvium, Lake *et al.* (1975) distinguish three broad lithological units: uppermost soft to very soft, grey-black silty clays and clayey silts, overlying medium dense, blue-grey silty fine to medium sands, which in turn overlie lower

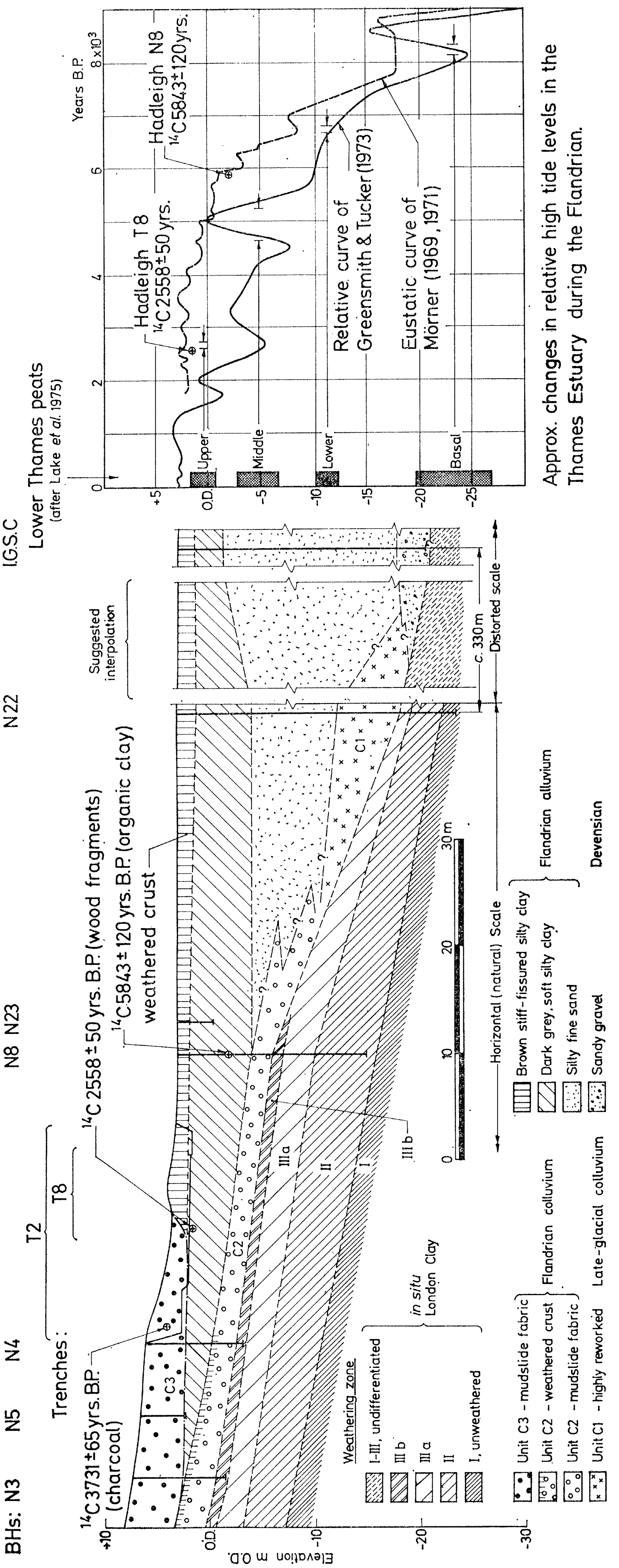


FIGURE 5. Detailed cross section of lower part of Hadleigh Cliff and the adjoining marsh, with details of the Flandrian transgression.

silty clays similar to the uppermost unit. The last unit is only intermittently developed. The approximate extent of these units on section 1–1 is shown in figure 3. In addition Lake *et al.* recognize four broad depth zones in the lower Thames in which peat or peaty layers are found. These are considered to represent temporary stillstands or slight regressions interrupting the general Flandrian sea level rise. Details are shown, in relation to the estimated curves of sea level variation, in figure 5.

Discussion of the development of Hadleigh Cliff following its abandonment, and of the relations between the resultant colluvium and the Flandrian alluvium at its foot, is deferred until a later section.

Topography of the site

The line of abandoned cliffs between South Benfleet and Leigh on Sea is discontinuous, being cut at intervals by small stream valleys trending south or southeast. Discounting the steeper crest formed by the Bagshot Sands and Claygate Beds where present, the upper slopes of the side valleys cut in the London Clay to the west and northeast of Hadleigh Castle are generally between 9 and 11°. This suggests that these valleys are older features than the abandoned Hadleigh Cliff, which in its upper parts has an average slope of over 12° (Hutchinson 1965).

Hadleigh Castle occupies an isolated knoll of London Clay between the above-mentioned side valleys, and Hadleigh Cliff is the abandoned slope formed on its southern face. The topography of the site has been established partly by levelled sections and partly by aerial photogrammetry. By using vertical aerial photographic cover at a scale of 1:4800, taken in July 1967, an orthophoto map with a contour interval of 1 m was produced. A reduced version of this is given in figure 6, plate 8. This illustrates the nature of the castle site and of the abandoned cliff falling southwards from it to Hadleigh Marsh. The crest of the cliff has an elevation of about +47 m O.D.: its intersection with the marsh is at +3 m O.D. The southeasterly trending side valley to the northeast of the castle is shown and also part of the more complex valley to the west. The Tilbury to Southend railway line runs across the marsh to the south of the slope toe. The linear feature trending SW–NE across the abandoned slope is the track of a buried pipeline, constructed in September 1964.

A preliminary description of the morphology of the landslides occupying Hadleigh Cliff has been given by Hutchinson (1965, 1967*a*). A more detailed plan of these features, prepared from the orthophoto and a field examination, is given in figure 7. In broad terms a degradation zone in the upper cliff, inclined at an average angle of about 12°, can be recognized, fronted by a more gently inclined accumulation zone of about 8° average angle extending down to marsh level. The most prominent feature is the large rotational slip which occupies the uppermost part of the slope and has encroached upon the south curtain wall of the castle. Below this is an irregular zone of open tension cracks followed by fresh toe features in the lower part of the degradation zone, which extends down to about borehole N6. The smoother, more gently inclined accumulation zone, which extends from this point down to Hadleigh Marsh, shows little sign of recent movement except for a slight ridge in the alluvium just clear of the slip toe, which is believed to represent a passive heave. A fuller discussion of these features is deferred until later. The landslides on the adjacent length of abandoned cliff to the west, beneath Sandpit Hill and Round Hill, were noted by Whitaker (1889).

Between 1891 and 1895 the Salvation Army set up a new brickworks on the western parts of the Hadleigh Cliff accumulation zone (Ordnance Survey 1897, Telford, not dated; Sandall

1955). This involved the digging of brickpits to the west of Castle Lane and the construction of a kiln and pottery to the east (figure 7). The possible effect of these works on the stability of Hadleigh Cliff is discussed subsequently.

Hadleigh Cliff is particularly well sheltered from marine erosion, especially from the gales of longest fetch, from the northeast. In this it makes a striking contrast with the cliffs of north Sheppey, on the opposite side of the estuary. These are closely similar to Hadleigh in geology and elevation but suffer the strongest erosion of any London Clay cliffs and have consequently a very different morphology and pattern of landsliding (Hutchinson 1973).

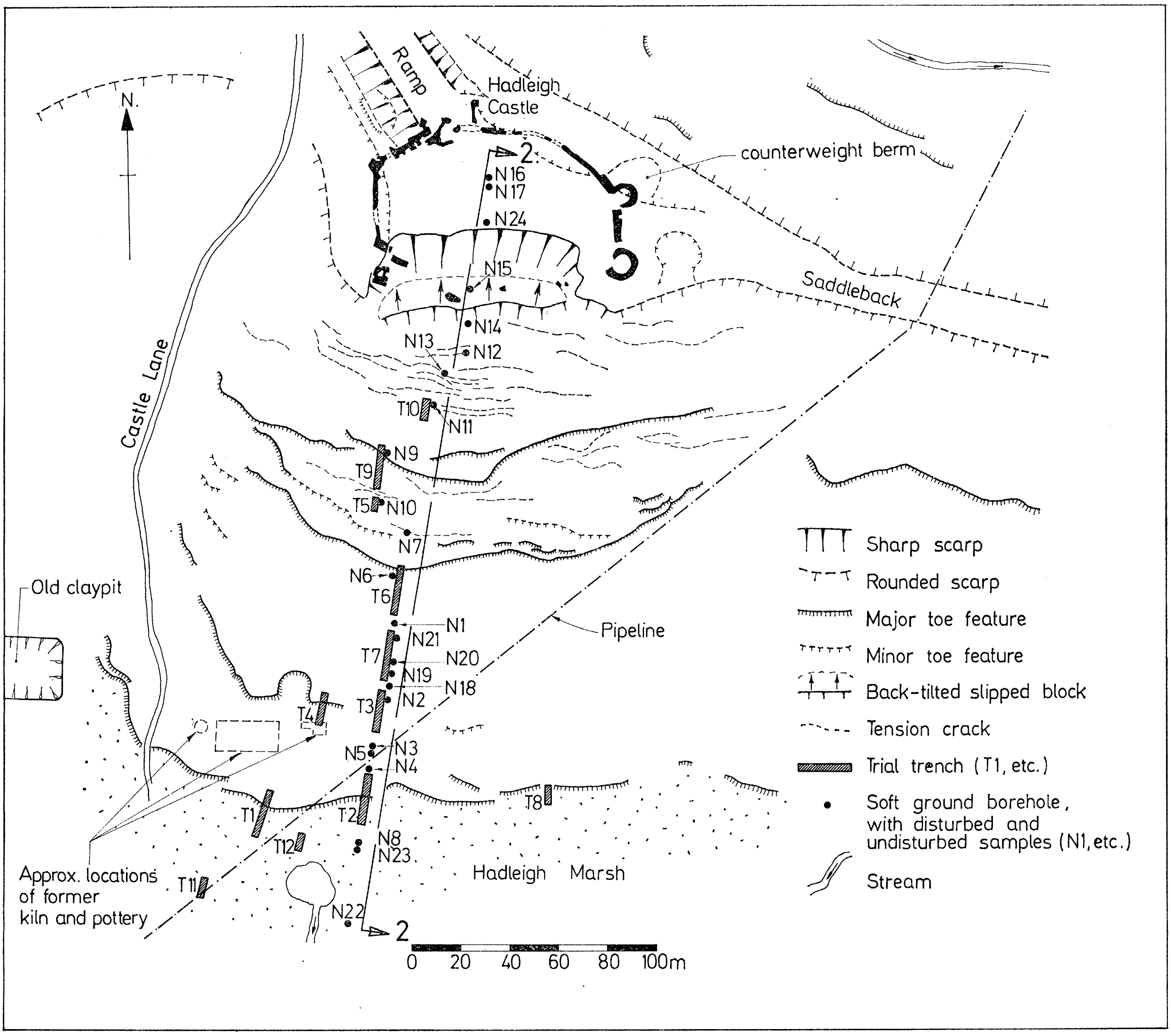


FIGURE 7. Site plan, with details of morphology and locations of boreholes and trenches.

HADLEIGH CASTLE

Hadleigh Castle (figure 8) was built under a licence granted by Henry III in A.D. 1230. The structure was allowed to deteriorate, despite minor repairs, until about 1360–70, when a major rebuilding was undertaken by Edward III. This included the construction of two eastern angle towers (B and C on figure 8), which were completed in about 1365. In 1552, Edward VI sold the castle to Lord Riche who probably began its systematic demolition for building materials (Brown, Colvin & Taylor 1963; Drewett 1975).

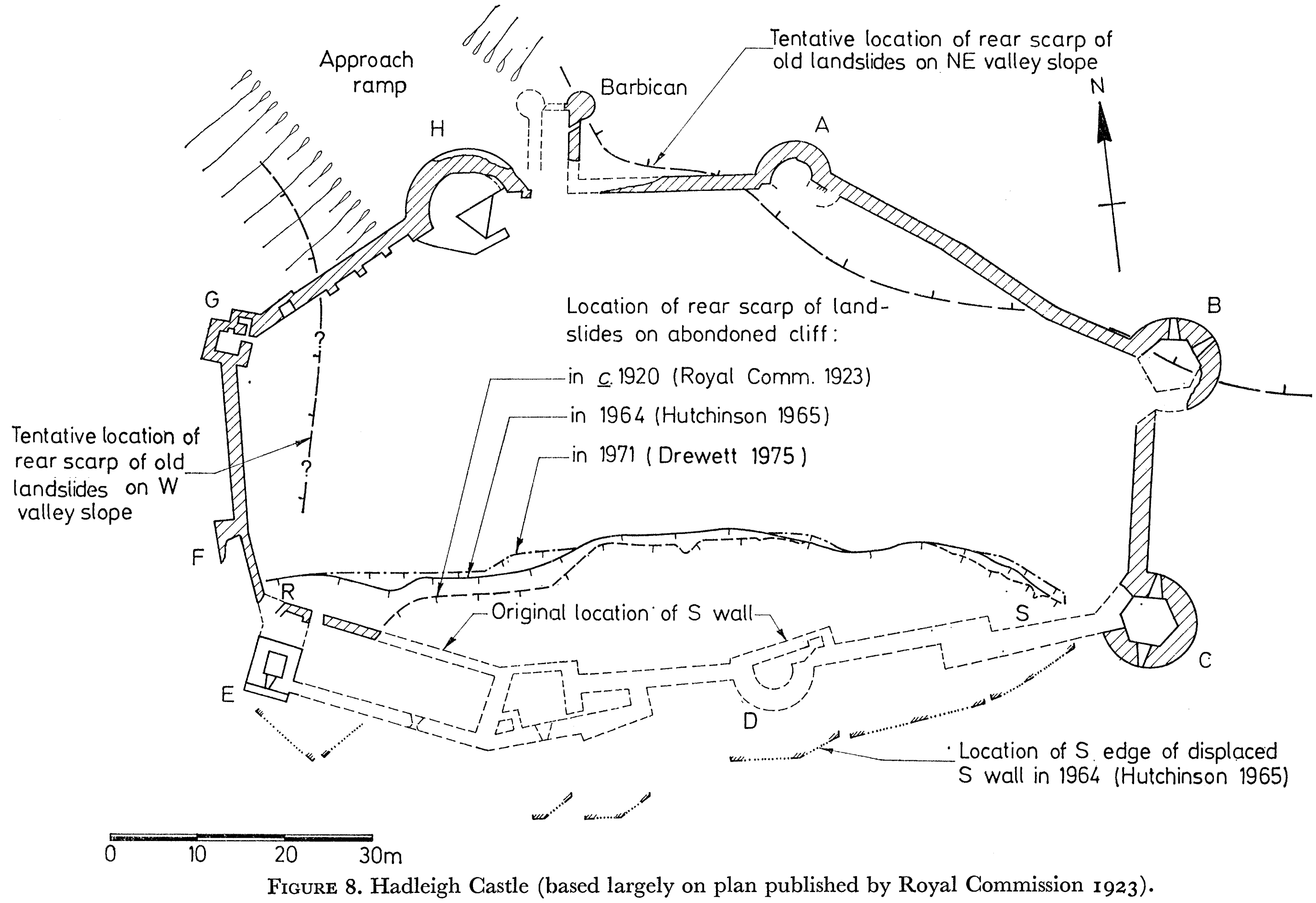


FIGURE 8. Hadleigh Castle (based largely on plan published by Royal Commission 1923).

A water-mill, perhaps a tide-mill, stood beneath the castle on the edge of the estuary from at least A.D. 1250. By this mill was a wharf which was in all probability used to bring in materials, chiefly Reigate stone and Kentish ragstone, for the building of the castle (King 1863; Royal Commission 1923; Brown *et al.* 1963). King states that the site of this mill was by the side of the creek now known as Mill Fleet† (figure 1) which, at the time when the castle was built, he believes was navigable to the foot of the slope. During the construction of culverts on the line of the Tilbury and Southend Railway, opened past Hadleigh in 1855 (Welch 1951), the workmen came across planks and timbers at a depth of 3.7 m which appeared to be the remains

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† This name was formerly applied to the creek between Hadleigh Marsh and Leigh Marsh (Chapman & André 1777), but King was clearly using it in the sense defined by figure 1 and the Ordnance Survey maps.

of sunken rafts or vessels† by which the ragstone had been brought from Kent, considerable quantities of that material being found with the old timbers (King 1863).

The knoll occupied by the Castle is bounded to the south by the fresh crest of the unstable abandoned cliff, and to the west and northeast by the subdued crests of the unstable, but less active, side-valley slopes (figures 6–8). The stable area available for the construction of the castle was therefore limited and, indeed, appears to have been inadequate for the size of structure built. As a result the western curtain wall and towers, from just northeast of tower G to tower F and probably tower E, were constructed below the crest of the unstable western side-valley slope and were thus founded almost certainly on old landslip material. It is not

Table 2. Some details of damage to Hadleigh Castle and its bailey caused by landslides

event and location (figure 8)	date	cause	reference
possible collapse of 'phase I structure', sited up to 22 m E of Tower F	1230–60	probably 'local movements in the underlying clay'	Drewett (1975)
castle gate and other buildings in need of repair	1240	not stated	Brown *et al.* (1963)
collapse of western curtain wall between towers F and G, the adjoining 'Phase II hall' and probably tower G	towards end of 13th Cent.	movement 'towards the SW due to slumping of the underlying clay'	Drewett (1975)
collapse of part of curtain wall, probably near the barbican	1317–18	not stated	Brown *et al.* (1963)
landslide to the S which carried away foundation of tower D, leaving the bulk of the S curtain wall intact	post 1738, pre 1863	continuing degradation of Hadleigh Cliff	Buck (1738) King (1863)
major landslide to the S which carried practically the whole S curtain wall downhill for about 12 m	post 1881, pre 1920, some movt by 1895	continuing degradation of Hadleigh Cliff	1:2500 O.S. maps of 1868, 1897 and 1922; Sparvel-Bayly (1881); Royal Commission (1923)
landslide to the NE which back-tilted NE half of tower B	post 1930, pre 1955	slipping at crest of the northeastern side valley	air photos of 1930 and 1955
collapse of most of remaining eastern part of tower B	29–30 Jan. 1965	continued ditto	Cooke (personal communication)
minor landslides to the S in the W part of rear scarp, roughly 20–30 m E of tower F: the largest was 6–7 m wide and sank 3 m	on and around 31 March 1969, following snow-melt	continuing minor degradation of rear scarp left by major, late 19th Cent. landslide	Hodson (personal communication)
minor landslides to the S in the W part of rear scarp, roughly 0–30 m E of tower F	winter 1969–70	ditto	Drewett (1975)
continuing minor landslides to the S on rear scarp, generally involving the spoil bulldozed there in 1971 and 1972	1975	softening of spoil, and renewals of movement in earlier slides due in part to loading of spoil	

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† Not to be confused with the charred timbers and bones from Danish long-boats reputedly discovered during construction of the same railway line around $3\frac{1}{2}$ km to the west, near Benfleet Station. These are believed to have been sunk during the battle of Benfleet in A.D. 894 (Welch 1951; Helliwell, personal communication).

surprising, therefore, that these western parts of the castle collapsed soon after their construction, as a result of landslide movements, probably on pre-existing shears, towards the west. A summary of the more important instances of damage to the castle and its bailey, resulting from landslides, is given in table 2.

