The History and Stability of two Lias Clay Slopes in the Upper Gwash Valley, Rutland [and Discussion]

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The history and stability of two Lias clay slopes in the upper Gwash valley, Rutland

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[Plates 3 and 4]

Two detailed valley side sections are described. Both are of landslipped slopes cut in Upper Lias at the point where the Inferior Oolite escarpment is breached by the eastward flowing river Gwash, a few kilometres east of Oakham, Rutland. Field mapping suggests that the slopes were cut in Ipswichian times either shortly before or during the deposition of the Second Terrace of the river Welland, of which the Gwash is a tributary.

One of the slopes (Barnsdale) was oversteepened by fluvial erosion which stripped the cambered Inferior Oolite and frost-disturbed Lias from the escarpment face, leaving, at the slope foot, a prominent erosion surface (the 'Hambleton Surface'). After cessation of erosion Head accumulated on the Surface and the slope degraded, much of the degradation possibly occurring in the Middle Devensian, though landslide movement continued to the end of the Late Devensian. The other slope (Hambleton) which had formerly been cambered, suffered only slight steepening contemporaneously with the Barnsdale slope and the large, shallow rotational landslide that developed in the frost-disturbed Lias clay was subsequently partly obscured by Late Devensian solifluction.

Stability analyses of these two landslides, together with three other previously published case records, show that the field values of residual strength of Upper Lias clay are strongly stress dependent, with the magnitude of ϕ_r' ($c_r' = 0$) falling to 10° as the normal stress increases. Laboratory measurements of residual strength using the ring-shear apparatus are similarly stress dependent, but show considerable strength variations between different samples with similar index properties. The ring-shear strengths underestimate the field strengths by up to 11 %.

INTRODUCTION

One of the major morphological features of Lincolnshire and the East Midlands is the escarpment formed by the Upper Lias and capped by the more resistant Inferior Oolite limestones. This escarpment, shown in figure 1, runs due south through Lincolnshire from the Humber to Grantham; south of Grantham the escarpment swings west, the result of east–west folds in the Jurassic strata (Linton 1954). Further south still the north–south alignment is resumed before the escarpment is extensively breached by the Welland and its tributaries flowing eastward to the Wash. As a result of downcutting by these rivers the escarpment is generally less well defined in Rutland and Northamptonshire, though it is well developed again on the east bank of the Welland in the region of Rockingham in north Northamptonshire.

The most northerly of the breaches of the escarpment associated with the Welland occurs just east of Oakham where the river Gwash, a tributary of the Welland, cuts a west–east valley through the escarpment into the Lias clays. Further east the Gwash crosses onto the overlying Inferior Oolite Series, and then turns abruptly south to join the Welland at Stamford, a few kilometres before reaching the Fenland margin.

This paper discusses the development of the Gwash valley slopes at the point where the twin streams of the Gwash and its parallel, more northerly, tributary cut through the main escarpment, forming the Vale of Catmose. The Vale is some 4–5 km wide, and is bounded at its eastern end by a prominent outlier which lies between the twin Gwash streams and on which the villages of Upper and Middle Hambleton are situated.

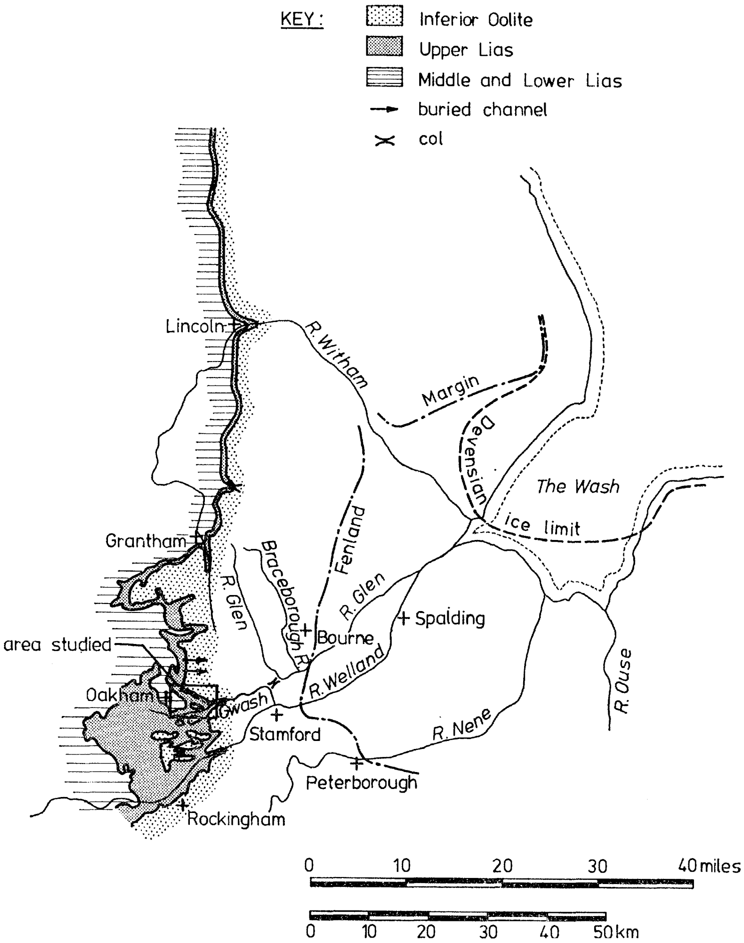

FIGURE 1. The Inferior Oolite/Upper Lias escarpment in Lincolnshire and the East Midlands. The study area is indicated. Devensian ice limits from Straw (1969)

The origin and history of the Gwash valley provide a framework for the interpretation of two slope sections, at Barnsdale and Hambleton, both at the eastern end of the Vale of Catmose and both involving major landslides. The area under consideration is indicated in figure 1, and is shown in figure 2, in the form of a combined geological and geomorphological map.

Most of the detailed information presented here has been obtained as a result of the construction of the Empingham Reservoir scheme, in particular from investigations for the diversion of the A 606 and the Hambleton access road.