Tower H and its immediately adjoining structures were probably founded clear of the old slips and their foundations are still essentially intact. As figures 7 and 8 show, however, tower A and the wall from there almost to tower B were sited below the crest of the unstable slope falling to the notheastern side valley. Tower A has accordingly disappeared and the curtain wall between there and tower B shows signs of marked outward displacement and cracking.

Tower B itself, completed in 1365, is located astride the degraded crest of the unstable northeastern valley slopes (figures 7 and 8). An exploratory excavation made in 1964 showed that this tower is founded over 3 m below ground level on its south side (at approximately +43 m O.D.) and, at least in its rearward half, rests on *in situ* London Clay. Its foundations appear to have remained stable until a few decades ago when a rotational slip, probably of first-time type, in the crest of the northeastern valley slope, carried down and back-tilted their forward (northeastern) part. From the evidence of aerial photographs (Plates 5.3 and 5.6 in Gostelow 1974) it seems that this landslip took place between 1930 and 1955. Control measurements made from 1960 to 1965 (H. Cooke, personal communication) show that the slipped part of the tower foundation was then still moving downwards and outwards with respect to its stable, inner part. In 1965 the back-tilt of the forward part of this tower was about 13° (Hutchinson 1965). Stabilization works, consisting chiefly of a counterweight berm about 1.5 m thick and 11 m wide (figure 7), were proposed by the Building Research Station in 1964 and executed in the autumn of 1966 (details on Ministry of Public Buildings and Works, Ancient Monuments Branch, job no. 623, drawing no. 6). These halted the slip movements, but were put in hand too late to prevent the collapse of much of the remaining back-tilted part of tower B, which occurred during the night of 29 January 1965 (H. Cooke, personal communication).

Tower C and the curtain wall between there and tower B appear to have been built on stable ground and their foundations are still in reasonably good condition, though tower C would, of course, be threatened by any further retrogression of the abandoned cliff in its vicinity.

The behaviour of the southern wall and towers of the castle, built at the crest of the abandoned cliff, is of chief interest in the present connection. The greater part of this wall dates from the original construction of the castle, which started in A.D. 1230. Tower D may be slightly later, though still of 13th century date (Drewett 1975). The exact relation between the south curtain wall and the crest of the abandoned cliff at the time of its construction is not known. It appears from Mr Drewett's excavations, however, that the curtain wall was probably built just south of the cliff crest, and backfilled on its north side to provide a level foundation for the range of buildings which formerly stood against it.

Although the partial demolition of the castle for building materials after the mid-16th century tends to confuse the issue, it appears from contemporary prints and sketches that the south curtain wall and tower D were still standing in the 18th (Buck 1738) and 19th (figure 9) centuries. In the course of the excavations carried out by H. M. and H. W. King in 1863, it was noted that the semi-annular mass of masonry forming tower D had been 'torn from the side wall, and upturned in the form of an inverted arch'. It was added that its position could only be accounted for by 'supposing that a landslip on the slope of the hill had carried away the foundations of the tower, and that this mass, the stones adhering by the extraordinary tenacity of the mortar, dropped into its present position' (King 1863). The inference is that the foundations of the south curtain wall were still intact, as indeed they are shown to be on the ground plan of the castle surveyed in 1863 (King 1863). A sketch by Miss Garrould, reproduced by Sparvel-Bayly (1881), confirms that by then tower D had fallen and suggests that the slip scarp may have begun to encroach on the eastern part of the south curtain wall, between towers D and C.

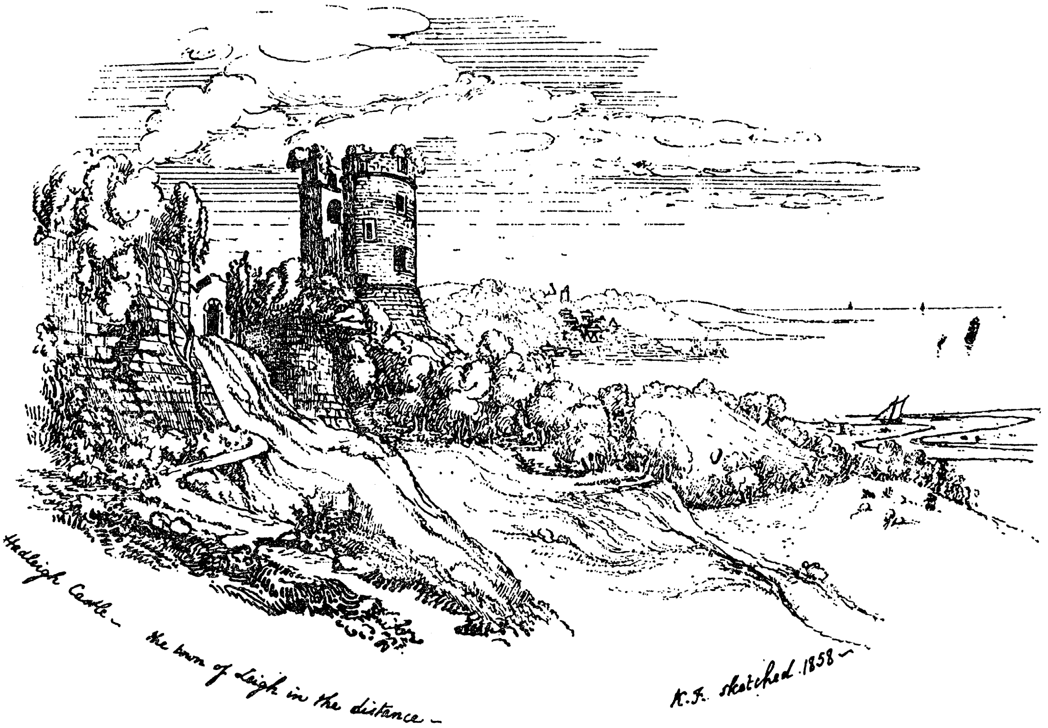

FIGURE 9. 'Hadleigh Castle – the town of Leigh in the distance'. Sketch of 1858 by 'K.F.' (Essex Record Office). View to the E showing the south curtain wall and tower C.

The firmest evidence for the date of the large rotational slip, which carried away all but the western few metres of the south curtain wall and encroached by between 10 and 20 m on to the area of the castle bailey, is provided by the various editions of the 1:2500 maps of the Ordnance Survey, published in 1868, 1897, 1922 and 1939. The first of these, surveyed in 1863, shows the castle intact. The second edition, revised in 1895, shows two significant breaks in the castle wall, at just the locations (points R and S on figure 8) where it is later cut by the rear scarp of the slip. It also suggests that the south curtain wall between these breaks may have moved slightly southwards at its western end. By the next edition, of 1922, which was revised in 1920, the south curtain wall is shown to have moved appreciably to the south, by at least about 7 m at its western end and 2.5 m at its eastern. A fence, crossing the slope about 70 m south of the castle, also appears to have been displaced over 10 m downslope. On the latest edition, the revision of 1939, the castle walls are shown in essentially the same position as on the 1922 map, but with a further break in the south curtain wall about half way between the two earlier ones. From this we conclude that this considerable rotational slip had started to move by 1895 but suffered its major displacement between then and 1920. It is also the independently reached opinion of L. Helliwell (personal communication)] that this slip took place either as one or several related movements in about the 1890s. For convenience it will be referred to as the 'late-19th century landslip'. Oblique aerial photographs of Hadleigh Cliff and Castle, showing this landslip, have been taken on various dates. Those of 1928 and 1967 are shown, respectively, in figures 10 and 11, plate 9. From these photographs, and particularly from that of 1928, the sharp eastern boundary of the landslip and the relative stability of the adjoining part of the cliff below tower C are evident. These may reflect better drainage conditions there, resulting possibly from the proximity of the side valley to the northeast.

Surveys of the location of the degrading rear scarp of the late 19th century landslip have been made by the Royal Commission (1923) in about 1920–2, by Hutchinson (1965) in 1964 and by Drewett (1975) in 1971. A comparison of these (figure 8) shows that during this period retrogression of this rear scarp has been most marked in its western parts. The slips involved have been minor, however, and represent merely the continuing degradation of the rear scarp of the late 19th century slip.

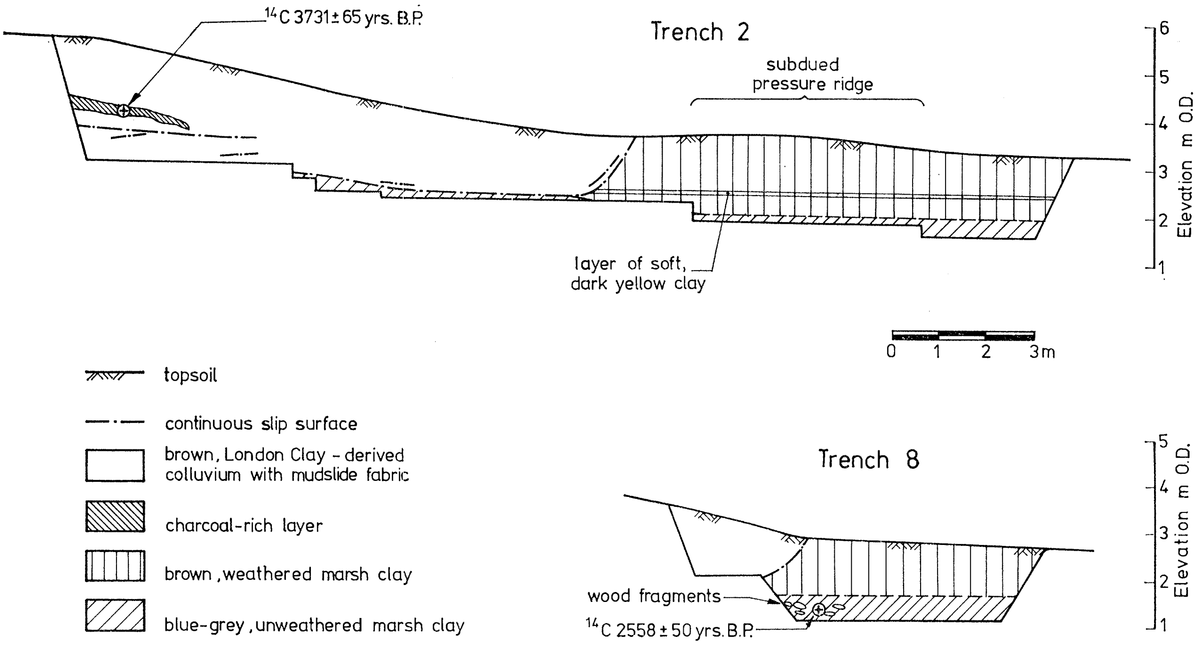

FIGURE 12. Logs of trial trenches 2 and 8.

GROUND CONDITIONS

General

The subsurface conditions at Hadleigh Cliff have been explored by means of trial trenches and boreholes, with disturbed and undisturbed sampling, and by piezometers. As shown by figure 7, these investigations were concentrated on a line (c.s. 2–2) down the abandoned cliff through the centre of the castle.

The 12 trial trenches were dug by a small excavator with a 0.9 m wide bucket and were all strutted. They were located at distinctive morphological features, and excavation and logging was generally completed in the same day. The logs of the more important of the trenches (2, 3, 5, 6 and 8–10) are given in figures 12–14. In these only the main shear surfaces are shown.

The 24 0.15 m diameter boreholes were put down by a soft ground rig to depths varying from about 3.5–31 m. Casagrande type piezometers were installed in 19 of the boreholes. Undisturbed block samples and disturbed samples were taken from the trial trenches: U 100 mm samples and disturbed samples were recovered from the boreholes.

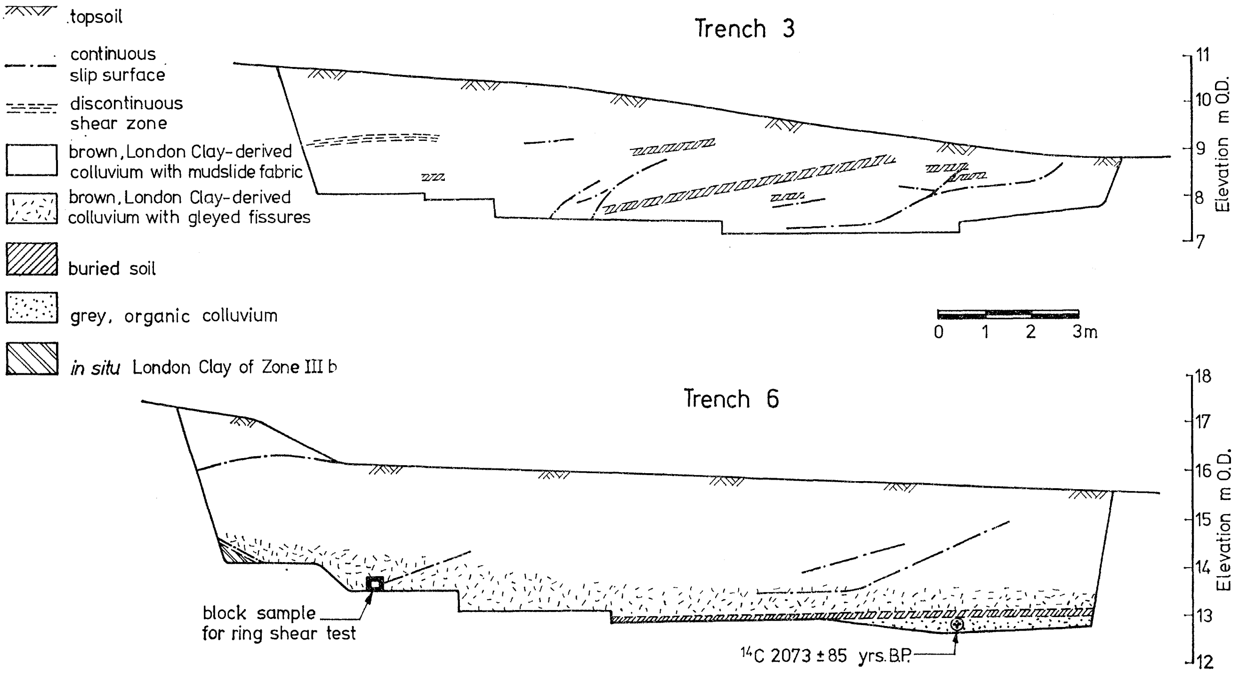

FIGURE 13. Logs of trial trenches 3 and 6.

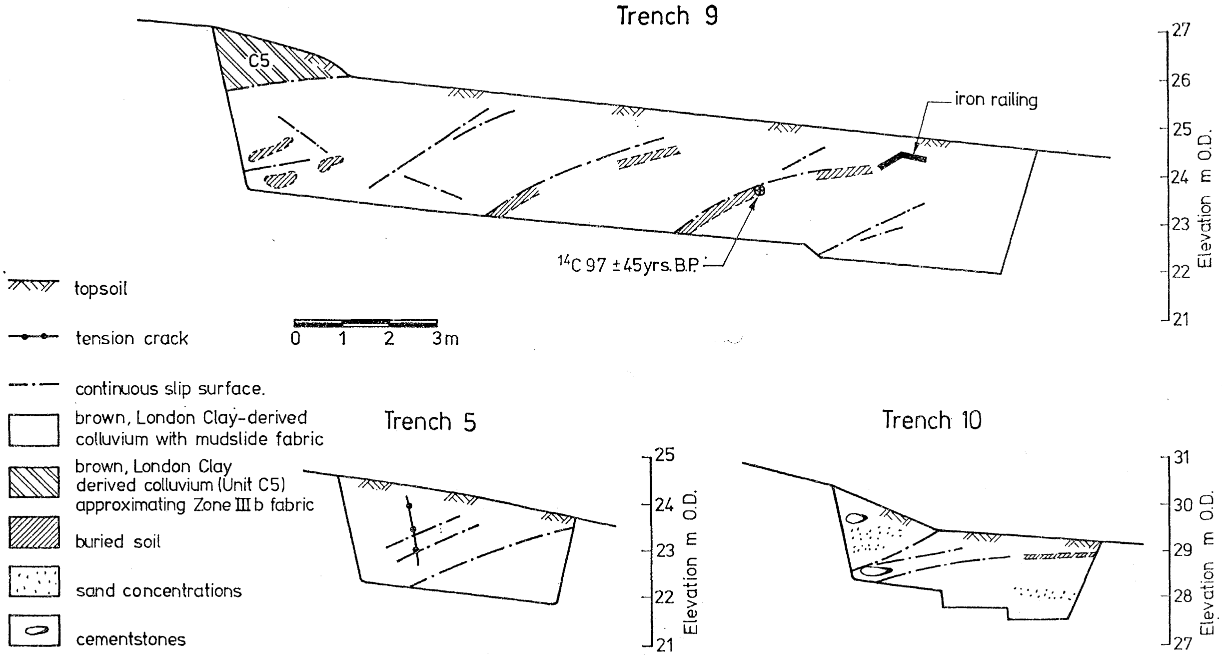

FIGURE 14. Logs of trial trenches 5, 9 and 10.

The main objectives of this work were:

(i) To define the geometry and interrelationships of the *in situ* London Clay, the colluvium and the alluvium.

(ii) To delineate the pattern of shearing and any significant internal features and properties of the colluvium and hence reconstruct the mode of degradation of the abandoned cliff.

(iii) To date the time of abandonment of the cliff and the subsequent stages in its degradation.

(iv) To measure the ground water conditions within the slope and hence, with the information on the unit weights, geometry and shearing patterns of the colluvium, to carry out back-analyses to estimate the shear strength, generally the residual, mobilized in the field.

(v) To measure the residual shear strength of the London Clay colluvium in the laboratory and to compare these values with those obtained from the back-analyses.

(vi) To explore the extent of weathering in the *in situ* London Clay and the effect of this on its mechanical properties.

The broad findings of the subsurface investigations are summarized in the sections of figures 3, 5 and 15.

The in situ *London Clay*

As described above, Hadleigh Cliff was formed by fluvial or niveo-fluvial processes associated with the cutting of the Hadleigh bench, the deposition of Hadleigh gravels upon it, and the subsequent partial removal of these in a second phase of strong erosion. The form of this bench has already been outlined, and is shown in general terms in figure 3. The form of the *in situ* London Clay surface beneath its mantle of colluvium in Hadleigh Cliff itself is shown in figure 15 and, in more detail for the lower part of the slope, in figure 5.

The London Clay forming Hadleigh Cliff is an overconsolidated, stiff fissured clay with plastic limits varying from about 25 to 30 % and liquid limits from about 75 to 80 %. Natural water contents in the unweathered material are usually a few percent below the plastic limit. The clay fraction (< 2 μm) lies, for the most part, between 50 and 65 %. A general idea of the clay mineral suite is given by Burnett & Fookes (1974), illite being preponderant with kaolinite and montmorillonite in lesser amounts. A detailed mineralogical analysis of the whole thickness of the London Clay at the 'Hadleigh borehole' (I.G.S. 'A' on figure 3) is reported by Merriman (1975).

Partly in order to check the local structure of the London Clay, a microfaunal study was made of some of the borehole samples (boreholes N12, 8.0 and 11.0 m; N16, 15.0, 19.5, 20.5, 25.0 and 28.5 m; N22, 25.0 m) by the Institute of Geological Sciences, and the results correlated with the standard microfaunal succession established by Lake *et al.* (1975) for the whole thickness of the London Clay at the nearby Hadleigh borehole. They are consistent with a very low dip in the London Clay beneath the site of around 1° in a southerly direction. At borehole N16 (figure 15) corresponding microfaunal assemblages were found in the samples from 15.0 and 25.0 m depth. In view of the other evidence in the borehole this repetition of the strata is thought to be due to a small fault.

The U100 samples from the various 'N' boreholes provided an opportunity to explore the degree of weathering in the *in situ* London Clay. The weathering scheme adopted follows broadly that of the Geological Society Engineering Group Working Party (1972) and that put forward for the Lias by Chandler (1972). At Hadleigh four weathering zones were observed, as described in table 3. These are also distinguished, as far as possible, on the sections

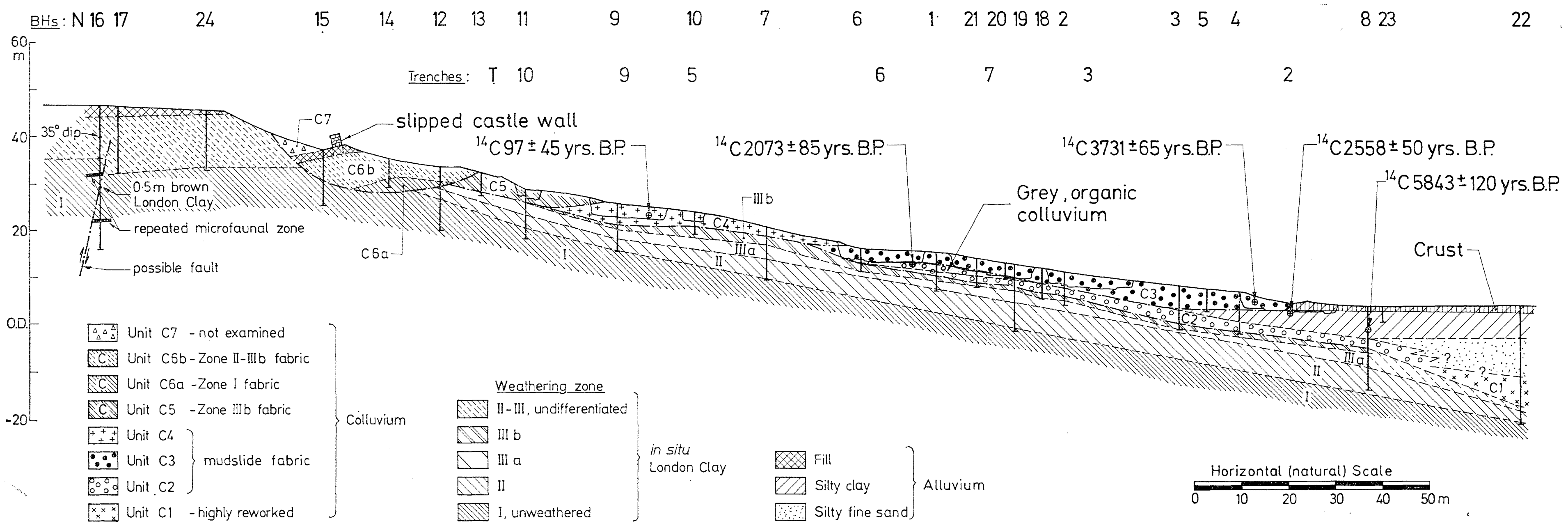

FIGURE 15. Overall cross section 2–2 showing the engineering geology of Hadleigh Cliff.

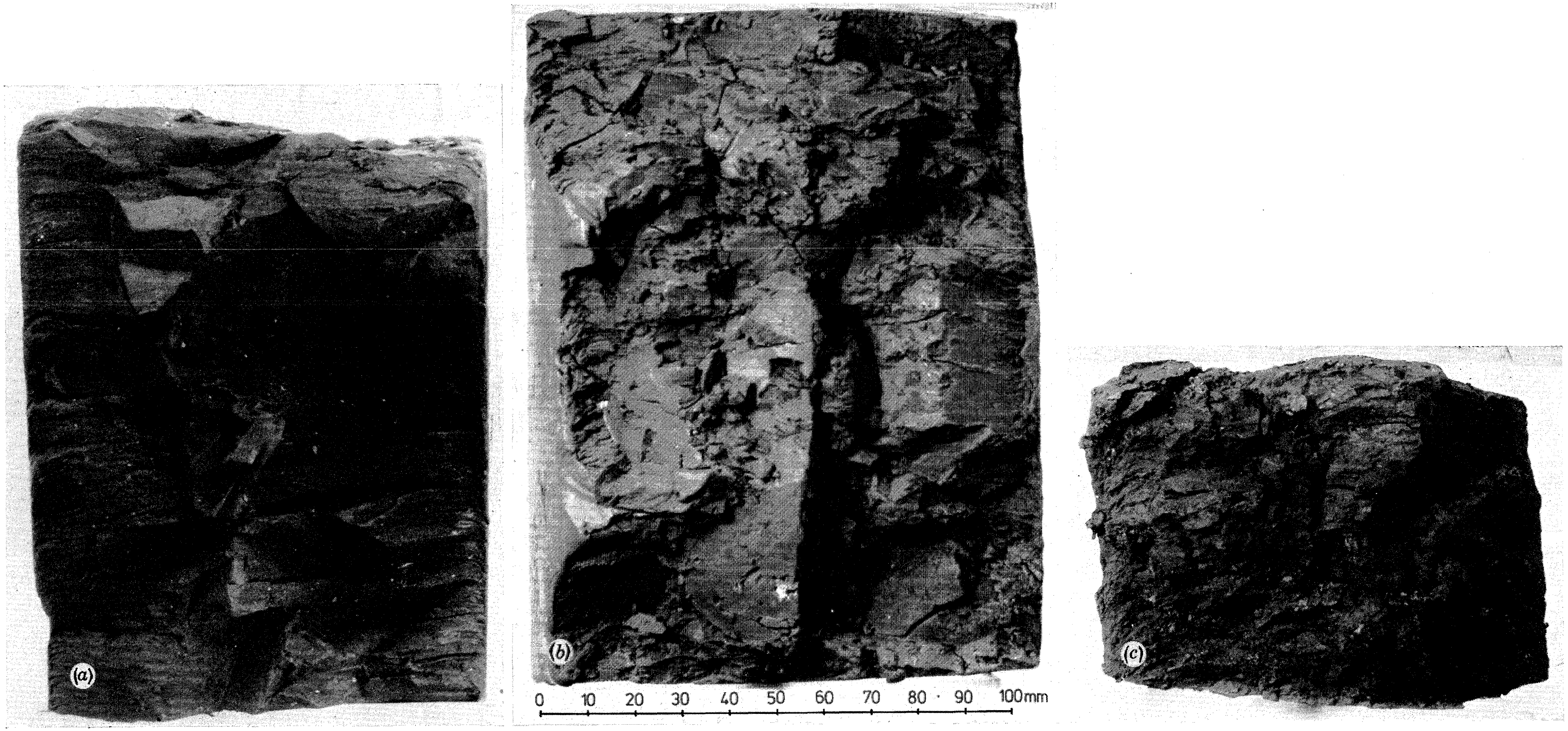

FIGURE 16. Photographs of hand specimens of different weathering zones of the London Clay.
(*a*) Zone I (unweathered), (*b*) zone II and (*c*) zone IIIb.

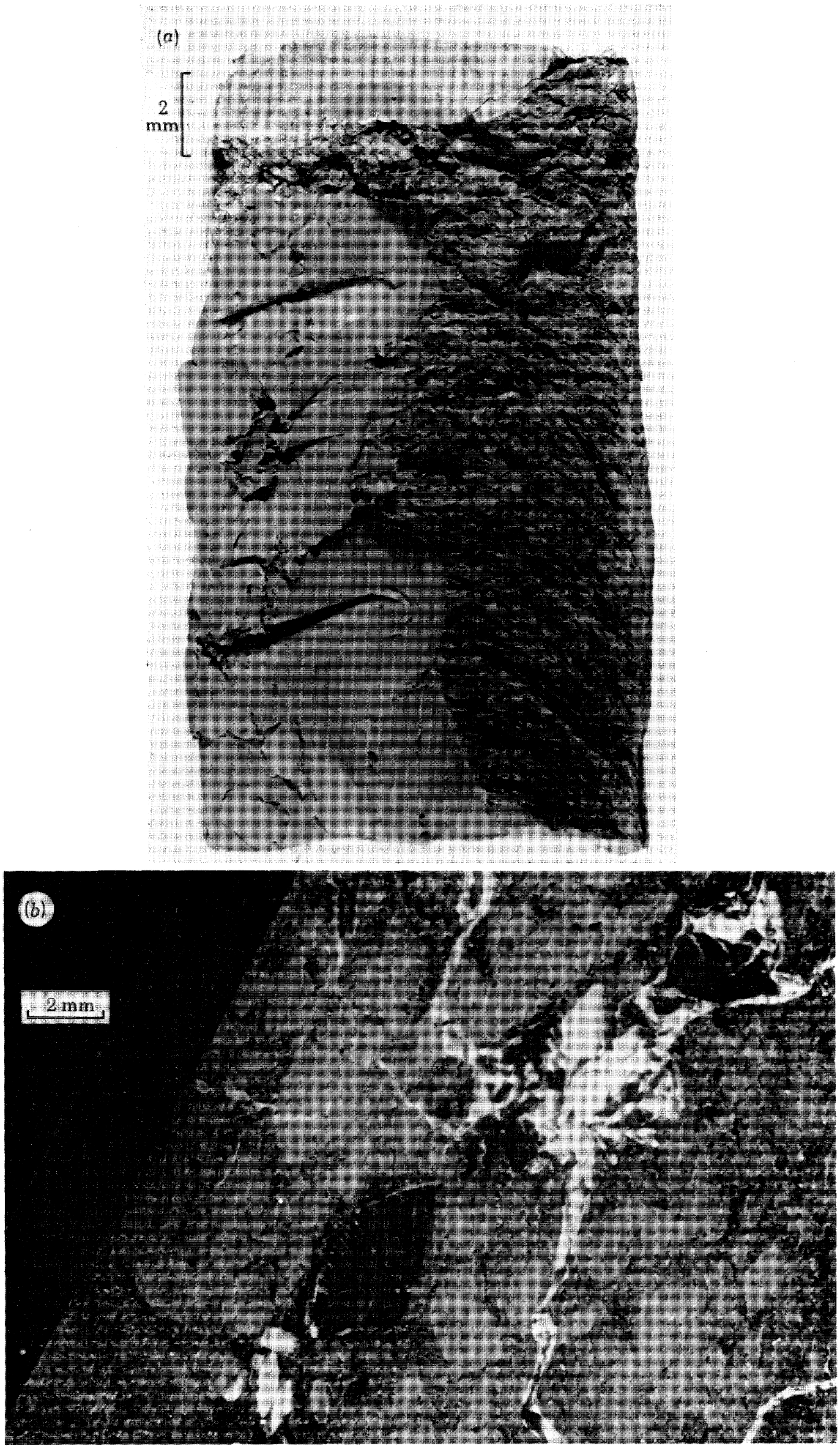

FIGURE 20. Photographs of the London Clay-derived colluvium of unit C3, (*a*) in hand specimen and (*b*) under the optical microscope. In the latter photograph the diamond-shaped light and dark areas indicate selenite crystals; the irregular light areas and lines represent intruded carbowax.

of figures 5 and 15. Photographs of hand specimens of London Clay from weathering zones I, II and IIIb are shown in figure 16, plate 10.

As borehole N22 (figures 1, 5 and 15) is the most southerly logged by ourselves, we are unable to define firmly the nature of the London Clay south of this point. From the Essex River Authority borehole logs examined, however (figure 1), it would appear that the Hadleigh bench consists generally of *in situ* London Clay except at boreholes 54 and 57, where small stones are reported down to depths of 0.7 m beneath the bench surface. This may indicate the presence of relict patches of Head. At both these locations the bench is overlain by the sandy

Table 3. Details of weathering zones at Hadleigh Cliff

	zone	description (colour on Munsell Chart 1954)	birefringence ratio	(1) av. water content (and range), (2) typical P.L., L.L. (%)	liquidity index
	(C) colluvium†	Light brown to yellowish brown generally firm to stiff, re-worked clay with secondary fissuring. Mudslide fabric with considerable matrix content and rotated lithorelicts up to 3 mm across. Frequent shears. 'Sugary' concentrations of selenite crystals present. Gleying in vicinity of water table. (5YR 5/6–10YR5/4)	0.75–0.85	(1) 33 (29–38) (2) *ca.* 26, 75	+0.15 to +0.04
In situ London Clay	(IV) highly weathered	Apparently not present on Hadleigh Cliff	—	—	—
	(IIIb) moderately weathered	Yellowish brown, firm to stiff, fissured clay. Bedding not readily discernible. Fissure spacing 10–30 mm. Fissure surfaces commonly gleyed. Minor shearing on discontinuities where matrix increasingly evident but still a minor constituent. Some selenite crystals. (10YR 5/4)	0.4–0.6	(1) 33 (29–40) (2) 27, 81	+0.14 to +0.11
	(IIIa) moderately weathered	Dark yellowish-brown, stiff, fissured clay. Bedding discernible with difficulty. Fissure spacing around 50 mm. Commencement of matrix development along discontinuities. Selenite crystals infrequent. (10YR 4/2)	Not measured	(1) 33 (30–35) (2) 29, 84	+0.09 to +0.07
	(II) slightly weathered	Brown, stiff, fissured clay. Bedding discernible. Fissure spacing 100–150 mm. Fissures surfaces generally iron-stained. Selenite crystals rare. (10YR 2/3–10YR 4/2)	0.4–0.58	(1) 30 (24–35) (2) 30, 80	+0.04 to −0.03
	(I) fresh (unweathered) parent soil‡	Grey-blue, stiff to hard, fissured clay. Bedding generally pronounced. Fissure spacing variable, but generally > 100 mm. No selenite seen. (5YR 2/1–5YR 2/2)	0.4–0.5	(1) 27 (24–31) (2) 30, 80	−0.04 to −0.09

† Description and properties apply to colluvial units C2–C4 only.
‡ Description and properties apply to uppermost 2 m of zone I only.

gravel. From the descriptions of the London Clay just below the surface of the bench, it seems to be generally of weathering zone II, but with a possible range from zone I to zone III a. Apart from EWC 9 (figure 1), which went through the whole thickness of the London Clay, the above-mentioned boreholes penetrated this stratum to between 0.5 and 3.1 m.

The influence of the degree of weathering on the mechanical properties of the London Clay has been explored to a limited extent. Nineteen unconsolidated, undrained triaxial tests on 100 mm diameter samples taken from U100 sample tubes have been carried out on material from weathering zones I, III a and III b and on the colluvium. The samples were tested at a strain rate of 0.26 % per minute. Although other variables are also involved, the typical test results (figure 17) illustrate the tendency for the undrained modulus, peak shear strength and brittleness to decrease as the degree of weathering increases.

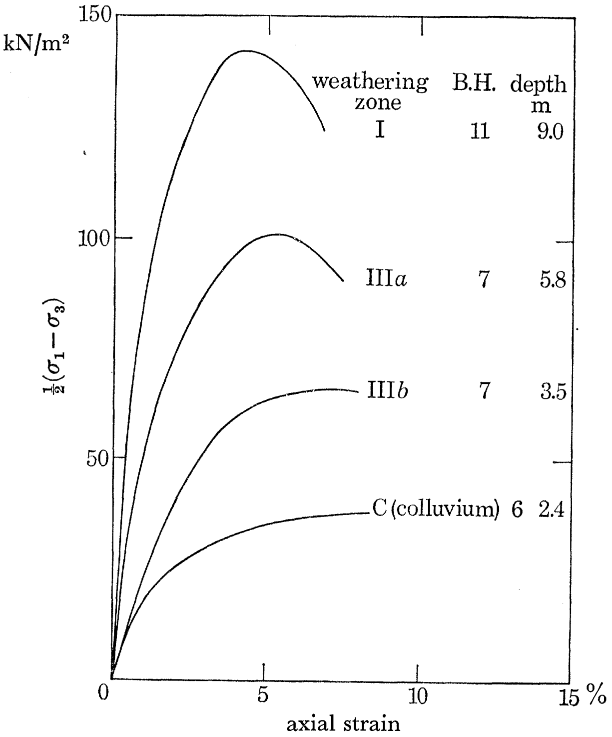

FIGURE 17. Stress–strain curves for quick undrained, 100 mm diameter triaxial tests on London Clay of various degrees of weathering.

Drained, 60 mm × 60 mm direct shear box tests have also been carried out on samples taken from U100 sample tubes. These tests were run at a rate of displacement of 0.001 mm/min and, when made on samples of *in situ* clay, were sheared parallel to the bedding. Representative results, for weathering zones I and II and for the colluvium, are given in figures 18 and 19. The drained stress–strain curves (figure 18) indicate, in general, similar tendencies to those noted above for the undrained tests. The peak failure envelopes (figure 19) suggest that in the early stages of *in situ* weathering the main effect is a reduction in c'; with continued weathering c' reduces further and ϕ' is also diminished slightly. For comparison, the residual strength envelope of the colluvium, measured in ring shear, is also shown.