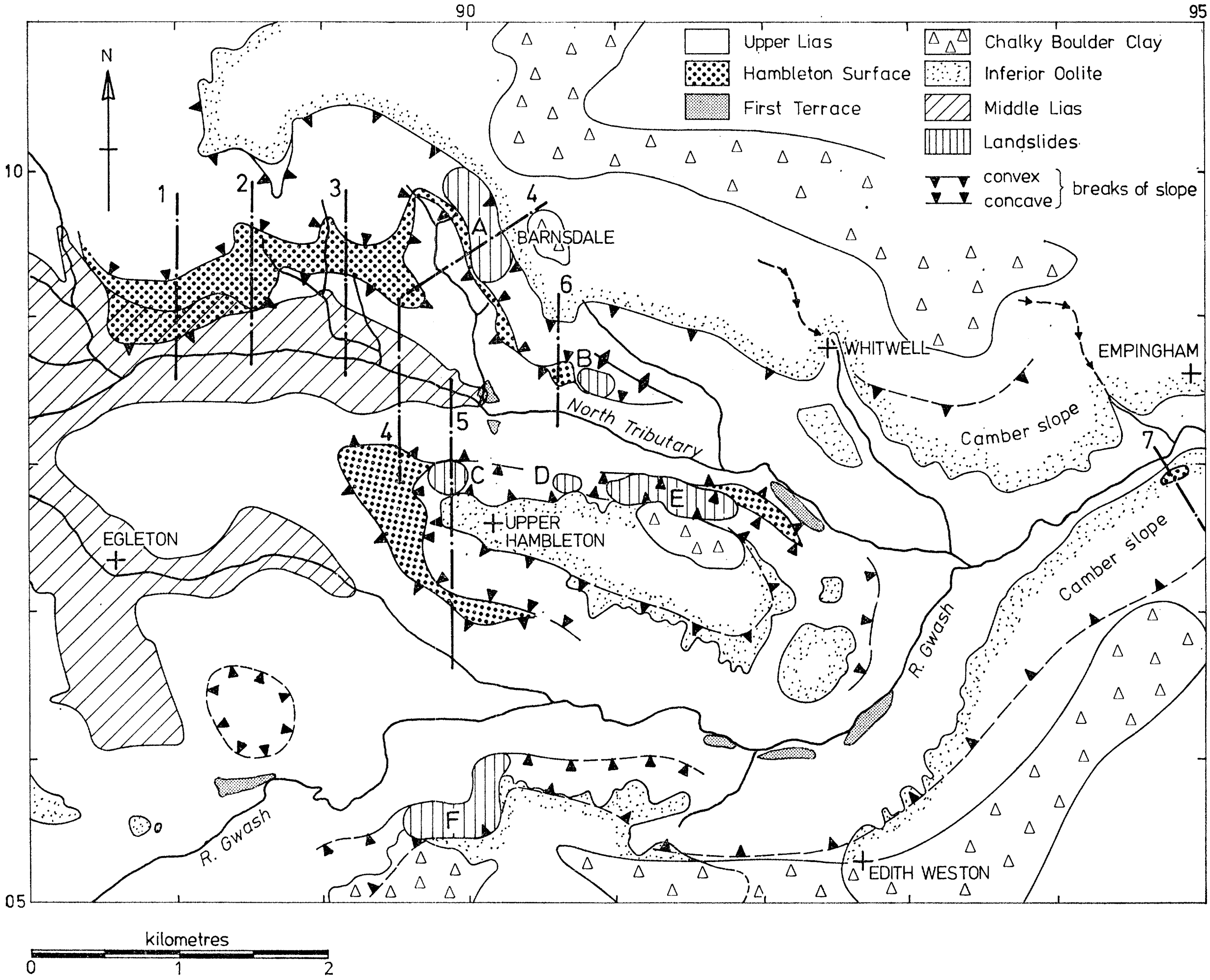

Figure 2. Geomorphology and geology of the Upper Gwash valley. Sections 1 to 7 are shown in figure 3. A–F show locations of landslides listed in table 3, p. 470.

Stratigraphy and lithology

The sequence of strata occurring in the Hambleton area is given in table 1.

Table 1. Stratigraphy of Hambleton area

			thickness m
Pleistocene	—	Chalky Boulder Clay	0–30
Jurassic	Inferior Oolite	Northampton Sand	5
	Upper Lias	Upper Lias clays	63–65
	Middle Lias	Marlstone Rock Bed	about 3
		Middle Lias silts and clays	about 20

In the Hambleton area the total thickness of the Upper Lias is close to 65 m, with records of 63 m at Ridlington (I.G.S. Well Record 157/208) and 65 m at Uppingham (Whitaker 1922, p. 114), both about 4 km to the south, and 65 m at Cottesmore 3 km to the north (Hollingworth & Taylor 1951, p. 11).

The Upper Lias, heavily overconsolidated by subsequent deposits now removed by erosion, consists of a sequence of soft mudstones or stiff, fissured clays, with two thin calcareous horizons, the 'Ammonite Nodule Bed' and the 'Pisolite Bed' respectively 18–20 m and about 10 m above the base of the Upper Lias. Beneath the Pisolite Bed are a series of laminated silty clays, the 'Fish Beds'. The stratigraphy and lithology of the Upper Lias is discussed in detail by Horton & Coleman (1976) and by Horswill & Horton (1976, this volume). In some localities, particularly in areas of camber, the Upper Lias has been affected by Pleistocene frost action which has produced a 'brecciated' fabric (Chandler 1972), an effect that is most extreme within 10 m of the ground surface.

Beneath the Fish Beds of the Upper Lias lies the Marlstone Rock Bed, a 2–3 m thick stratum of ferruginous, oolitic limestone which is in turn underlain by the very silty Middle Lias clays.

The typical ranges of the engineering index properties of the Lias clays in the Hambleton area are given in table 2.

TABLE 2. INDEX PROPERTIES (RANGE AND AVERAGE VALUES) OF THE LIAS CLAYS IN THE HAMBLETON AREA

	liquid limit (%)	plastic limit (%)	natural water content† (%)
Upper Lias			
(i) general	54–65 (60)	25–30 (28)	17–30 (27)
(ii) micaceous horizons and Fish Beds	44–54 (48)	20–25 (24)	15–28 (21)
Middle Lias (silty clays)	40–55 (50)	20–25 (22)	15–25 (20)

† *In situ*, but at depths not exceeding 10 m.

Overlying the Upper Lias is the lowest member of the Inferior Oolite Series, the Northampton Sand Ironstone, in this area an oxidized oolitic limestone typically 5 m thick.

The Chalky Boulder Clay which forms remnant fragments on the interfluves, as shown in figure 2, is a sandy Jurassic derived clay, rich in flints and Bunter-type pebbles. The subsequent Devensian glaciation did not reach the Gwash valley, though most authorities are agreed that it entered the Wash, less than 50 km distant (figure 1).

THE POST-CHALKY BOULDER CLAY DEVELOPMENT OF THE GWASH VALLEY

Prior to the entry of Chalky Boulder Clay ice into the East Midlands the drainage of the area was by a system of west–east streams, a pattern established by various workers, notably Kellaway & Taylor (1953), Rice (1965), Wyatt (1971) and Harrod (1972).