The colluvium and its relation to the alluvium

A primary object of the investigation was to discover the extent and properties of the colluvium mantling Hadleigh Cliff. Differences of lithology within the colluvium and the fact that, at and below marsh level, it interdigitates with the adjacent alluvium, make it possible to distinguish seven colluvial units. These are described, from bottom to top of Hadleigh Cliff, as follows (figure 15).

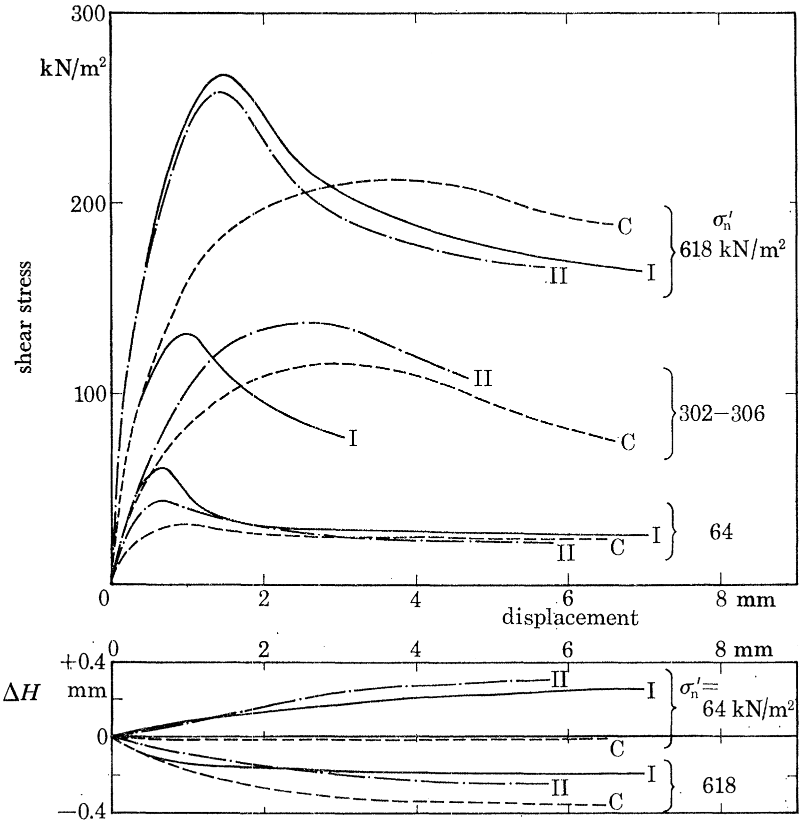

FIGURE 18. Stress–strain curves for drained, 60 mm × 60 mm direct shear box tests on London Clay of various degrees of weathering.

Unit C1

This was encountered only in borehole N22, immediately below the soft marsh deposits, where it extends from −12.3 to −18.4 m O.D. The sandy gravels which generally overlie the Hadleigh bench are absent at this point on its extreme northern edge, and the colluvium rests directly on *in situ* London Clay, here of weathering zone IIIa. In the next borehole to the south, I.G.S. 'C' (figures 1 and 5), over 2.8 m of these gravels were found, though not penetrated, but no colluvium overlies them. The relationship of the unit C1 colluvium to the Hadleigh gravels is therefore not established, but the colluvium is probably the later deposit, as suggested in figure 5. As this figure shows, the C1 colluvium is also absent in borehole N8, 32 m to the north, so the unit is restricted to the obtuse angle formed in the *in situ* London Clay at the original foot of Hadleigh Cliff.

Lithologically, unit C1 contrasts with all other colluvial deposits on Hadleigh Cliff in being much more completely reworked. Although clearly derived almost entirely from the London Clay forming the slopes of the contemporary Hadleigh Cliff, lithorelicts of this could not readily be distinguished in hand specimens. The material has plastic and liquid limits of 27 % (26–28) and 68 % (65–71) respectively, i.e. around the lower end of the ranges for the parent London Clay. It is over-consolidated, with a water content equal to the plastic limit and thus a liquidity index of zero. The clay fraction is 55 % (53–57). A few hair roots were observed. From the highly reworked, fine fabric and the complete lack of sorting, it is concluded that the material represents a subaerial mudslide deposit, probably produced by periglacial solifluction.

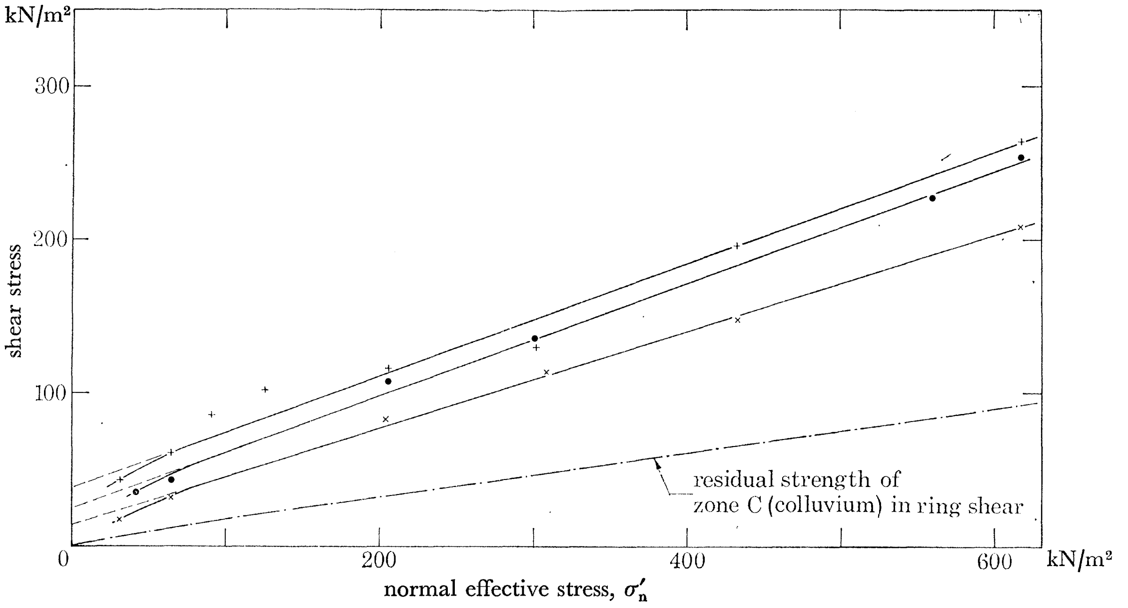

FIGURE 19. Drained peak failure envelopes for the London Clay samples tested in direct shear.

weathering zone	peak strength results in direct shear	approx. effective stress peak parameters for σ'_n range of 300–600 kN/m^2	
		c'(kN/m^2)	ϕ'
I	+	38	20°
II	●	24	20°
C (colluvium)	×	14	17½°

Material of zone IIIa not tested. Peak strength for zone IIIb essentially the same as for the colluvium.

Dr M. P. Kerney kindly examined two samples of this unit. He found no clearly contemporary fauna but noted the presence in the reworked London Clay of detrital quartz and occasional platey calcite, the latter possibly from the crack infillings of septarian nodules. He agreed that the material is not waterlain and is probably colluvial in origin.

Units C2–C4

The colluvium of units C2–C4 (figures 5 and 15) is lithologically uniform, having a well-marked mudslide fabric (Hutchinson 1970), with lithorelicts of stiff London Clay, generally less than 5 mm across, arranged randomly in a matrix of softer reworked London Clay. Secondary fissuring, in places slightly slickensided, with a spacing of about 0.15 m has developed, and sugary concentrations of selenite crystals are relatively common. Figures 20*a* and *b*, plate 11, show the appearance of the material in the hand specimen and under the optical microscope. Plastic and liquid limits are typically about 26 % (23–29) and 75 % (64–93) respectively, and the average water content, excluding dried crusts, is about 33 % (29–38), giving an average liquidity index of + 0.14 (+ 0.04 to + 0.15). The general consistency is firm to stiff. At present and former ground surfaces formed by this colluvium, dried crusts up to about 0.5 m thick are found, with prismatic structure, in which water contents down to 22 % have been measured.

Colluvium of *unit C*2 was encountered in boreholes N8, 4, 3, 2, 18, 19, 20, 21, 1 and 6, and in trenches 7 and 6. It forms a sheet, varying in thickness between about 1.7 and 2.8 m, which occupies approximately the lower half of Hadleigh Cliff (figure 15). Where proven, it rests everywhere on *in situ* London Clay of weathering zone III b. Below about + 2 m O.D. it is overlain by *in situ* marsh deposits. Between boreholes N8 and 22 its relationships are not proven: it probably overlies the colluvium of unit C1 and is overlain by, or possibly interdigitates with the marsh deposits (figure 5).

From the borehole evidence it is concluded that a dried crust, between 0.5 and 1.0 m thick, exists on the buried top surface of unit C2 from about borehole N19 to borehole N4 (figures 5 and 15). It is absent upslope of borehole N19, where the upper layers of colluvium C2 are organic and grey in colour, probably reflecting the presence of a swampy area on this part of the slope at the time when colluvial unit C2 formed its surface. The dried crust is also absent downslope of borehole N4, at borehole N8.

Colluvium of *unit C*3 forms the visible accumulation zone and toe of Hadleigh Cliff (figures 5, 12 and 15). It was penetrated by boreholes N4, 5, 3, 2, 18, 19, 20, 21, 1 and 6, and exposed in trenches 1–4, 7 and 6 (figure 7). It consists of a slightly thicker sheet of debris than that comprising unit C2, ranging from about 2.3 to 5 m in thickness. In its upper and middle parts (trenches 3 and 6, figure 13), it exhibits numerous shears of generally passive attitude, presumably formed in response to pressure from the later colluvium upslope. In the lower middle section of this unit (trench 3), the accompanying over-thrusting is well illustrated by several gently back-tilted, buried soil layers. Relative movements of at least 7 m are indicated.

For a short distance at its head, unit C3 rests directly on *in situ* London Clay of weathering zone III b, but for most of its length it overlies unit C2. From a point just upslope of borehole N3, it has overridden the marsh clays for a distance of 25–30 m on a near-horizontal slip surface which swings sharply upwards to the ground surface at the visible toe feature. This slip surface is generally located in a mixture of unit C3 colluvium with marsh clay and is striated in a southerly direction. It is underlain directly by unweathered dark-grey marsh clay. The brown, weathered clay forming the surface crust of the marsh is found only to the south of the toe of the colluvium. It appears, therefore, that deposition of the alluvium was essentially completed by the time that the colluvium advanced into the marsh and that the weathered crust of the alluvium formed largely subsequent to this.

An interesting morphological feature is the subdued pressure ridge, about 6 m wide and 0.25 m high, which is situated just to the south of the colluvial toe in trench 2 (figures 5, 12, 15 and 16). This suggests that slight movement of the landslides mantling the lower slopes of the abandoned cliff has taken place fairly recently, since the formation of the weathered crust. A similar feature, though on a much bigger scale, was produced by the passive thrust from the toe of the Furre landslide in Norway (Hutchinson 1961).

The colluvium of *unit C4* is again sheet-like in form, with a thickness ranging from 1.7 to 4.5 m. As it occupies the lower part of the degradation zone it has a steeper average slope than unit C3. Also, at its toe, it shears over the latter for a distance of around 8 m. Apart from this, unit C4 rests everywhere on *in situ* London Clay of weathering zone IIIb. In the upper and middle parts of this unit of colluvium (trenches 5 and 9, figure 14), frequent shears of passive attitude and back-tilted buried soil layers, overridden by up to 5 m, again suggest that considerable thrusting was exerted by the colluvium up-slope.

TABLE 4. SUMMARY OF RING SHEAR TEST RESULTS ON THE HADLEIGH COLLUVIUM

test stages, in order of execution	normal effective stress σ'_n (kN/m^2)	$\frac{\tau_r}{\sigma'_n}$	equivalent ϕ'_r if $c'_r = 0$	total displacement in particular stage of test (mm)
A	174.8	0.154	8.75°	904
B	63.8	0.176	9.98°	298
C	27.5	0.210	11.9°	142
D	9.81	0.264	14.8°	148
E	2.94	0.354	19.5°	146

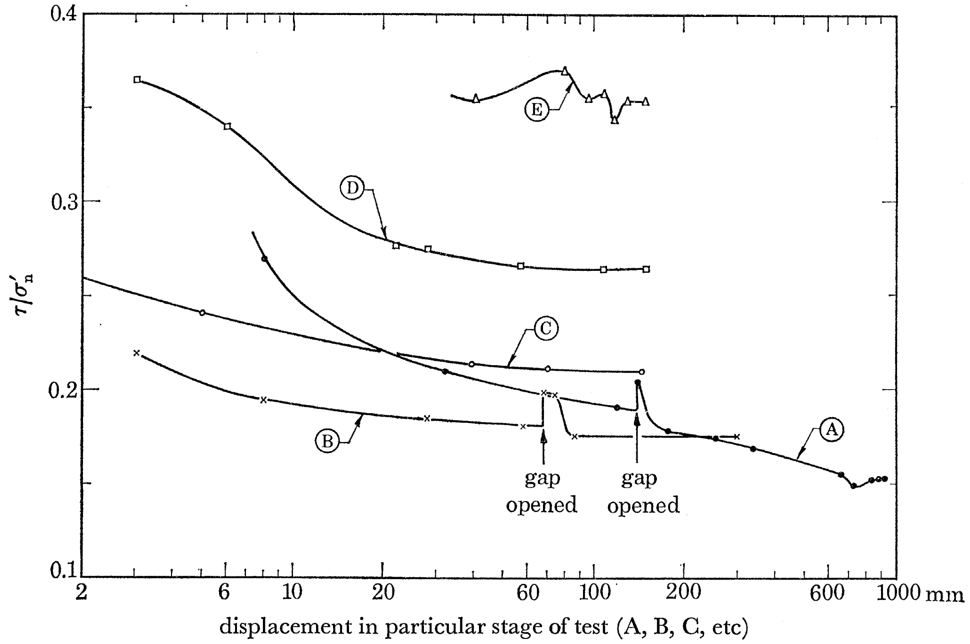

FIGURE 21. Stress–strain curves for drained ring shear tests on London Clay-derived colluvium of unit C3.

A block sample of unit C3 colluvium was taken from a depth of 2.5 m in trench 6 (figure 13) for measurement of its drained residual strength in the ring shear apparatus (Bishop *et al.* 1971). This sample had plastic and liquid limits of 28 % and 82 %, respectively, and a clay fraction of 57 %. After the removal of selenite crystals, the clay was remoulded and built in to the apparatus at a water content of 45 %. After initial consolidation under a normal pressure of 467 kN/m^2, the consolidation pressure was reduced to 174.8 kN/m^2 for the first shearing stage. In this, a displacement of about 0.7 m was required to reach the residual strength. Subsequently the clay was tested under various smaller consolidation pressures down to 2.94 kN/m^2 (table 4). The rate of shear used was generally 0.014 mm/min. The stress displacement curve is given in figure 21 and the plot of the shear stress-effective normal stress ratio against effective normal stress in figure 22. On the latter figure the results obtained by Bishop *et al.* (1971) on brown London Clay colluvium from Walthamstow, are shown for comparison. For tests on an undisturbed sample, these are slightly lower than the measurements made on the remoulded Hadleigh colluvium: for tests on a slurried sample, the results are practically identical with those at Hadleigh.

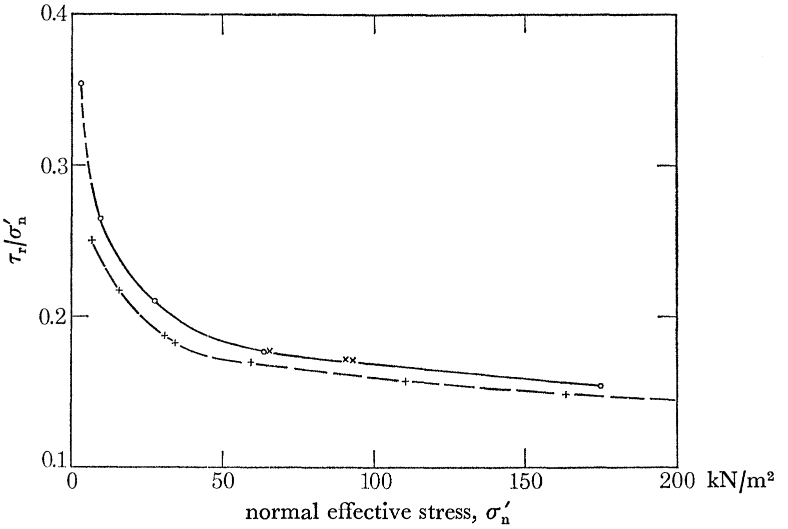

Figure 22. Drained residual failure envelope for the London Clay-derived colluvium of unit C3 in ring shear The results for the similar colluvium from Walthamstow are shown for comparison.

		w_P	w_L	C.F. (< 2 µm)
	○ Hadleigh (remoulded)	28	82	57
after Bishop *et al.* (1971)	+ Walthamstow (undisturbed)	24	66	53
	× Walthamstow (slurried)	25	68	64

Unit C5

The colluvium of unit C5 comprises an irregular slab of debris which has been thrust over the rear of the unit C4 colluvium by perhaps 14 m. It varies between about 3 and 4 m in thickness and lies directly on *in situ* London Clay of weathering zone III a. Its lower end is marked by a clear toe feature. A second such feature is located at about the middle of the unit (by borehole N11 and trench 10) where, again, a gently back-tilted soil layer has been overridden.

Lithologically, the bulk of unit C4 approximates to slipped London Clay of weathering zone III b. However, at the toe of the unit the fabric is transitional to that of unit C4, while towards the base of the upper part of the unit it approaches that of weathering zone III a. The average water content is about 32 % (29–38 %).

Unit C6

The colluvium of unit C6 consists of the landslide which carried away the south curtain wall of Hadleigh Castle in the late 19th century. It is a fairly deep-seated rotational landslide, somewhat non-circular in cross-section (figure 15). The slipped mass has a maximum thickness of about 10 m, a length downslope of 40 m, and a cross-slope width of between 75 and 80 m (figure 7).

The slipped material consists essentially of two components. At its base is a lens of unweathered grey-blue London Clay of zone I, with a maximum thickness approaching 3 m. This is designated as unit C6a on figure 15. Conformably overlying this is a considerably larger mass consisting predominantly of London Clay of weathering zones II to IIIb, shown as unit C6b in section 2–2. The top of the slipped mass is occupied by the back-tilted remains of the castle wall, and about 2 m of fill. The average water content of the whole unit is about 33 %.