When the ice-sheet decayed the modern drainage system was initiated. In some instances it is clear that the early valleys have at least in part been re-excavated, no doubt where the glacial deposits incompletely filled the former valley. Examples of such re-excavation are some lengths of the Nene and the Ouse (Horton 1970) and possibly the Witham south of Grantham (Wyatt 1971), though an ice eroded origin for this part of the Witham valley has been suggested by Straw (1969). In other instances entirely fresh streams have developed, such as the Glen and the Bracebrough River (figure 1) which appear to have originated either on or at the margin of the ice sheet, in places cutting at right angles across the pre-glacial drainage lines (Kent 1939; Wyatt 1971; Harrod 1972).

Elements of the pre-glacial west–east drainage cut through the main escarpment just north of the Gwash, where till-filled channels cut the crest of the escarpment (figure 1). In view of its west–east alignment it seems possible that the Gwash too is a re-excavated pre-glacial valley.

Two infilled cols occur to the south of the Gwash valley (figure 2) (Kellaway & Taylor 1953). The easterly of these two cols is the deeper, descending to around 95 m O.D., while Alluvium level in the neighbourhood is at 62 m O.D. Although Chalky Boulder Clay occurs extensively on the higher ground on either side of the Gwash valley and also on the Hambleton outlier (figure 2), with the exception both of the infilled cols and also of some gulls in the camber sheets that are similarly filled with till, all relatively high on the valley sides, till has not been encountered on the valley slopes in spite of the extensive and detailed investigations for the Empingham Reservoir scheme. The present valley is thus, in the context of the valley side slopes, without doubt entirely of post Chalky Boulder Clay age.

The Hambleton Surface

Morphological mapping of the gently undulating floor of the Vale of Catmose shows that to the west and south of the Hambleton outlier and along the northern edge of the Vale is a gently sloping bench or surface, the 'Hambleton Surface', seen in figure 2. The back edge of the Surface is formed by the main valley-side slopes, while the front edge is defined by slopes falling to the Alluvium or, locally, to the First Terrace; at some localities it diminishes laterally to be replaced by a concave break of slope.

A series of sections showing the Hambleton Surface is given in figure 3, drawn from 1:2500 contoured (1 m intervals) plans of the reservoir area. The geological detail is based on borings, and on outcrop positions mapped by the Institute of Geological Sciences and confirmed by recent work for the Empingham scheme. At the western end of the Vale (section 1 of figure 3) the Surface is developed on the Marlstone Rock Bed, but it falls downstream at a lower gradient than the general dip (sections 2–6), and so is cut successively higher-up the geological sequence. The Surface is best developed on the Marlstone (section 1) and at two localities southwest of both Barnsdale and Hambleton (sections 4 and 5) at about the horizons of the Pisolite and Ammonite Nodule Beds in the Upper Lias. Presumably the Surface here owes its preservation to the greater resistance to erosion of these strata.

A number of borings and trial pits have been located on the Hambleton Surface, and almost without exception these show about a metre of Head. The Head is very clayey and is clearly derived in the most part from the Upper Lias. However, scattered Northampton Sand fragments, occasional small angular flints and Bunter-type quartzite pebbles and also rare lenses of sand occur, confirming the superficial nature of this deposit. These constituents suggest that the Head was either deposited during erosion by a sluggish braided stream system in the broad valley floor, or derived subsequent to the erosion phase by wash or sludging from the adjacent slopes. Figure 4, plate 3, shows Head on the Hambleton Surface in the locality of section 1, figure 2.

In figure 3*b* the Hambleton Surface segments are superimposed in relation to the present Alluvium level and stream position. This shows the Surface to be generally at an altitude of between 12 and 16 m above Alluvium level, with a suggestion that it rises towards the valley sides.

The small stream just south of the Barnsdale landslide, section 4 of figure 3, has cut down well below the Hambleton Surface, almost isolating the Head-capped spur that the Surface forms

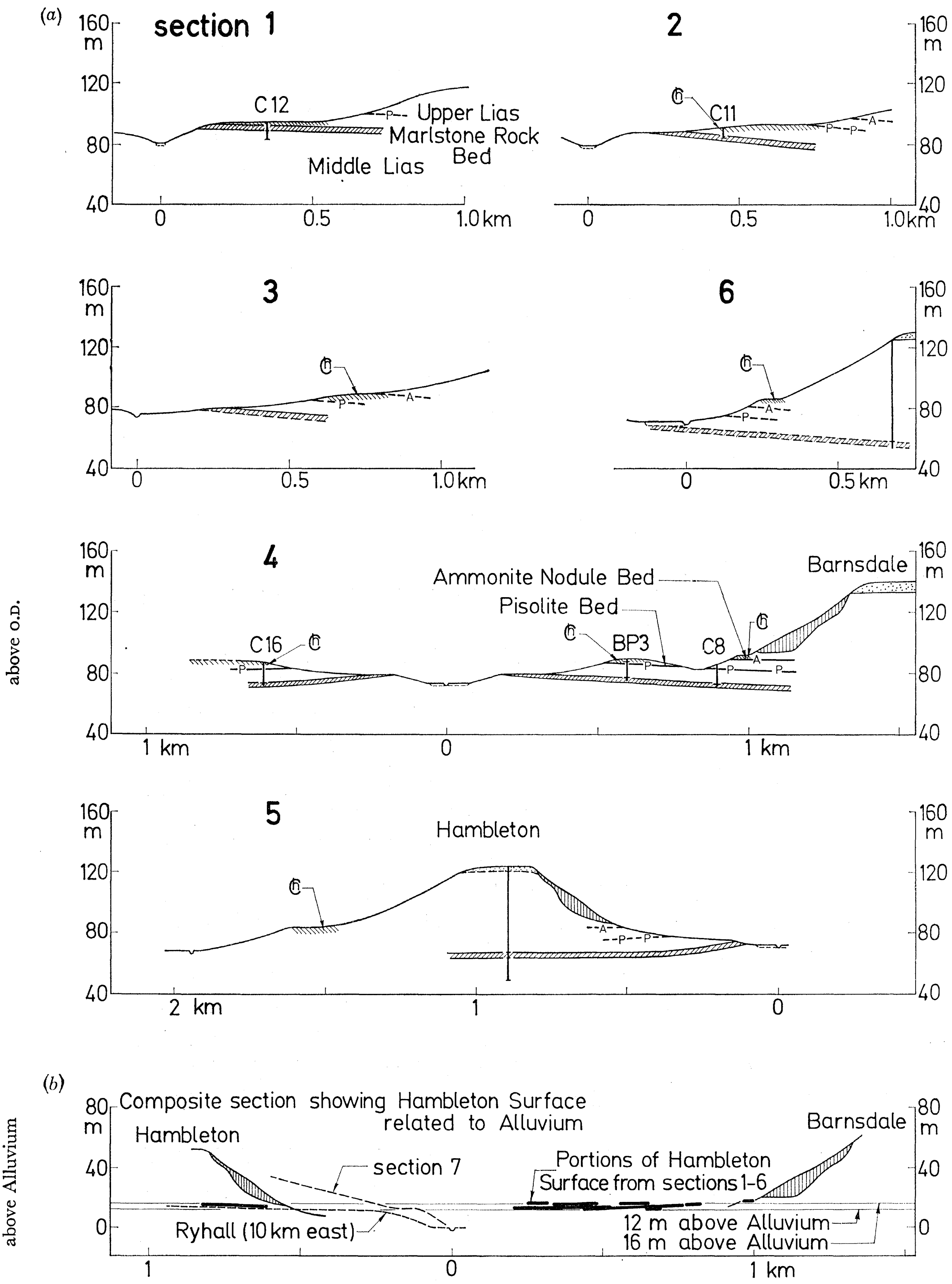

FIGURE 3. Sections showing the position of the Hambleton Surface in the Gwash valley; for location of lines of section see figure 2. Vertical exaggeration × 5.