Unit C7

The colluvium of unit C7 consists of a small wedge-shaped mass of shallow landslip debris and talus which has formed through degradation of the rear scarp left by the late 19th century landslide (figure 15). It has a maximum thickness of about 4 m. A small amount of fill is also present.

METEOROLOGICAL AND GROUND-WATER CONDITIONS

The nearest Meteorological Office rain gauge to Hadleigh Castle is 3.4 km away on Canvey Island (at Grid ref. TQ 800828 and at the altitude of Ordnance Datum). Other nearby gauges are 6.4 km distant at Southend Waterworks (Grid ref. TQ 874853, altitude +37 m O.D.) and 13.8 km distant at Shoeburyness (Grid ref. TQ 948857, altitude +3 m O.D.). The average annual rainfall at these three stations is broadly similar, being respectively 556, 537 and 539 mm over the period 1941–70.

A feature of the meteorology of much of southeast England is that the average annual rainfall (r.) and the average annual potential evaporation (p.e.) are of similar magnitude. The effective rainfall (r. – p.e.) is thus very sensitive to relatively minor variations in either or both of these quantities, and the soil moisture can fluctuate markedly between a surplus and a deficit with attendant consequences upon, for instance, the growth of vegetation and the activity of mass movements, particularly where these are shallow.

Within this general southeastern region of frequent soil moisture deficits (s.m.d.), there is a tendency for these to increase in duration and intensity towards the east and southeast (Grindley 1967). Thus Shoeburyness, the nearest weather station to Hadleigh for which s.m.d. and p.e. estimates are made, has the highest 1941–70 average end-of-month composite soil moisture deficits of all the 190 such stations in Great Britain.† This arises through a significant preponderance of potential evaporation over rainfall at Shoeburyness, the average annual figures for these quantities over the 15 years 1959–74, for example, being 553 and 534 mm, respectively.

In the southeast of England generally, a soil moisture deficit develops in the spring and summer, but is made good in the following autumn or early winter. At Shoeburyness, however, this pattern does not generally obtain, and soil moisture deficits can be maintained continuously for periods of several years. A plot of the end-of-month, composite soil moisture deficits there since 1968 (figure 23) shows that the soil was continuously below field capacity for the six years between 19 March 1969 and 7 March 1975.

Piezometer observations have been made at Hadleigh from April 1973 to the present. Depths and locations of the 19 piezometers are shown in figures 7 and 24. All are of Casagrande type

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† The single exception to this is the month of September, when the average s.m.d. at Ipswich over this period is 102 mm compared with 101 mm at Shoeburyness.

with standpipes of 23 mm bore. Each tip is surrounded by a sand plug 0.6 m long above which is a 4 m long seal of bentonite-cement grout, tremied into place. All the piezometer readings are shown, in comparison with a histogram of effective rainfall at Shoeburyness, on figure 25. When viewed against the background provided by figure 23, it is clear that the highest piezometer levels recorded during the winter of 1974–5 are likely to approximate to the maximum contemporary values, while the highest levels recorded during the previous winter seriously underestimate these.

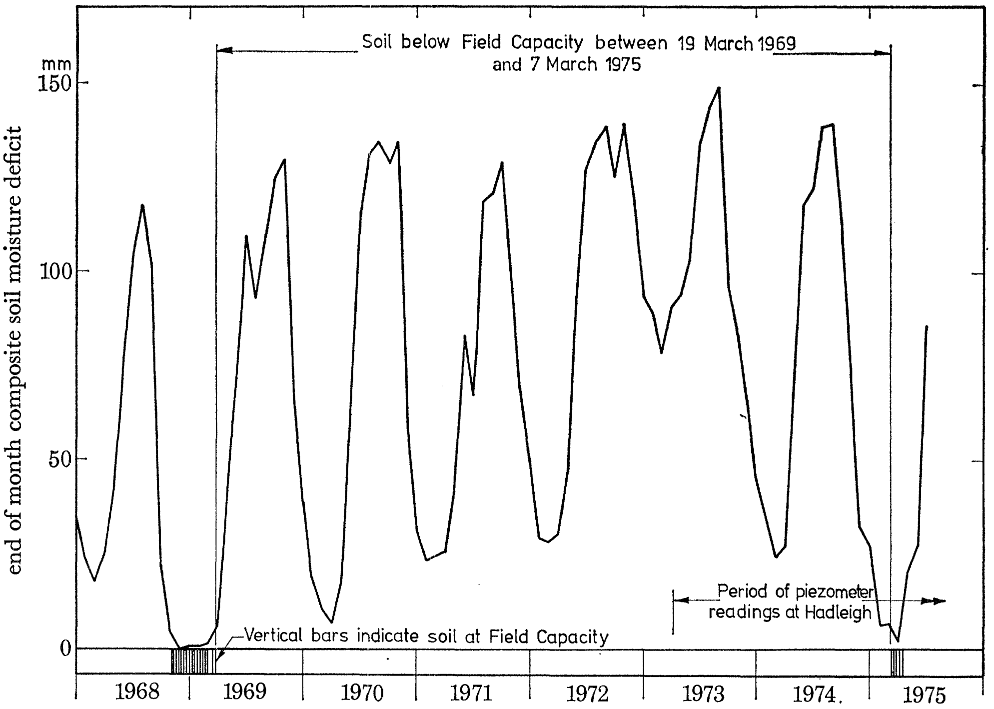

FIGURE 23. Plot showing variation in end of month, composite soil moisture deficit at Shoeburyness for the period 1968–75.

The general point to be drawn from the s.m.d. plot in figure 23 is that the conventional approach to the determination of maximum seasonal ground-water levels, of reading piezometers through the winter and spring, or even for a complete year, can be entirely inadequate in a climatic situation of the present type, where the ground-water levels may have to be observed through a number of consecutive winters before a reasonable approximation to their true maximum is found.

The highest piezometer levels observed at Hadleigh during the past two and a half years are summarized on the section of figure 24. On the basis of these, an estimate of the highest position of the piezometric surface for the main landslips is also shown. The possibility that, in addition, small perched water tables exist at shallower levels cannot be ruled out.

R. Hodson (personal communication) reports that the snow which fell at the end of February 1969 formed drifts 1.0–1.5 m deep on the upper parts of Hadleigh Cliff, chiefly upslope from about borehole N9 (figure 7). Drifting clearly provides a mechanism whereby the amount of precipitation at a particular location can be increased significantly above the general level as recorded at weather stations. It is not known to what extent drifting and

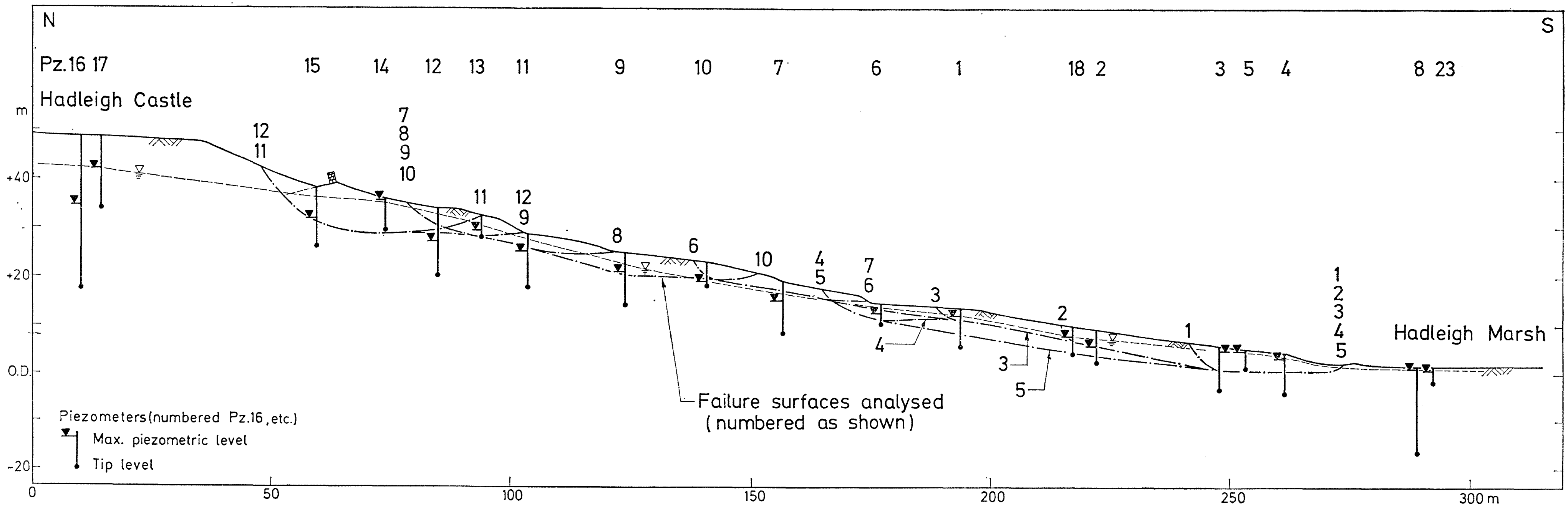

FIGURE 24. Overall cross section 2–2 showing the ground-water conditions in Hadleigh Cliff and details of the failure surfaces analysed.

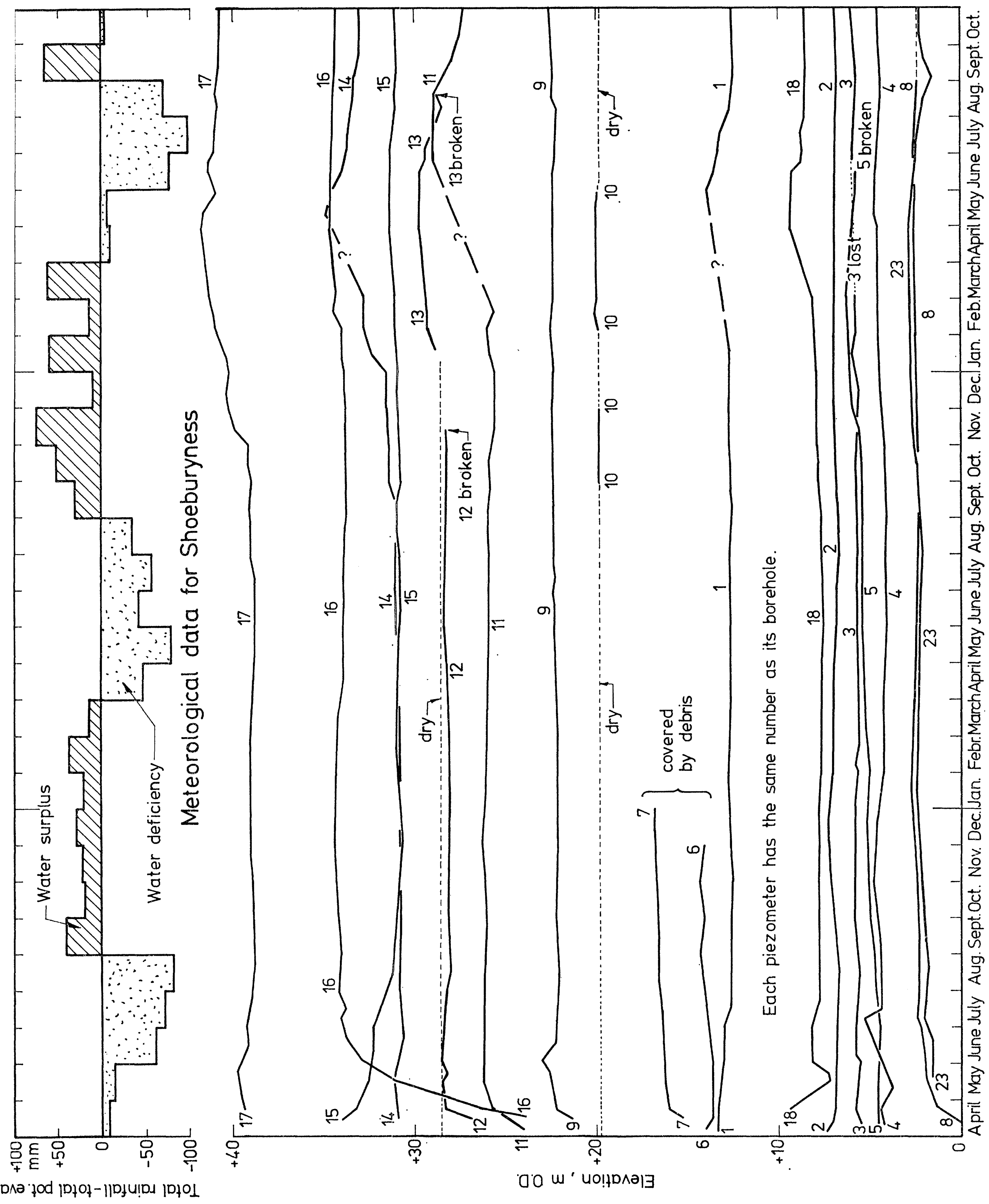

FIGURE 25. Observations of piezometric levels in Hadleigh Cliff from April 1973 to October 1975.

subsequent snow melt are important factors on Hadleigh Cliff, but thawing of the drifts of February 1969 was followed by a shallow slide at the western end of the main rear scarp and by a fairly general reactivation of movement in the degradation zone.

No measurements of negative pore-water pressures have been made at Hadleigh. From the work of Black, Croney & Jacobs (1958), however, it is evident that a reasonable correlation exists between soil moisture deficits estimated from meteorological data (as above) and pore-water tensions in the capillary zone.

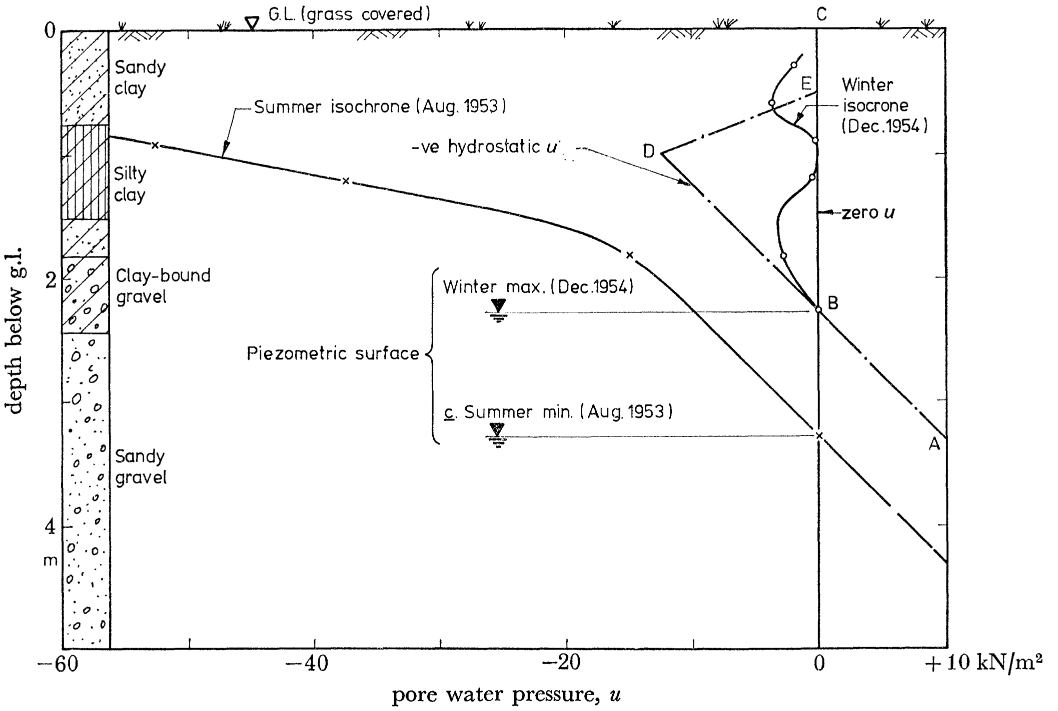

Figure 26. Summer and winter isochrones observed in a ground profile at Harmondsworth (after Black, Croney & Jacobs 1958).

The site most closely studied by Black *et al.* was in the grounds of the Road Research Laboratory at Harmondsworth, about 75 km west of Hadleigh. Pore-water pressures, predominantly negative, were measured there over a period of nearly five years, at each 0.3 m of depth down to 1.8 m in a profile consisting of 1.8 m of brickearth (sandy to silty clay) overlying 0.6 m of clay-bound gravel and 3.7 m of sandy gravel. The brickearth has average plastic and liquid limits of about 20 % and 35 %. The ground-water table was usually within the sandy gravel at a depth of around 3.0 m, but rose occasionally into the clay-bound gravel. The average annual rainfall and potential evaporation there over the five-year period 1951–5 were 636 mm and 529 mm respectively.

Illustrative measurements from Harmondsworth, made beneath an essentially horizontal, grass covered surface, are given in figure 26. The results for August 1953 show the high negative pore-water pressures existing at a time near to that of the minimum summer ground-water level. Even greater negative pore-water pressures existed at the actual time of this minimum, probably in excess of about 1 atmosphere negative (-100 kN/m^2) at depths down to about a metre, but these were not fully recorded as they were generally beyond the range of the tensiometers used.

The results for December 1954 show the isochrone at a time coincident with the maximum level of the ground-water recorded during the five consecutive winters of observations (*ca.* 2.3 m below g.l.). It is of interest that, even then, appreciable residual negative pore-water pressures existed in the capillary zone.

At Hadleigh, by reason of the fatter clay and the stronger soil moisture deficits involved, it is likely that the negative pore-water pressures remaining in the capillary zone at times of ground-water maxima will be greater than those recorded at Harmondsworth, particularly where the phreatic surface is also situated fairly deep. Accordingly, in the stability analyses, two pore-water pressure assumptions have been made. Both take the highest observed piezometric surface as the basis for calculating the positive pore-water pressures acting on the various slip surfaces. In the capillary zone, however, the conventional assumption of zero pore-water pressure is treated as an upper bound value and a lower bound value is taken as being defined by negative hydrostatic pore-water pressures acting from the piezometric surface to a nominal depth of, in general, 1 m below ground level, to allow for tension cracks and other surface effects. These upper and lower bounds are shown, respectively, by the lines ABC and ABDEC on figure 26. In the absence of pore-pressure measurements in the capillary zone, they are assumed to bracket the actual pore-pressures obtaining there at the time of highest winter ground-water levels.

Slope stability

Stability analyses, in terms of effective stresses, have been carried out on the various failure surfaces shown in figure 24, which have been chosen to follow the actual or probable slip surfaces revealed by the subsurface investigations. An average unit weight of 18.5 kN/m^3 for the sliding masses has been taken throughout. The highest observed piezometric line for the base of the colluvium, also shown in figure 24, has been used to determine the positive pore-water pressures acting on the various slip surfaces. In the capillary zone, the upper and lower bound pore-water pressure assumptions defined in figure 26 have been followed as far as possible. The implied negative pore-water pressures are taken as acting not only on the interslice surfaces used in the analyses but also on the relevant parts of the slip surfaces. Some support for the assumption that pore-water tensions can be sustained on fairly shallow slip surfaces is provided by Hutchinson, Prior & Stephens (1974).

In the stability analyses the method of Sarma (1973) has been used. In view of the generally bench-like character of the movements, corrections for side friction have not been applied. All the failure surfaces shown on figure 24 are assumed to be pre-existing and therefore to be at, or close to, their residual strength. Away from failure surfaces, the shear parameters of the colluvium are taken as $c' = 5$ kN/m^2 and $\phi' = 18°$, approximately as measured in direct shear over the relevant range of normal effective stress (figure 19). The results of the various analyses are detailed in table 5. In the upper plot of figure 27, all these results are plotted: in the lower plot only the five most critical are shown.

The field evidence indicates that the most active present movements are taking place in the upper parts of the degradation zone, where the most critical slip surfaces, 8 and 12, are also situated. These two surfaces are therefore taken as having a factor of safety of unity and used to construct a field strength envelope for failure on pre-existing slip surfaces up to a normal effective stress, σ'_n, of 70 kN/m^2. In the case of both these slip surfaces, the difference between the strengths indicated by the upper and lower bound pore-water pressure assumptions (figure 26) is small. The field failure envelope is thus closely established. It is defined up to a normal effective stress of 50 kN/m² by the parameters $c' = 0$, $\phi' = 13.3°$; above this stress level the envelope flattens slightly (figure 27).

On the basis of these parameters derived from the degradation zone, the factor of safety of the most critical surface (5) of the accumulation zone is 1.00 for the upper bound pore pressure

Table 5. Summary of results of stability analyses made on Hadleigh Cliff

	with zero u in capillary zone			with negative u in capillary zone		
slip surface	normal effective stress σ'_n kN/m²	for $F = 1.0$ and $c' = 0$		normal effective stress σ'_n kN/m²	for $F = 1.0$ and $c' = 0$	
		$\tan\phi'$	ϕ'		$\tan\phi'$	ϕ'
accumulation zone						
1	33.69	0.2063	11.66°	34.80	0.1987	11.24°
2	35.72	0.2343	13.18°	41.01	0.2030	11.47°
3	34.48	0.2336	13.15°	40.05	0.2019	11.41°
4	34.14	0.2277	12.83°	38.56	0.2012	11.38°
5	44.97	0.2356	13.26°	48.82	0.2166	12.22°
degradation zone						
6	37.98	0.1897	10.74°	43.40	0.1626	9.24°
7	51.24	0.2137	12.06°	53.12	0.2055	11.61°
8	48.49	0.2395	13.47°	49.37	0.2342	13.18°
9	48.46	0.2000	11.31°	50.46	0.1915	10.84°
10	54.28	0.2086	11.78°	56.53	0.1992	11.27°
11	67.35	0.2079	11.74°	68.76	0.2033	11.49°
12	66.84	0.2344	13.19°	67.55	0.2307	12.99°

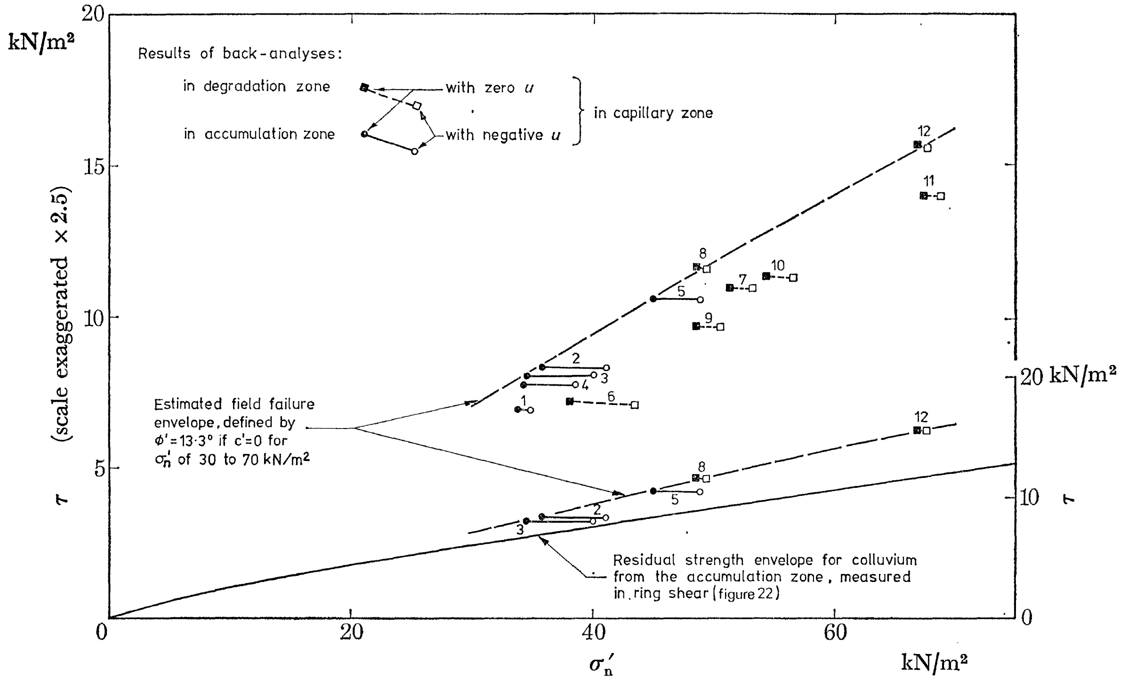

Figure 27. Comparison of values of residual shear strength derived from back analyses with those measured in ring shear.

assumption, and 1.09 for the lower bound assumption. As the value of σ'_n for this surface is very similar to that for failure surface 8, these estimates are unaffected by the observed slight convexity of the failure envelope. The field evidence indicates that the present factor of safety of the accumulation zone is undoubtedly greater than unity, and this provides further support for the existence of significant negative pore-water pressures in the capillary zone there, even at the time of highest seasonal ground-water levels. From the present data it is reasonable to conclude, therefore, that the overall factor of safety of the accumulation zone approximates to the average of the upper and lower bound estimates, i.e. about 1.05 in round terms.

On figure 27 a comparison between the values of ϕ'_r indicated by the back-analyses and those measured on the Hadleigh colluvium in ring shear shows the latter to be appreciably the lower, generally by about 20%. As in all such comparisons, however, an element of uncertainty attaches to the degree to which the materials tested in the laboratory are representative of those associated with the actual slip surface.

A broadly similar relationship between the ring shear and inferred field values of ϕ'_r has been observed for the Etruria Marl by Hutchinson, Somerville & Petley (1973) and for the Lias clay by Chandler (1976). As suggested in both these papers, this discrepancy generally still persists after side friction effects are taken into account. In the present case, as shown by figure 27, the discrepancy is somewhat reduced if allowance is made for negative pore pressures in the capillary zone.

An attempt has been made to reconstruct and back-analyse the late 19th century, first-time slide, but uncertainties regarding its geometry and piezometric conditions are such as to prevent a reliable result being achieved. Stability analyses of the present rear scarp of Hadleigh Cliff, on section 2–2, indicate that it has a reasonable degree of security against a further deep-seated landslide (Gostelow 1974). This conclusion should not be applied to the adjacent part of the scarp beneath tower C (figure 8), which has not been investigated.

Stages of degradation: description and dating

It has been shown that Hadleigh Cliff has its origin in two phases of strong erosion associated with the cutting of the Hadleigh bench and the subsequent partial removal of the Hadleigh gravels, and these events have been tentatively assigned to about 27000 and 17000 years B.P. Here we are concerned chiefly with the degradation of Hadleigh Cliff subsequent to this final phase of major erosion. Although not firmly dated, it would seem to have been essentially completed by a time in the region of 15000 B.P., and this date is taken as a convenient starting point for a discussion of the degradation process. At that time, the freshly eroded Hadleigh Cliff would have been standing with its toe in the vicinity of borehole N22 (figures 5 and 15), at about -19 m O.D. South of this would have stretched the Hadleigh bench, largely covered by its spread of gravel. The contemporary sea level would have been well below the gravel surface, possibly around -80 m O.D. according to Flint (1971).

In this paper, all dates quoted in years B.P. are in radioacarbon years (based on a half-life of 5568 ± 30 years), with no dendrochronological or other corrections (Ralph & Michael 1974). Historical dates are quoted in calendar years A.D.

The earliest colluvium associated directly with Hadleigh Cliff is unit C1, extending from -12.3 to -18.4 m O.D. in borehole N22. Although imperfectly explored, this appears to form an apron at the now buried foot of the cliff. From its fabric, described earlier, it is concluded that the unit is not waterlain. It must, therefore, have been deposited in its present location before the Flandrian transgression had risen to that level. The deposition of unit C1 must thus have taken place before about 8000 or 9000 B.P. (figure 5). In addition, comparison of the fabric of this unit with that of soliflucted London Clay elsewhere suggests that it is likely to be a product of mudsliding resulting from periglacial solifluction. These two factors both point to a Late-glacial age for colluvium C1, with its formation ending at the close of the Younger Dryas period (*ca.* 10000 B.P.).

The subsequent Postglacial period was characterized by considerably warmer, but variable, climatic conditions (Godwin 1956; Starkel 1966). Recent evidence (Osborne, in Coope 1975) suggests that already by about 9500 B.P., in the Pre-Boreal period, the climate was such that a thermophilous fauna could flourish in central England. The succeeding Boreal period (*ca.* 8800–7000 B.P.) was warm and dry and seems to have been a time of relative stability on Hadleigh Cliff. During this time, in response to the continuing rise of sea level, aggradation of Flandrian deposits in the estuary was proceeding, and by about 7000 B.P. these would have buried the colluvium of unit C1.

TABLE 6. DETAILS OF RADIOCARBON DATES AT HADLEIGH CLIFF

(To be published in *Radiocarbon*)

provenance and nature of sample	elevation m O.D.	reference no.	normalized ^{14}C date years B.P.	δ^{13}C (‰)
borehole 8 (organic alluvium)	−2.0	SRR 320	5843 ± 120	−24.8
trench 2 (charcoal)	+4.2	SRR 319	3731 ± 65	−23.4
trench 8 (wood)	+1.5	SRR 224	2558 ± 50	−25.2
trench 6 (organic colluvium)	+12.7	SRR 223	2073 ± 85	−26.9
trench 9 (wood)	+23.3	SRR 222	97 ± 45	−27.6

The second stage of marked mass movement is represented by the colluvium of unit C2 (figures 5 and 15). This sheet of debris occupies the lower half of the cliff and directly overlies the *in situ* London Clay. Its upper surface, at a minimum proven elevation of −4 m O.D. in borehole N8, is overlain by the marsh deposits and it is probable that this situation holds down to an elevation of between −5 and −6 m O.D. (figure 5). The corresponding toe level of the cliff was then at about −7 to −10 m O.D., roughly 10 m higher than the level of the original cliff toe. A radiocarbon date of 5843 ± 120 years B.P. (table 6) has been obtained from an organic clay sample taken from the marsh deposits 2 m above the surface of this colluvium in borehole N8. At the time in question, the rate of rise of sea level (figure 5) was of the order of 1 m per century. Assuming that aggradation occurred at a corresponding rate, the age of the marsh deposits immediately overlying the lower parts of the unit C2 can be estimated as between 6000 and 6400 B.P. This colluvium must therefore have moved into place before these dates.

Following the dry Boreal period was the wetter Atlantic period (7000–5000 B.P.). Starkel (1966) reports the first half of this period in particular (*ca.* 7000–6000 B.P.) as being characterized in England by 'frequent landsliding', and it is likely that the unit C2 colluvium formed during this time. The fabric of this unit, as well as that of units C3 and C4, is entirely consistent with its formation by temperate mudsliding, as described by Hutchinson (1970) for the contemporary situation on London Clay cliffs on the opposite side of the Thames.

The succeeding sub-Boreal period (*ca.* 5000–2500 B.P.) was warm and dry and conditions on Hadleigh Cliff again appear to have been relatively stable. During this time the dried crust observed on the surface of the unit C2 colluvium between about boreholes N4 and N19 (figures 5 and 15) probably developed. Its lower parts, between boreholes N4 and N3 must, indeed, have formed early in this period, before coming within reach of the high tides. Higher on the slope, certainly upslope of borehole N19 and probably in the contemporary degradation zone above about borehole N6, a charcoal-rich layer was formed on the ground surface. This has been radiocarbon dated to 3731 ± 65 years B.P. and probably results from local Neolithic forest clearance.

At around 2500 B.P. a sharp deterioration of the climate, in the direction of increased wetness and coldness, heralded the start of the sub-Atlantic period (2500 B.P. to present). The earliest evidence of this on Hadleigh Cliff is the presence of a lens of grey, organic colluvium at the head of the sheet forming unit C2 (figure 15). A radiocarbon assay on a sample from the upper part of this lens gave a date of 2073 ± 85 years B.P. It seems probable that the lens marks the site of a pond or marsh which developed on the slope, probably in a hollow formed by landsliding, during the first 500 years of the sub-Atlantic.

Subsequently colluvium of unit C3 has overridden both the lens of organic C2 colluvium and the dried crust on the surface of that unit, apparently with little or no erosion (figures 5 and 15). It follows that the debris of unit C3 must be from a contemporary degradation zone upslope of borehole N6 and that the associated mass movements must immediately post-date about 2100 B.P. Further evidence for the unit C3 colluvium being derived from such a position is provided by the fact that the charcoal layer, deposited high on the Hadleigh slopes during the sub-Boreal period, was found within the unit C3 colluvium close to its toe (figures 5, 12 and 15).

This date of about 2100 B.P. for the third major stage of colluviation on Hadleigh Cliff is supported by findings in the region of the toe of unit C3. From a point 25–30 m back from its toe, this colluvium has sheared forward across the marsh clays on a sub-horizontal slip surface, which falls in level from about +2.5 m O.D. at its northern end to +2.2 m O.D. at its southern. A sample of wood from the marsh clays at the toe, 0.7 m below this latter level, gave a radiocarbon date of 2558 ± 50 years B.P. This evidence is consistent with the date of around 2100 B.P., put forward above, for the advance of the C3 colluvium over the surface of unit C2 and across the virtually completely aggraded marsh. It also reinforces correlation of the associated reactivation of mass movement activity on the cliff with the climatic deterioration early in the sub-Atlantic period. During this third stage of colluviation the toe level of Hadleigh Cliff was essentially at marsh level (*ca.* +3 m O.D.), where it has remained since.

The stages of degradation discussed so far have involved chiefly colluvium which is at present situated in and beneath the accumulation zone of Hadleigh Cliff, and the relations of the various colluvial units to the Flandrian alluvium at the cliff foot have considerably aided their differentiation and dating. The remaining stages in the slope development, now to be discussed, involve more recent events affecting chiefly the degradation zone of the cliff and the castle on its crest.

At the close of the third stage of colluviation, approximately 2000 years ago, unit C3 had been emplaced and the appearance of the lower half of the cliff was probably rather similar to that of today. The upper part of the cliff was then probably occupied by a thinner continuation of the unit C3 colluvium, running upslope into shallow, successive slips, while the slope crest would have been approximately 20 m in advance of its present position, as shown later. It seems likely that this situation in the degradation zone persisted, with little further mass movement, until the occurrence of the major rotational landslide in the cliff crest in the late 19th century.

The evidence for a period of relative stability on the cliff between the third and fourth stages of colluviation may be summarized as follows:

(i) There is no colluvium that can be referred to this interval.

(ii) Since the third stage of colluviation, when unit C3 was emplaced and sheared 20–25 m across the marsh deposits, the toe of that unit has moved only slightly, to produce the subdued pressure ridge in the adjacent marsh. As this subtle feature is fresh enough still to be seen in a marsh that is doubtless ploughed occasionally, it is probably associated with the late 19th century landslide. This, combined with the fact that, within the accumulation zone, the unit C3 colluvium has not been overridden by any subsequent debris, suggests that mass movements on the cliff in the interval between the third and fourth stages of colluviation have been relatively minor.

(iii) The castle was planned and constructed just beyond the middle of this interval. The decision to build the south curtain wall on or very near the then crest of the cliff and the fact that much of the building material was transported from ships up the abandoned cliff to the site, both suggest that at that time the slopes were relatively stable.

(iv) A number of 18th and 19th representations show the cliff to be well vegetated. One of these is the sketch of 1858, reproduced in figure 9. This also shows a situation on the upper cliff which, to judge from Mr Drewett's (1975) impressions, is probably not markedly different from that at the time when the castle was constructed.

Between about A.D. 1550 and 1850 Britain suffered an appreciable climatic deterioration, often referred to as the 'Little Ice Age' (Lamb 1959). This seems to have been characterized by cold winters and wet summers (Lamb 1963) and was probably a time of abnormally high groundwater levels. A preliminary review of the historical evidence suggests that there were periods of increased incidence of inland landslides, notably between about 1550 and 1600 and again between about 1700 and 1850, which may have reflected such a climatic influence (Hutchinson 1965). However, on Hadleigh Cliff no clear evidence of mass movements associated with the Little Ice Age has been found. While the possibility of such movements cannot be ruled out, the evidence presented above indicates that they are unlikely to have been of major consequence.