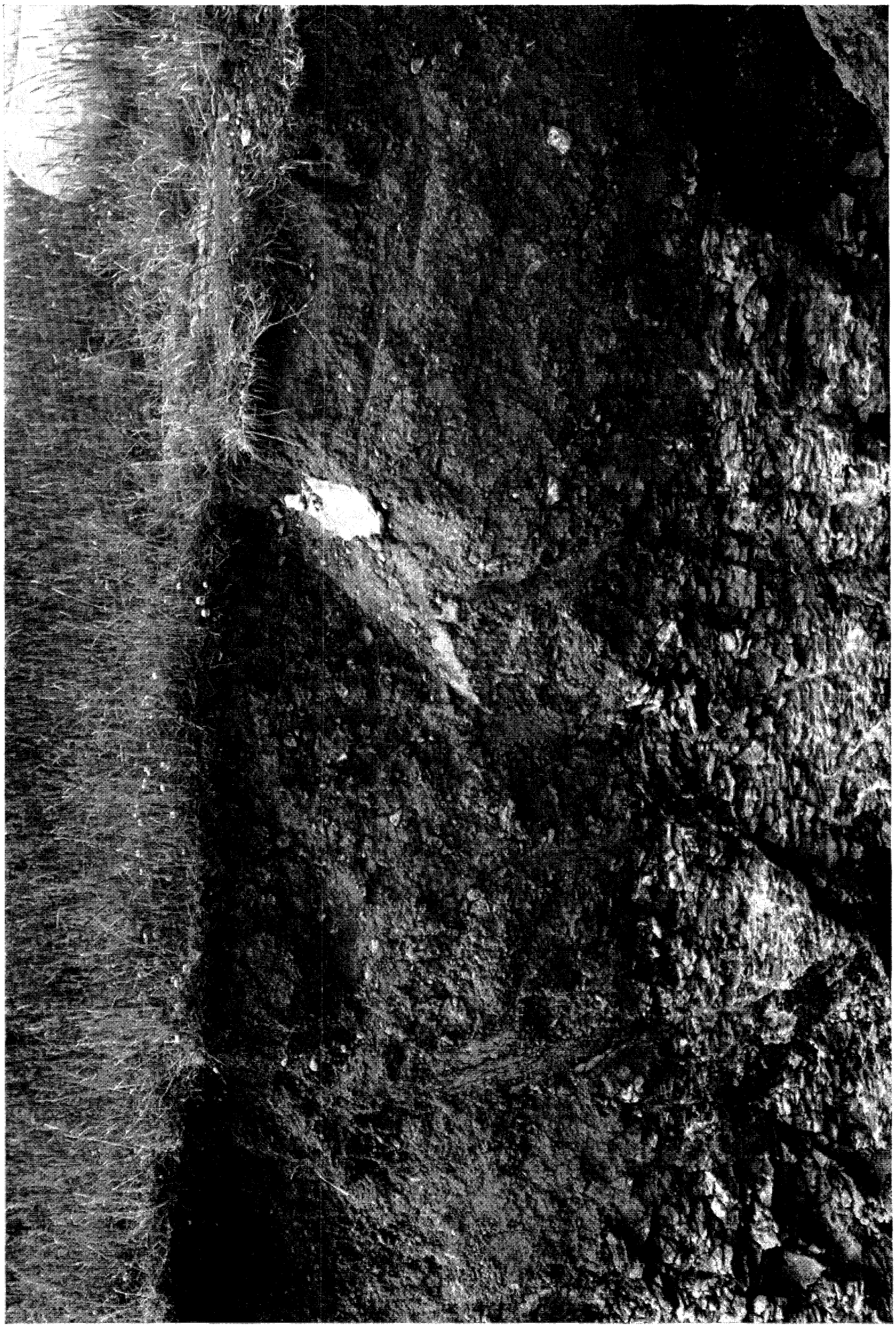

FIGURE 4. Head on the Hambleton Surface. This locality is just east of section 1, figure 2, where the Hambleton Surface is cut across the Marlstone Rock Bed which here underlies the Head.

FIGURE 8. Chalky Boulder Clay infilled gulls in the Northampton Sand Ironstone in the plateau beyond the crest of the Barnsdale slope.

to the west. In the sides of the stream channel, only just above the bed, is a distinctive ironstone-rich gravel with occasional angular flints and quartzite pebbles. This gravel can be traced to the stream's confluence with the North Tributary of the Gwash, where it spreads to form a local development of the First Terrace, up to 2 m thick, with its surface 1.5–2.5 m above Alluvium (figure 2).

This range of altitude is typical of the First Terrace fragments in the Gwash valley, and indicates the considerable further downcutting that occurred between the formation of the Hambleton Surface and First Terrace times.

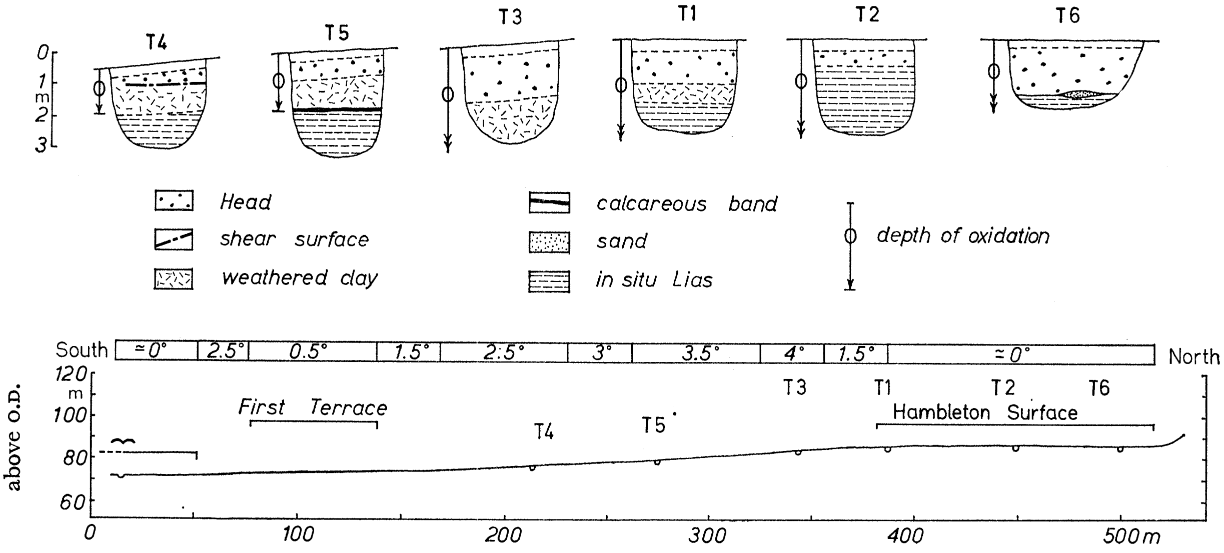

Figure 5. Section of the Hambleton Surface at Hambleton Old Hall.

The Hambleton Surface at Hambleton Old Hall

The Old Hall, Hambleton, is located on a well preserved remnant of the Hambleton Surface to the southwest of the Hambleton outlier; this is the southerly surface remnant of section 5, figure 3. A number of trial pits and excavations have been made here, both in the Surface and in the slope falling from the Surface, and for this reason this is regarded as the 'type locality' for the Hambleton Surface.

Figure 5 illustrates the deposits encountered on both the Surface and the slope beneath; the line of section does not quite correspond with that of section 5, figure 3. The deposits on the Surface consist of up to 2 m of Head, composed of yellow-brown structureless clay with a few scattered erratics of Northampton Sand, small quartzite pebbles and very occasional angular flint fragments. In pit T2 erratics only occurred in the top soil, while a pocket of sand was encountered in pit T6.

Downslope from the Surface the Head thins, and a shear surface at the base of the Head in pit T4 shows it to have been transported, at least in part, by periglacial mudsliding, for the slope is at a much lower inclination than would allow sliding movements under present climatic conditions.

This spread of reworked Head down the slope falling from the Hambleton Surface may not always be as extensive as here, for although almost a metre of Head occurs at the end of the

Hambleton Surface spur just southwest of the Barnsdale landslide, none was found in a series of pits down the slope beneath (P. Horswill, personal communication).

The depth of oxidation beneath the Hambleton Surface is also notable, being greater than 3 m (the maximum pit depth) on and at the edge of the surface, but only 2 m or less on the slope beneath.

The feature marked as First Terrace in figure 5 is a low clayey shelf, about 2 m above the Alluvium, morphologically separated from the alluvial belt by a gentle step in the slope.

The age of the Hambleton Surface

In figure 3, sections 4 and 5 show that the Barnsdale and Hambleton landslides lie only just above the Hambleton Surface, and the landslides are therefore presumed to be the result of the degradation of slopes formed or steepened at the time of the erosion of the Surface. A number of other major landslides also occur in the upper Gwash valley as shown in figure 2. These too have their toes at or just above the height of the Hambleton Surface, though in most cases, as with the Hambleton landslide, section 5, the Surface is not developed, but is represented only by a break of slope. The altitudes of the toes of these landslides are given in table 3. It is seen that they lie between 12 and 17 m above the Alluvium, compared with the altitude of 12–16 m of the Hambleton Surface.

TABLE 3. ALTITUDES OF LANDSLIDES ABOVE THE RIVER GWASH AND ITS NORTHERN TRIBUTARY

location of landslide	altitude of toe of landslide m A.O.D.	altitude of Alluvium m A.O.D.	altitude of toe above Alluvium m
north tributary of River Gwash			
(A) Barnsdale	90	73	17
(B) Barnsdale Wood	81	67	14
(C) Hambleton	87	72	15
(D) Home Farm	83	69	14
(E) Armley Wood	75	63	12
River Gwash			
(F) Gibbet Gorse	85	72	13

In view of the close association between the landslipped slopes and the Hambleton Surface it is clearly of considerable interest to examine the possible age of the latter.

Downstream from Hambleton the valley narrows (figure 2) and as the Inferior Oolite thickens down-dip, cambering extends progressively further down the valley sides. It is presumably the gradual down-dip lowering of the more competent horizons down the valley side, thus increasing the erosional resistance, that results in the pronounced narrowing of the valley east of the Hambleton outlier. Similar and quite dramatic narrowing also occurs in the Welland valley near Harringworth, Northamptonshire (SP 920 980), at the comparable geological position.

A second consequence of the erosional resistance of the down-dip thickening of the Inferior Oolite is that there are few morphological features downstream of the Hambleton outlier with which the Hambleton Surface may be related. Poorly developed benches occur by Empingham bridge about 12 m above Alluvium, section 7, figure 3*b*, and at Shacklewell Hollow (SK 977 082) 11–14 m above Alluvium, while two patches of Second Terrace gravel occur at Casterton (TF 012 100), 10–12 m above Alluvium.

At Ryhall, where the Gwash turns abruptly south to join the Welland, there is a series of meanders, the major one being at the bend. The core of this meander, cut in the Lower Lincolnshire Limestone, is planed off at about 12 m above the Alluvium. The profile of this meander core is compared with the altitude of the Hambleton Surface in figure 3*b*. Bench features also appear still further downstream, again about 12 m above the Alluvium, at Borderville, Stamford (TF 036 089). From here the bench can be traced continuously into the Welland valley at Stamford where Second Terrace gravels occur on its surface (TF 038 076).