The late 19th century landslide, which involved the colluvial unit C6a and b (figure 15), has initiated the fourth and latest major stage of colluviation at Hadleigh Cliff. In addition to being a considerable mass movement in its own right, with a downhill movement of about 12 m, this slide had significant secondary effects both up- and downslope. The colluvial unit C5, immediately downslope, was thrust forward by over 10 m, so that it overrode the rear of unit C4. In response to the associated undrained loading (Hutchinson & Bhandari 1971) this unit in turn suffered downslope displacement, which carried its toe over the rear of unit C3 by up to 8 m, and internal imbricate thrusting, which buried soil layers and an iron railing and resulted in an upslope thickening of the unit. A radiocarbon assay on one such soil layer gave a date of 97 ± 45 years B.P., confirming the recent age of these movements. Finally, the loading of the rear of unit C3 by the overriding toe of unit C4 may, as suggested above, have led to a slight downslope shift of unit C3 which produced the relatively fresh pressure ridge in the marsh

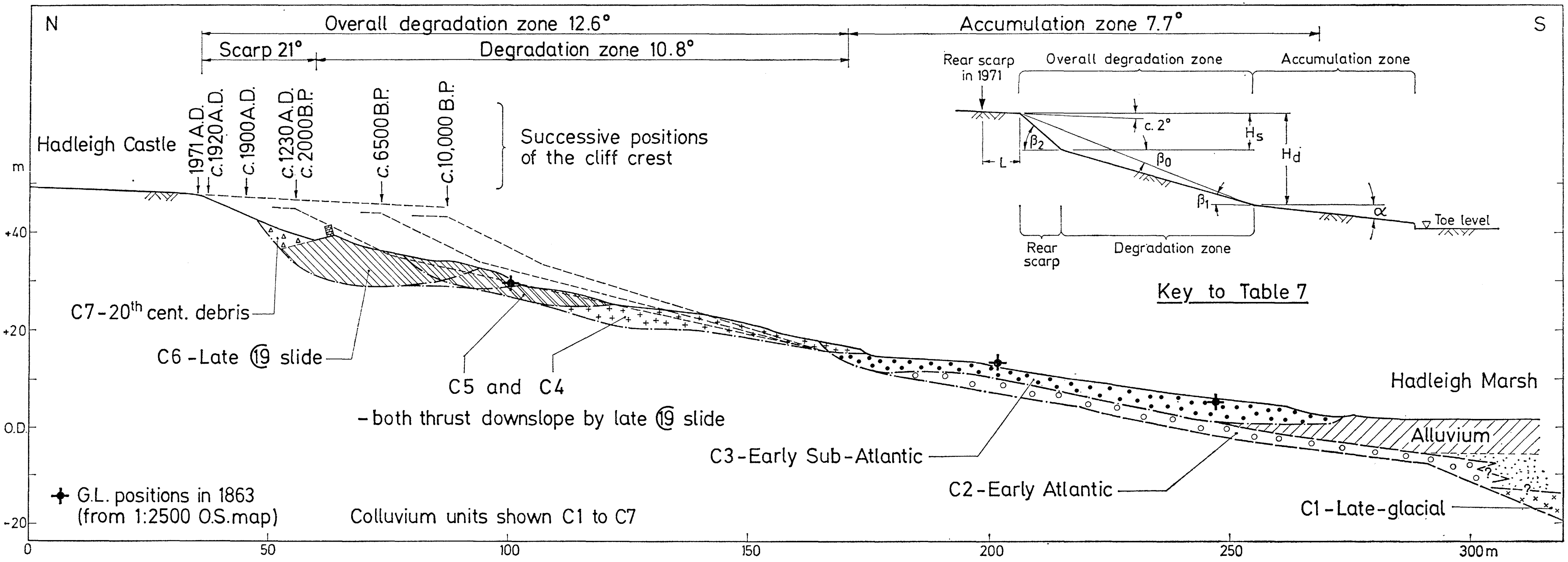

FIGURE 28. Overall cross section 2–2 showing the present morphology of Hadleigh Cliff and reconstructions of its former profiles.

at its toe. The accompanying shifts in position of the slope contours are evident from a comparison of the various 1:10560 Ordnance Survey maps: their positions in 1863 are shown on figure 28.

No single event or explanation emerges to explain why the late 19th century landslide should have occurred when it did. The following factors may have contributed, however:

(i) The continuing progress of weathering in the upper slopes.

(ii) Creep and progressive failure.

(iii) Unrecorded, slow downslope movements of the colluvium in the lower parts of the degradation zone, which would reduce support at the toe of the eventual late 19th century landslide.

(iv) A general cooling of the climate during the 1890s to a general level typical of the Little Ice Age and surpassed only during the period around 1700 (Manley 1958).

(v) An isolated extreme climatic event.

(vi) Human disturbance of the slope beneath the castle.

In the last connexion, it is noteworthy that the time of development of this landslide coincides approximately with the opening by the Salvation Army of the nearby brickworks and pottery, referred to above. Although the brickpits themselves were probably sited sufficiently far west to avoid influencing Hadleigh Cliff, a kiln, pottery and ancillary buildings (figure 7) were constructed between 1891 and 1895 in the accumulation zone beneath the western end of the castle, as indicated earlier. It is possible that the associated disturbance may have caused retrogressive movements up-slope and thus triggered the landslide in the slope crest. The revelevant 1:2500 Ordnance Survey maps indicate the main movements of this slide to have occurred on a line directed towards the buildings mentioned above.

From the similar mudslide fabric of units C3 and C4 and their relative geometry (figure 15), it is inferred that, before being thrust forward by the 19th century landslide, the latter represented the upslope continuation of unit C3. Unit C5, on the other hand, has the fabric of slipped London Clay of weathering zone III b and is thought to comprise the remains of the shallow, apparently successive rotational slips which occupied the head of the slope prior to the late 19th century failure. Two of these are shown in figure 9.

The scarp left upslope by the 19th century slide has naturally degraded to produce the small colluvial unit C7 (figure 15). The minor encroachments on to the bailey of the castle, reported at various times up to 1970, merely represent minor steps in the continuing degradation of this rear scarp. Subsequently, however, the true rear scarp has been obscured by having spoil from Mr Drewett's excavations of 1971 and 1972 bulldozed over it. By the latter half of 1975 small slips were developing there, partly in the softening spoil and partly by the renewal of movement in earlier slips buried by the spoil.

Over a similar period, more general slow movements have been in progress in the upper parts of the degradation zone. These have resulted in the distance between the stable and the lowest slipped parts of the west wall of the castle increasing at an average rate of 0.31 m/year between April 1969 and January 1976, and in the formation of cracks and scarps in the sub-adjacent slopes (R. Hodson, personal communication). In November 1975 recent cracks and fresh scarps up to 0.6 m high were particularly evident in the area extending from just above borehole N12 to about borehole N11. These signs are consistent with the continuing movement of the late 19th century landslide (figure 15). Although certainly influenced by the natural climatic factors, these movements have probably been exacerbated by the tipping of spoil over the rear scarp on to the head of this landslide and by the stripping of vegetation from much of Hadleigh Cliff by bulldozer in December 1973.

SLOPE DEVELOPMENT

From the history of Hadleigh Castle, it is possible to define reasonably closely the amount by which the cliff crest has receded since the building of the castle in the 13th century. As the units of colluvium mantling the cliff have been defined and dated, it is also possible, though with less certainty, to make estimates of earlier positions of the cliff crest and profile at various times during the Postglacial period.

In these reconstructions a number of points arise:

(i) As in general a given dry mass of over-consolidated *in situ* clay occupies a smaller volume than the colluvium formed from it, a reduction factor has to be applied to the colluvial volumes to convert these to equivalent pre-slipped volumes (Hutchinson 1970). At Hadleigh, the colluvium is partially desiccated and has an average water content only slightly above that of the weathered *in situ* London Clay from which it is derived. Taking the average water content of these materials as 33 % and 31 %, respectively, a volumetric reduction factor of 0.97 is obtained.

(ii) A reasonable reconstruction can only be made if little or none of the colluvium involved has been removed by erosion. This condition is closely satisfied by colluvial units C3 to C7 inclusive, which have formed since the cliff was essentially abandoned by the sea. Colluvial unit C2 may have suffered some erosion at its toe during the period when the Flandrian sea level rose from about -10 to -5 m O.D. The corresponding Flandrian sediments at this locality indicate rather low energy conditions, however, and any erosion of the colluvium is likely to have been moderate. In the case of colluvial unit C1 an unknown amount of erosion may have occurred and, furthermore, the present volume is only known very approximately.

(iii) The implicit assumption is made that all the colluvium derives from the degradation zone and that only deposition occurs in the accumulation zone. In the case of colluvial units C1 and C2, however, and possibly to a minor extent for C3, further material has doubtless been added to the colluvium during its passage down the accumulation zone, by the process of basal incorporation (Hutchinson 1970). In these cases, therefore, the estimated crest and profile positions in the degradation zone shown in figure 28 will tend to be too far to the south.

(iv) The implicit assumption is also made that all the mass movements involved took place directly down the line of section. This condition is probably met reasonably well for all the Hadleigh colluvium along section 2–2 (figure 15).

(v) Even where the equivalent *in situ* volume of a colluvial unit is accurately known, there is some uncertainty as to the shape which it occupied prior to slipping. This uncertainty tends to increase as one goes back in time.

In reconstructing the previous positions of the cliff crest at Hadleigh, colluvial unit C4 has been considered, as discussed above, as originally an up-slope continuation of unit C3, and the line of the original cliff top has been assumed to be a southward continuation of the surface, beneath the fill, which still remains. The greatest uncertainties attach to the shape of each colluvial unit before its failure. In reconstructing these it has been assumed that, prior to the late 19th century landslide, the topmost 9.5 m of the cliff exhibited parallel retreat at an average inclination of 26°. This height and angle of slope are intermediate between those at present obtaining at Hadleigh and those recorded at Beltinge (Hutchinson 1970). The remaining lower part of the degradation zone is then idealized, in each case, as a straight slope descending from the base of the 26° scarp so as to tangent the surface of the 'hump' in the *in situ* London Clay surface beneath the colluvium, between boreholes N7 and N6 (figures 15 and 28), which is discussed later.

TABLE 7. SUMMARY OF RECONSTRUCTIONS OF EARLIER PROFILES OF HADLEIGH CLIFF

(See figure 28 for key to symbols used.)

date	main stages of colluviation		approx. toe level m O.D.	estimated geometry of Hadleigh Cliff profile						
				L (m)	H_s (m)	H_d (m)	α	β_0	β_1	β_2
B.P.										
	1st	start	−19	> 51						
ca. 10000		finish	−9	51	assumed to be 9.5	30.5	?	19.2°	17.1°	assumed to be 26°
ca. 7000	2nd	start	−9							
ca. 6500		finish	−9 to −7	38		30	10.5–9.6°	16.5°	13.8°	
ca. 2100	3rd	start	+3							
ca. 2000		finish	+3	20		28	7.7°	14.7°	11.7°	
A.D.										
ca. 1890	4th	start	+3	modified by castle wall			7.7°			
ca. 1900		immediately post 19th C. slip	+3	10	10.0†		7.7°			
1971		just prior to spoil tipping	+3	0	9.0†	29†	7.7°	12.6°	10.8°	21°

† These figures include *ca.* 1 m of fill.

The reconstructed profiles of Hadleigh Cliff, based on the above assumptions, are indicated on figure 28, and the main changes in slope geometry are summarized in table 7. The maximum slope angles indicated by the reconstructions do not transgress the probable geotechnical constraints in the cliff, and are well within the range of angles exhibited by related natural slopes at the present day. The estimated pattern of retreat in the crest of the cliff during the past 10000 years is shown, against the background of the corresponding climatic variations in figure 29. This illustrates the strongly episodic, largely climatically controlled nature of the four main stages of degradation and, in the case of the first three of these, demonstrate the validity for this site of Starkel's (1966) three periods of 'frequent landslides' in Europe. The same figure also reveals that the average rate of retreat of the cliff crest, which had a nearly constant value of about 3.9 m per thousand years during the first three stages of degradation, increased to approximately 10 m per thousand years in the recent, fourth stage. This surprising behaviour adds weight to the suggestion that the late 19th century landslide may have been triggered by human interference, particularly when its unexpectedly deep-seated nature is also taken into consideration.

The average angle of the accumulation zone is now 7.7° (figure 28 and table 7), and this has altered little since the emplacement of colluvial unit C3 about 200–100 B.C. This angle is virtually coincident with the ultimate angle of stability of the London Clay against landsliding

(Hutchinson 1967*a*). Hence, as suggested earlier (Hutchinson 1967*b*, 1973) the inclination of the accumulation zone of an abandoned cliff may be considered, in many cases, to anticipate the eventual overall slope of the fully degraded cliff.

Although abandoned between about 10000 and 15000 years ago, Hadleigh Cliff has a degradation zone that, overall, is inclined at over 12° and is still actively landslipping. This indicates that the total time required, after abandonment, for degradation to the ultimate angle of stability, of about 8°, may be several times that which has elapsed so far.

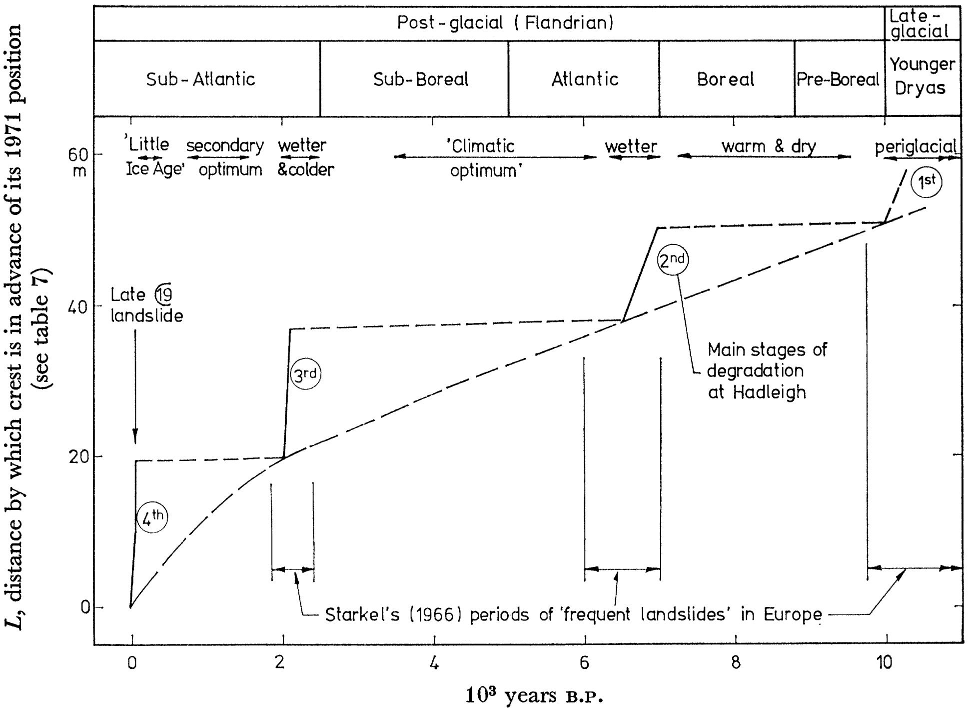

FIGURE 29. Estimated pattern of retreat in the crest of Hadleigh Cliff during the past 10000 years. (The slight slope given to the plot in the periods of relative stability is purely nominal.) The main trends in the climate during that time (after Godwin 1956, Lamb 1959) are also shown.

From the geometry, fabric and date of the various colluvial units it is concluded that the first stage of degradation, represented by unit C1, took place by periglacial mudsliding, the second and third stages, producing units C2 to C4, by temperate mudsliding and the fourth stage, involving predominantly units C5 and C6, by landslipping, broadly of successive rotational type. There thus tends to be a decreasing scale of fabric breakdown from the first to the fourth episodes of degradation. Also in general the mass movements become younger as the crest of the cliff is approached or, put in other words, the cliff is degrading from the top. Thus the present degradation zone is dominated in its upper parts by the most recent significant landslip (unit C6), of the late 19th century. The same pattern is exhibited by the colluvial unit C7, which post-dates the above landslip and now occupies the very top of the degradation zone. Other examples of abandoned, freely degrading clay cliffs, where the latest slip is at the crest of the slope are provided by the slopes of London Clay at Bushy Hill, Essex, where a rotational slip occurred in 1936 (EA 28 in Hutchinson 1965), and at Primrose Hill, London, where the painting by Linnell (Fitzwilliam Museum, Cambridge), dated 1811, shows a fresh rotational slip in the slope crest. In the abandoned cliff of Weald Clay, capped by Hythe Beds, at Lympne, Kent, the latest known landslip again occurred in the slope crest, in about 1725 (Hutchinson 1968).

It is convenient to discuss here the pattern of weathering zones in the *in situ* London Clay beneath the colluvium, described earlier. These are shown in figure 15. If a slope were to be eroded very rapidly into a plateau formed by a horizontal stratum exhibiting a horizontal system of weathering zones below the plateau surface, the horizontal zonation would initially be preserved. With time, a weathering front would advance in from the slope face so that in the long-term a new zonation, running approximately parallel to the slope, would form. At Hadleigh, with one major exception, the weathering zones do conform fairly closely to this pattern, which suggests that the slope is of considerable age and in general is not changing very quickly with time. Although differences in lithology and hydrology prevent a close comparison, these conclusions are supported by the fact that the maximum thickness of the combined weathering zones II–III b beneath the slope (*ca.* 10 m) approaches that obtaining beneath the plateau, just N of the slope crest (*ca.* 12 m). As noted earlier, weathering zone IV is absent, having presumably been removed by the mass movements.

With respect to the thickness and make-up of the weathering zones beneath the colluvium, four main features are evident (figure 15), in addition to those discussed above. The greatest proven thickness of the combined zones II–III b is at borehole N7, which is located in the hump in the buried surface of the *in situ* clay. In the same vicinity the colluvium is, correspondingly, at its thinnest. Downslope from the hump, zones II–III b are everywhere present, but the uppermost, zone III b, is rather thinner, possibly as a result of basal incorporation (Hutchinson 1970) by the mudslide which forms colluvial unit C2. Upslope of the hump, zone III b again thins, and is absent at boreholes N11 and N13. As the overlying colluvial unit C5 (and to a transitional extent the upslope parts of unit C4) also has a fabric similar to zone III b, it seems reasonable to conclude that here, too, the uppermost layers of *in situ* clay have been removed, but by shallow rotational landsliding rather than by mudsliding. Further upslope, the more deep-seated late 19th century landslide (unit C6) has involved all the weathered London Clay and, rather surprisingly, up to about 3 m of the unweathered (zone I) material. Clearly in this area the rate of removal of *in situ* material by mass movements far exceeds the rate at which the weathering front can advance into it.

From the above it can be seen that the present pattern of weathering beneath the colluvium is consistent with the most recent landslides being highest in the slope. In the future it is probable that there will be little change in this pattern beneath the accumulation zone as there the *in situ* material concerned is sealed in beneath a considerable thickness of stationary colluvium with a high ground-water table. Beneath the upper degradation zone, however, the recent landslides have tended to remove the protective weathered cover, and to encourage the further advance of weathering into the London Clay. In the long term, in combination with further downslope movement of the existing colluvium in the degradation zone, this may bring about a further major rotational slip in the slope crest.

The hump in the surface of the *in situ* clay beneath the colluvium, between boreholes N6 and N9, is believed to be a feature of some generality. From its position, at or just above the junction between the degradation and accumulation zones, it seems likely that it is in the nature of an erosion remnant, left between the head of the basally incorporating mudslides downslope and the toes of the successive rotational landslips upslope. Other degrading, predominantly clayey slopes which exhibit a similar feature include those at Horscombe Vale (Chandler, Kellaway, Skempton & Wyatt 1976), Sarukuoji (Fukuoka, in Skempton & Hutchinson 1969) and Weirton (D'Appolonia, Alperstein & D'Appolonia 1967), though at the latter site, in particular, some elements of lithological control may also be involved. The sea cliff exposed to moderate erosion at Beltinge (Hutchinson 1970) provides a further possible analogy.