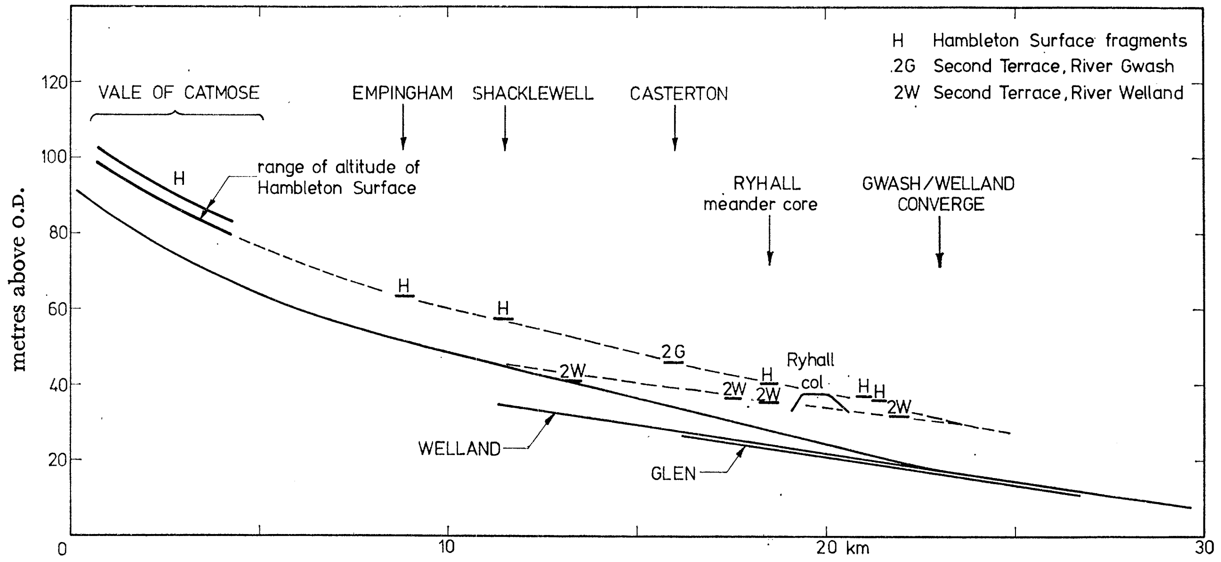

Figure 6. The long-profile of the River Gwash.

The long-profile of the river Gwash is shown in figure 6, to which is related the Hambleton Surface and the associated bench fragments. It will be seen that the bench fragments lie the same distance above the Alluvium as the remnant patches of the Gwash Second Terrace at Casterton and appear to merge into the Second Terrace of the Welland.

The origin of the col east of Ryhall (see figures 1 and 6), at an altitude which corresponds closely with that of the Hambleton Surface benches, is not easy to explain. Kellaway & Taylor (1953) and Harrod (1972) have suggested that the col was formerly used by the Gwash which then flowed into the Glen. However, at the present day the Glen is at a slightly lower level than the Gwash (figure 6), and presumably the same situation would have existed in the past, so that it is difficult to see why the diversion should have occurred. The continuation of the Hambleton Surface bench features along the present course of the Gwash downstream of the col at Ryhall shows that the capture must have occurred by Hambleton Surface times. It is possible that the col, which is a broad and rather subdued feature, may be an exhumed remnant of the pre-Chalky Boulder Clay drainage system, with the north–south Ryhall–Stamford reach of the Gwash originating on or against the wasting Chalky Boulder Clay ice-sheet as previously discussed (p. 466) for the similarly oriented reaches of the Glen and Braceborough Rivers.

The correspondence in altitude of the Hambleton Surface and the Second Terrace of the Welland suggests that these two may be correlated. The Hambleton Surface, however, being of essentially erosional origin, may possibly be rather the older.

Unfortunately there is little evidence for the age of the Second Terrace of the Welland, but some inferences may be drawn from what is known of the Quaternary history of other rivers draining to the Wash. In the Cam/Ouse system the Cam First Terrace, at typically 1.5 m above Alluvium, has yielded a coleopteran fauna dated as *ca.* 30000 B.P. (Coope 1968), while the Cam First/Second Terrace complex, with a surface ranging from 1.5 to 5.5 m above Alluvium, has yielded ^{14}C dates of 42140 B.P. and > 45000 B.P. (Bell 1970). Similarly the First Terrace of the Nene (up to 4.5 m above Alluvium) has produced a ^{14}C date of 28225 B.P. (Morgan 1969). The similar altitude range, 1.5–4.5 m, of the Welland and Gwash First Terrace deposits, suggests that these are also a complex of deposits developed during the Middle Devensian.

Higher terraces in the Cam/Ouse system are the Third (Barnwell) Terrace at about 6 m above Alluvium, with an Ipswichian fauna (see, for example, Worssam & Taylor 1969) and the Fourth Terrace (at 9–15 m) of unknown but presumably earlier date. No biogenic deposits have been reported from the Second Terrace of the Nene (4.5–9 m above Alluvium), though an extensive interglacial molluscan fauna from the Third Terrace (10.5–16.5 m above Alluvium) has been listed by Porter (1861). Near Peterborough the Nene Third Terrace gravels overlie the estuarine and lacustrine Woodston Beds, which contain a probable Hoxnian flora (Horton, Lake, Bisson & Coppack 1974 and personal communication).

Thus the simplest correlation, and the one accepted here, is broadly to relate the Cam Third Terrace, with its Ipswichian fauna, to the Second Terraces of the Nene, Welland and Gwash. This is turn implies an Ipswichian date for the Hambleton Surface, and for the formation of the slopes with which this paper is primarily concerned.

Support for the correlation is provided by the Trent, which, though not directly comparable with the rivers discussed above since it does not flow to the Wash, none the less has a First Terrace (Flood Plain Terrace) at 2–3 m above Alluvium with an associated ^{14}C date of 32160 B.P. (Coope & Sands 1966) and a Second Terrace, 4.5–9 m above Alluvium, with an Ipswichian fauna that includes *Hippopotamus* (Jones & Stanley 1974).

The equivalents of the Cam Fourth Terrace and the Nene Third Terrace do not seem to be represented in the Welland valley.

THE SLOPE SECTIONS

Methods of investigation

Both the Barnsdale and Hambleton slopes were investigated by means of soft-ground, 'shell-and-auger' borings and relatively shallow trial pits. Continuous, undisturbed, 100 mm diameter open-drive tube samples (U100 samples) were taken in all the borings, together with the intermediate cutting shoe samples, and in this way samples were recovered from well over 95% of the total depth drilled. All these samples were split, examined and described, particular care being taken to locate all shear surfaces.

The trial pits were dug with a small excavator, giving a maximum depth of about 4 m, and because of their shallow depth were located only at positions where they could provide detailed information. Each pit was carefully examined and logged in detail.

Casagrande-type open-tube piezometers were installed in many of the borings; where possible these were placed with their tips close to or on major landslide shear surfaces. This was generally achieved at Barnsdale, but the piezometer location was less satisfactory at Hambleton. The piezometer tips were surrounded by sand over a depth of about one metre and the boring was then grouted up to the ground surface using a stiff bentonite:cement grout.

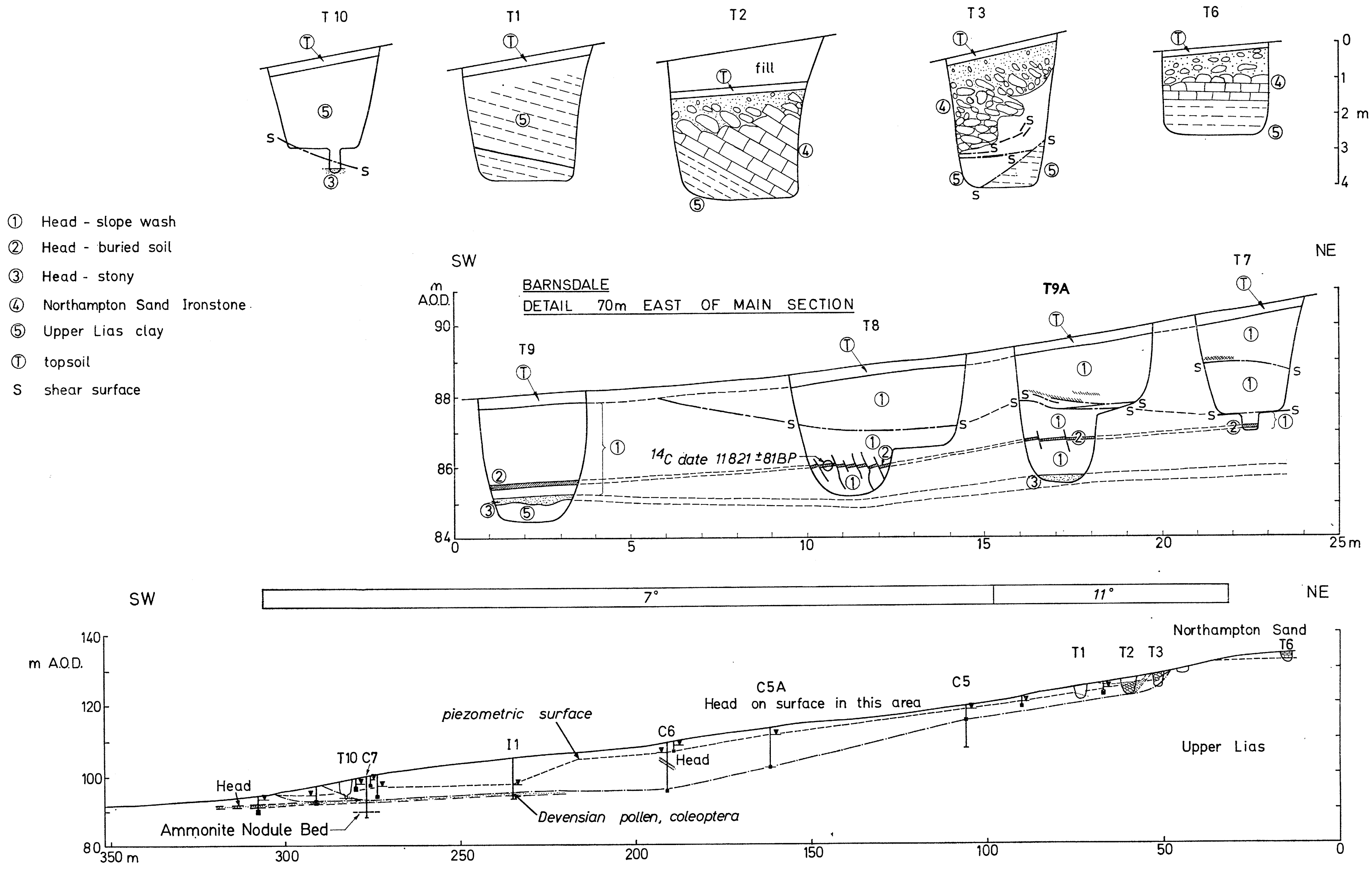

Figure 7. Cross-section of the Barnsdale slope.

The Barnsdale slope section

Barnsdale, an isolated country house, lies on the northeastern side of the Vale of Catmose. At this location (SK 903 093) the valley side may be regarded as an eastward extension of the main escarpment, and is about 40 m high above the level of the Hambleton Surface, consisting of a series of shallow embayments with intervening spurs about 250 m apart. Falling directly from the almost plateau-like interfluve the upper part of the slope within the embayments is relatively steep, typically 10–12°, below which there is an extensive lower slope 'apron' inclined at about 7°, the lower limit of which is formed by the toe of the landslipped area which encroaches onto the Hambleton Surface. The feature formed by the toe of the landslide is not fresh enough to suggest that there has been very recent movement, though it seems probable that limited instability may have developed in the last few decades. A section of the Barnsdale slope, on a line directly downslope in the centre of a shallow embayment some 300 m wide, is shown in figure 7.

At the crest of the slope in trial pit T6 the Northampton Sand Ironstone is horizontally bedded with no evidence of cambering; beneath the ironstone the Upper Lias was not only horizontally bedded, but also much less brecciated than is usual. Later excavation here for the A 606 road diversion showed this impression of the absence of cambering to be a slight oversimplification, for a few narrow gulls were encountered in the ironstone. These all lay in the plateau (figure 8*a*, *b*, plate 4), parallel to the crest of the slope, and within 100 m of the slope crest. Some of the gulls were open cracks up to 15 cm wide. These occurred within 20 m of the slope crest and were of comparatively recent origin, for they extended up into the weathered near-surface material. Further back from the slope the gulls were rather wider, 0.8 m being the maximum recorded, and were infilled with Chalky Boulder Clay. This appears to have been emplaced in a very wet state for infilled cracks as narrow as 10 cm were observed.

Below the crest of the slope trial pits T1, T2 and T3 showed backtilted, landslipped Northampton Sand and Upper Lias clay, the depth of which, though not proved in the trial pits, was shown by boring C5 to be about 4 m. Below the shear surface in C5 the Upper Lias clay is horizontally bedded and again relatively unbrecciated.

Downslope from boring C5, which was located close to the break between the steep upper slope and the lower angled apron, the landslip mass rapidly increases in thickness, reaching a maximum of 13 m in boring C6. Virtually the whole of the landslide mass consists of disturbed, brecciated Upper Lias clay; minor shear surfaces occur fairly frequently, and original bedding planes dipping up to 40 and 50° are common. From C6 to the toe of the landslide, the basal shear surface dips at about 2°, and at boring I1 (located a few metres east of the line of section) it overlies the following sequence of deposits:

depth/m	description	interpretation
9.60–9.75	Dark grey brecciated clay with several major polished subhorizontal shear surfaces	Landslipped material
9.75–9.79	Grey brecciated clay with small ironstone fragments	
9.79–9.82	Pale brown crudely stratified silt with a thin seam of moss (containing a fossil of the weevil *Phytonomus obovatus* Cki.) at base	Head (upper member)
9.82–10.31	Grey structureless clay; darker in upper part, with vertical root channels down to 10.15 m; occasional angular ironstone and rare flint fragments becoming more frequent below 10.25 m	

depth/m	description	interpretation
10.31–10.73	Grey-brown sandy clay with many ironstone fragments, becoming greyer and more clayey at 10.40 m	Head (lower member)
10.73– (seen to 13.63)	Grey horizontally bedded brecciated clay with small selenite crystals; extremely broken with a maximum fragment size of 2 mm above 11.05 m, though less disturbed below this depth	Upper Lias clay, *in situ*

These deposits are the product of cold conditions. The extremely shattered Lias beneath the Head appears to be the result of frost action, while the ironstone-rich clayey basal Head was derived by sludging, a process that subsequently gave way to the deposition of an upper Head of poorly bedded clay derived from sheet wash. Both the two Head members were also encountered within the landslip in a very disturbed state in boring C6, upslope of I1, so they must be slope derived deposits.