It is evident from the complexity of the slope development found at Hadleigh that it does not lend itself to mathematical modelling. However, of the various theoretical geomorphological treatments of this theme, that proposed by Bakker & Le Heux (1947) under the title 'central rectilinear recession', although originally intended mainly for application to rock slopes, has some relevance.

In this, a straight slope of initial inclination β is considered, from which all debris removal from the foot has ceased. As the slope weathers it is supposed to decline in angle by rotation about its original foot. The resulting colluvium is assumed to build up at the slope foot at a constant smaller angle α. As a result of the increasing protection afforded to the lower cliff as the colluvium accumulates, and the consequent reducing height of the degradation zone, the theory predicts that the core of *in situ* material beneath the colluvium will develop a curvilinear, convex shape, the exact form of which will depend on the amount of bulking that is involved in the transformation from *in situ* to colluvial material and on the values of α and β. Time is not introduced explicitly into the treatment, but the degradation and accumulation are supposed to occur not 'suddenly by rockfall and landslide, but little by little'. It is implicit that both processes are considered to take place as infinitely thin, essentially translational movements.

The first difficulty in applying the theory to Hadleigh Cliff, is that the phases of degradation there have been associated with three different main toe levels (table 7). Consideration is concentrated, therefore, on the latest of these (*ca.* +3 m O.D.), with which the third and fourth phases of degradation can be approximately associated.

In the accumulation zone, represented by colluvial unit C3, although the material has not moved into place by a series of infinitely thin movements, it has arrived in a broadly translational manner. Also it seems likely that the inclination of the accumulation zone α has remained and will continue to remain fairly constant at about 8° during the degradation associated with the latest toe level (table 7), although in the preceding second phase of degradation, represented by unit C2, α had a value of around 10°.

Changes in the degradation zone at Hadleigh are effected mainly by intermittent episodes of moderately deep-seated, rotational landslipping. This behaviour deviates fundamentally from that assumed in the Bakker & Le Heux theory. As a result its conclusions with regard to the shape of the intact core beneath the degradation zone and to the convexity of divides do not apply here. Furthermore, the profile of Hadleigh Cliff at the start of any particular phase of degradation will have been concave upwards, rather than straight as supposed by Bakker & Le Heux. As a result a better fit to the successive positions of the degradation zone is obtained by using a line declining about a point upslope from the original cliff foot, rather than through it as proposed in the Bakker & Le Heux theory. In making the reconstructions of table 7, therefore, the point of rotation has been taken at the crest of the hump in the core of *in situ* London Clay, which is located at approximately a third of the cliff height (with respect to the latest toe level of *ca.* +3 m O.D.). The other general conclusions of Bakker & Le Heux, however, that the degradation zone declines and diminishes in height from the base with the progress of degradation, while the accumulation zone grows at a constant, lesser angle, are supported by the Hadleigh evidence (table 7). The reduction in the height of the degradation zone would appear more marked were it not for the effect of the slope of about 2° towards the south in the ground forming the cliff top.

No evidence for any appreciable slope wash has been found at Hadleigh.

MAIN CONCLUSIONS

The main conclusions of this investigation may be summarized as follows:

(1) Hadleigh Cliff was cut in the London Clay by two phases of strong fluvial erosion. The first of these formed a bench at about -27 to -30 m O.D.: the second partially eroded the gravels deposited on this bench and formed the, now buried, toe of the cliff at -19 m O.D. These two periods of erosion are tentatively assigned to the Middle Devensian (*ca.* 27000 B.P.) and the Late Devensian (*ca.* 17000 B.P.). Weaker erosion may have continued into the Late-glacial, or early Postglacial, since when the cliff has been essentially abandoned. The lower third of the cliff height is now buried beneath Flandrian alluvium.

(2) Although abandoned between about 10000 and 15000 years ago, the cliff has an overall degradation zone inclination of over 12° and is still actively landslipping. This indicates that the total time required after abandonment for degradation to the ultimate angle of stability, of about 8°, may be several times that which has elapsed so far.

(3) Since the weakening and eventual cessation of erosion at its toe, the cliff has degraded in an episodic manner, controlled largely by climatic variations. In the colluvium mantling the cliff, four main stages of degradation have been recognized and dated, as follows:

(i) Late-glacial mudsliding (completed by *ca.* 10000 B.P.) under periglacial conditions to a toe level of -19 m O.D.

(ii) Early Atlantic mudsliding (*ca.* 7000–6500 B.P.) to a toe level raised by Flandrian aggradation to about -9 m O.D.

(iii) Early Sub-Atlantic mudsliding (*ca.* 2100–2000 B.P.) to a toe level of $+3$ m O.D., approximating to present marsh level.

(iv) Recent landslipping (*ca.* 1890 A.D.), possibly due in part to human interference.

The first three of these periods are believed to represent times of generally increased mass movement activity throughout much of Britain and Europe.

(4) Degradation of the cliff takes place from its crest. The age of the resultant colluvium and its degree of fabric breakdown both tend, therefore, to increase from crest to toe of the cliff.

(5) Four weathering zones have been recognized and delineated in the *in situ* London Clay beneath the colluvium. These, in general, run parallel to the slope and hence indicate that it is of considerable age. As might be expected, the upper, more weathered zones thin out under the higher parts of the degradation zone. Surprisingly, however, the late 19th century landslide in the slope crest involves not only the weathered, but also 3 m of the unweathered London Clay. Drained and undrained laboratory shear strength tests carried out on the various zones of weathered clay illustrate the tendency for its modulus, peak strength and brittleness to decrease as the degree of weathering increases.

(6) In this area the average annual potential evaporation exceeds the average annual rainfall. As a result soil moisture deficits, and hence pore-water tensions in the capillary zone, are particularly high and persistent. A period of deficit which extended unbroken for nearly six years is recorded close to the site, at Shoeburyness. Ground-water observations in the area may thus have to be continued through a number of consecutive winters in order to establish

reliable maximum piezometric levels. Furthermore, at Hadleigh, even at times of maximum ground-water levels, appreciable negative pore-water pressures are believed to exist in the thicker parts of the capillary zone.

(7) Stability analyses in terms of effective stresses have been made on 12 actual or probable pre-existing slip surfaces in Hadleigh Cliff. The most critical of these involve the upper part of the degradation zone, where slow, continuing movements indicate that the safety factor is currently unity. In these analyses the conventional assumption of zero pore-water pressure in the capillary zone is treated as an upper bound value: a lower bound value, defined by negative hydrostatic pore-water pressures in all but the uppermost metre of this zone, is also considered. The field residual failure envelope inferred from the most critical back-analyses is defined by the parameters $c' = 0$ and $\phi' = 13.3°$ up to a normal effective stress of 50 kN/m^2, beyond which it shows a slight tendency to flatten. On the basis of these parameters, the overall factor of safety of the accumulation zone is estimated to be approximately 1.05.

(8) Comparison of the values of drained residual strength inferred from the back-analyses with those measured on the Hadleigh colluvium in ring shear shows the ring shear values to be appreciably the lower. In making such comparisons it is appropriate to allow in the analyses for any negative pore-water pressures that are present.

(9) Hadleigh Castle is shown to have been built partly on *in situ* London Clay and partly on slipped masses of this material. In the latter case collapses occurred shortly after construction in the 13th century, doubtless as a result of reactivation of pre-existing slips. Damage has also resulted to parts of the castle founded on *in situ* clay, namely the south curtain wall and the northeast tower, as a result of two first-time slips which have taken place during the past 100 years.

(10) The present morphology of Hadleigh Cliff comprises a straight crest scarp inclined at about 20°, an irregular and actively unstable degradation zone sloping at about 11° and, below this, a more even, quasi-stable accumulation zone with an average inclination of about 8°. Reconstructions of earlier cliff profiles indicate that during the last 10000 years the accumulation zone has grown slightly at a relatively constant slope of 8–10°, while the degradation zone has declined, about a point near its lower limit, from about 17° to its present slope. During the same period the crest scarp has receded by about 50 m, probably by parallel retreat.

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APPENDIX: WOOD AND CHARCOAL

BY J. F. LEVY

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(1) *Sample C. trench* 6 (associated with material carbon-dated to 2073 ± 85 years B.P.)

Several pieces of partially decayed wood, which had probably formed part of branch or stem which was between 8–12 cm in diameter.

The pieces were distorted by considerable shrinkage. They showed the typical brash fracture and high shrinkage of material decayed by a soft-rot fungus.

Boreholes and frass of a wood boring beetle were present.

The anatomy of the wood was that of a diffuse porous hardwood, with fine rays, 1–4 seriate and small vessels, of the same order of diameter as the tangential breadth of the ray. The rays were separated by a distance equal to 3 or 4 times the diameter of the vessel.

The secondary cell wall of all cells was not seen, which is further evidence of a soft-rot type of decay, and possibly long term burial in wet conditions.

Identification – uncertain, in view of the distortion and decay, but probably the field maple, *Acer campestre*.

(2) *Sample B, trench* 6

Pieces of partially decayed wood very similar to the previous sample in every way, but with a more obvious annual growth ring.

Identification – uncertain; possibly maple or a member of the Rosaceae.

(3) *Wood from alluvium, trench* 8 (carbon-dated to 2558 ± 50 years B.P.)

Pieces of twig or small branch up to 3 cm diameter. Partial charring with some distortion and loss of anatomical detail.

The wood is a ring porous hardwood, some pieces being oak (*Quercus* sp.) and some pieces ash (*Fraxinus* sp.).

The growth ring patterns on several samples show a striking difference in the rate of growth. The rings are relatively broad for the first few years, then show a period of slow growth for up to twenty rings, followed by a few years of much faster growth. The number of rings of slow growth varies within the samples examined and ranges from six to twenty.

(4) *Charcoal from colluvium, trench* 2 (carbon-dated to 3731 ± 65 years B.P.)

The material consisted of small fragments of wood charcoal in mud. All the samples examined were charred.

The wood was a ring porous hardwood with broad and fine rays.

Identification – oak (*Quercus* sp.).

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6

FIGURES 2 AND 6. For description see opposite.

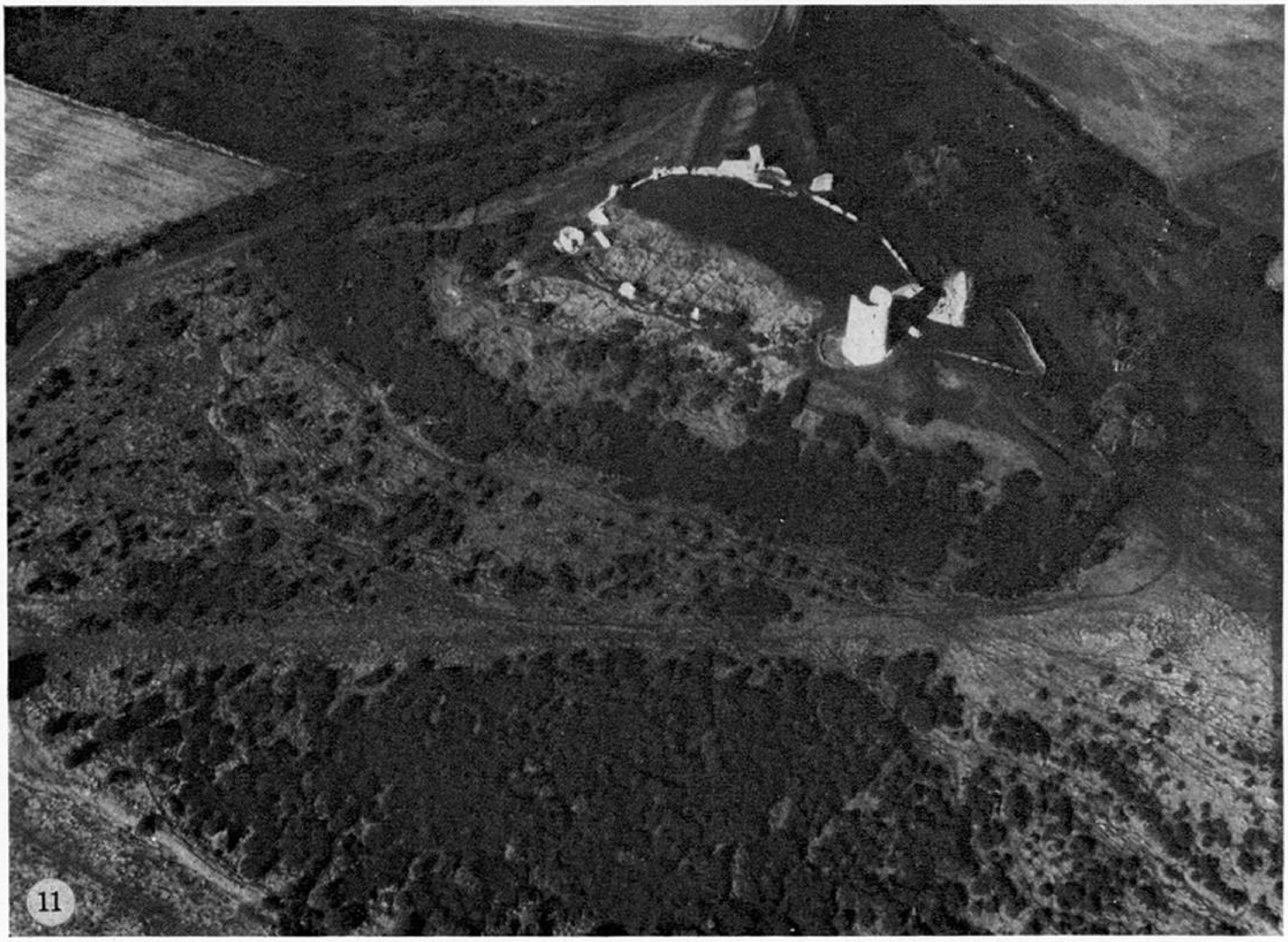

FIGURE 10. Oblique aerial photograph of Hadleigh Cliff, looking NW, taken 6 October 1928 (with acknowledgements to Aerofilms Ltd).

FIGURE 11. Oblique aerial photograph of Hadleigh Cliff, looking NW, taken 7 November 1967 (with acknowledgements to Aerofilms Ltd).

FIGURE 16. Photographs of hand specimens of different weathering zones of the London Clay. (*a*) Zone I (unweathered), (*b*) zone II and (*c*) zone IIIb.

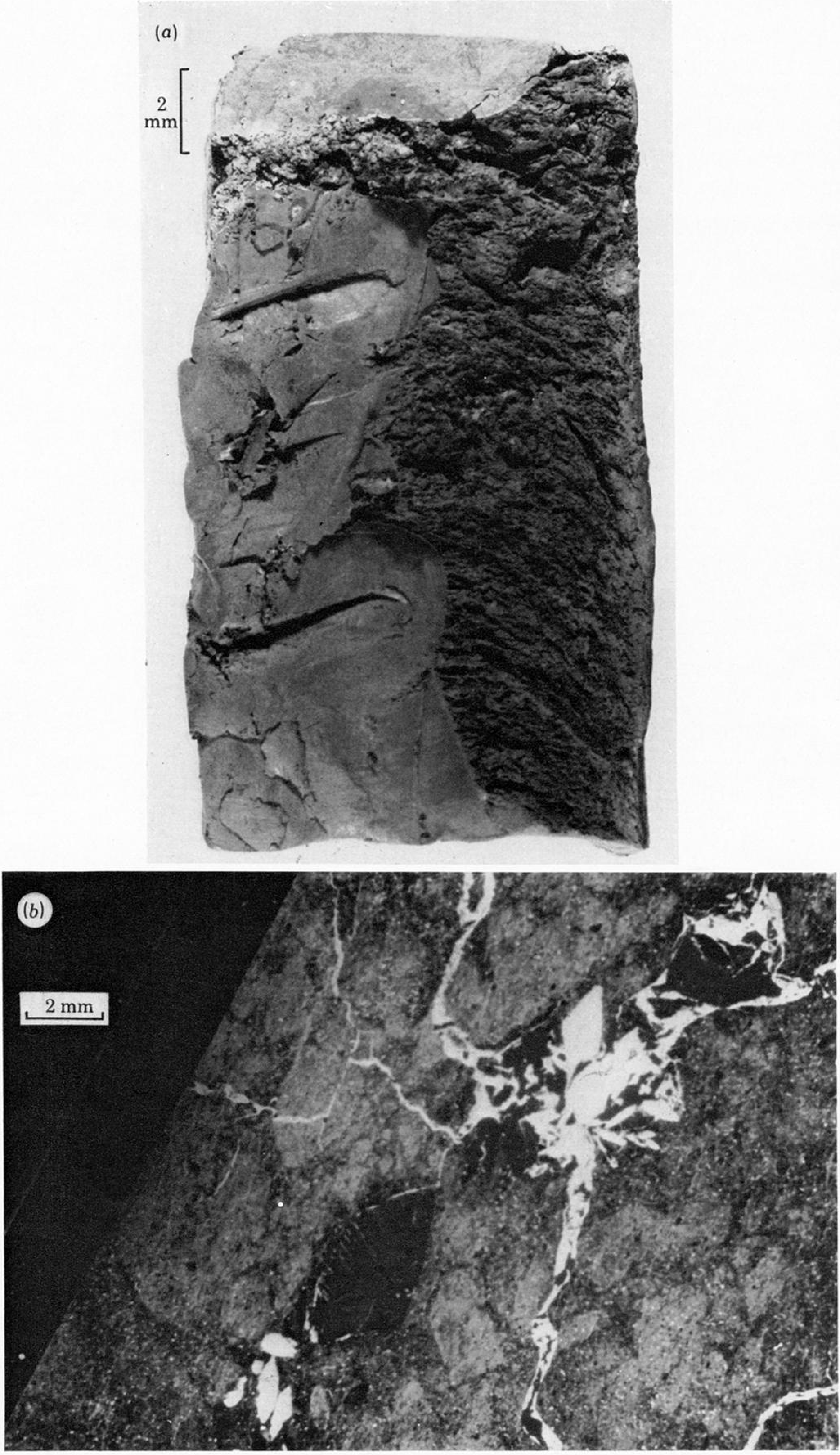

Figure 20. Photographs of the London Clay-derived colluvium of unit C3, (*a*) in hand specimen and (*b*) under the optical microscope. In the latter photograph the diamond-shaped light and dark areas indicate selenite crystals; the irregular light areas and lines represent intruded carbowax.