Carbonized root fragments occur within the wash deposits and culminate upwards in the development of a moss horizon. A beetle obtained from this horizon was identified by Dr G. R. Coope as the weevil *Phytonomus obovatus* Cki., which is now extinct in Britain and at the present day lives in northern Fennoscandia, Siberia and Mongolia. Dr Coope reports that 'this species must be indicative of cold conditions and has been found as a fossil in Britain from the cold parts of the Middle Devensian, from the early "Late Glacial" (i.e. before 13200 B.P.) and from the Late Devensian Zone III cold period'.

The Head deposits were examined for pollen by Mr Allan Hall, the detailed results being given in the Appendix. At all levels the deposits were nearly barren, the limited pollen present indicating a cold climate and a treeless, herbaceous vegetation, assuming the *Pinus* content to be due to long-distance transport. No particular comment is called for, except to note that the single grain of *Ilex* in the base of the Head is consistent with a derived Ipswichian origin in view of the apparent Ipswichian age of the Hambleton Surface on which it rests. The moss, *Helodium blandowii* (Web. & Mohr.) Warnst., is thought to be an indicator of subarctic glacial climates (Dickson 1973).

The Head deposits are thus a sequence of cold climate deposits of either main Devensian or Zone III date. As deposits of the Late-glacial Interstadial (Coope 1975) occur elsewhere in the slope, the absence of any indication of material of this age from beneath the moss horizon shows that the Head sequence is likely to be no younger than Late Devensian Zone I, and may be considerably older. Thus assuming there to have been little or no erosion by the overriding landslide – and Upper Head deposits have not been located within the landslide mass down-slope of boring I1 – then the location of I1 is the position of the landslide toe no later than the early Late-glacial.

All the borings downslope of I1, both on the line of section and for at least 120 m east, located Head deposits lying on frost shattered Lias. The basal Head layer is rather irregular in level presumably reflecting irregularities of the surface on which it was deposited, and also suggesting that the subsequent wash deposits, which are patchily distributed, formed only locally in hollows incompletely filled by the basal Head. A further complication is that the basal Head composition is rather variable, the ironstone rich clayey material of I1 giving way in other borings to material with a sandy or silty matrix and containing not only ironstone fragments but also fairly frequent Bunter-type pebbles and cobbles (one, from a boring, was 15 cm × 9 cm × 5 cm).

This type of deposit is suggestive of some degree of water transport along the Hambleton

Surface, for flints and Bunter pebbles are rare in the more clayey slope-derived Head. Since the stream at the foot of the Barnsdale slope appears to have cut well down below the Hambleton Surface by First Terrace (Middle Devensian) times, an early Devensian age seems probable for the Head on the Hambleton Surface underlying the landslide, and would accord with the Ipswichian age of the Hambleton Surface.

Clayey Head, containing ironstone, up to 1.5 m thick and in places underlain by a polished shear surface, also occurs on the surface of the landslide, where it was encountered in borings C5, C5A and I1, and also at several points off the line of section. This appears to be a mudslide or solifluction layer of much later date than the Head underlying the landslide.

Further Head deposits also occur downslope from the landslide toe, and were revealed in detail in pits T7, T8, T9 and T9A. The most complete sequence occurred in T9 where a basal Head, brown clayey sand with ironstone fragments, lies on *in situ* frost shattered Lias, and is overlain by 3.0 m of soft orange-brown mottled structureless clay. At a depth of 2.5 m there is a continuous 50 mm thick layer of very dark grey clay. This proved to be organic, and a sample taken from this layer in pit T8 gave a ^{14}C date of 11820 ± 85 B.P. (SRR-144), within the Late-glacial Interstadial (Coope 1975). This layer is thus considerably later than the moss horizon in boring I1 and, since it is overlain (in T9) by a further 2 m of wash-clay Head, shows that slope wash continued after the Interstadial.

An extensive shear surface occurs within the sequence of wash-clays beyond the landslide toe in pits T7, T8 and T9A. The organic horizon is displaced by this shear surface in pit T9A, so it is clear that this movement is not solifluction but landsliding within the soft slope-wash clays due to thrusting or overriding either by the toe of the landslide or by the solifluction-Head layer that covers the landslide surface. The movements within the wash deposits must have been minor for the shear surface dies out between Pits T8 and T9 without producing any break of slope great enough to be preserved to the present day.

In pit T8 the organic layer is displaced by minor ‘normal faults’. These appear to be desiccation cracks displaced downslope by drag from the overriding slide movement.

The Ammonite Nodule Bed in the Upper Lias was encountered at some depth below the landslipped slope in boring C7, showing the whole of the slope to be developed in the uniform clays of the upper part of the Upper Lias sequence.

The formation and degradation of the Barnsdale slope

The absence of all but the most minor camber structures and also the relatively unbrecciated state of the Lias in the upper part of the slope demonstrates that there has been considerable erosion of the slope subsequent to the last phase of cambering. The valley cross-section (figure 3) shows that this erosion is related to the Hambleton Surface stage and from figure 7 it is clear that the landslide mass encroaches nearly 100 m on to the Hambleton Surface. The present slope thus originated at the Hambleton Surface stage and has been degrading since that time.

It is possible to reconstruct in broad outline, though not in detail, the various stages in the formation and degradation of the Barnsdale slope. The following points have to be considered in the reconstruction which is shown in figure 9.

(i) Head extends back under the landslide for at least 65 m and probably rather further, and thus the original foot of the slope must have lain between distances 190 m and about 225 m in figures 7 and 9.

(ii) The presence of Head deposits *within* the landslide mass in boring C6 show that at least part of the similar Head sequence beneath the landslide is locally derived from the slope above.

(iii) Surface wash appears to be an important element in the slope degradation, the more so since an unknown quantity of material would have been entirely removed from the area. Thus, even allowing for a bulking factor for the slipped material, at any time during the degradation the volume of material removed from the slope is likely to exceed the accumulated volume of landslide debris.

(iv) Since the slope retreat appears to have produced the shallow embayment now occupied by the landslipped mass there will have been some convergence of material moving from the

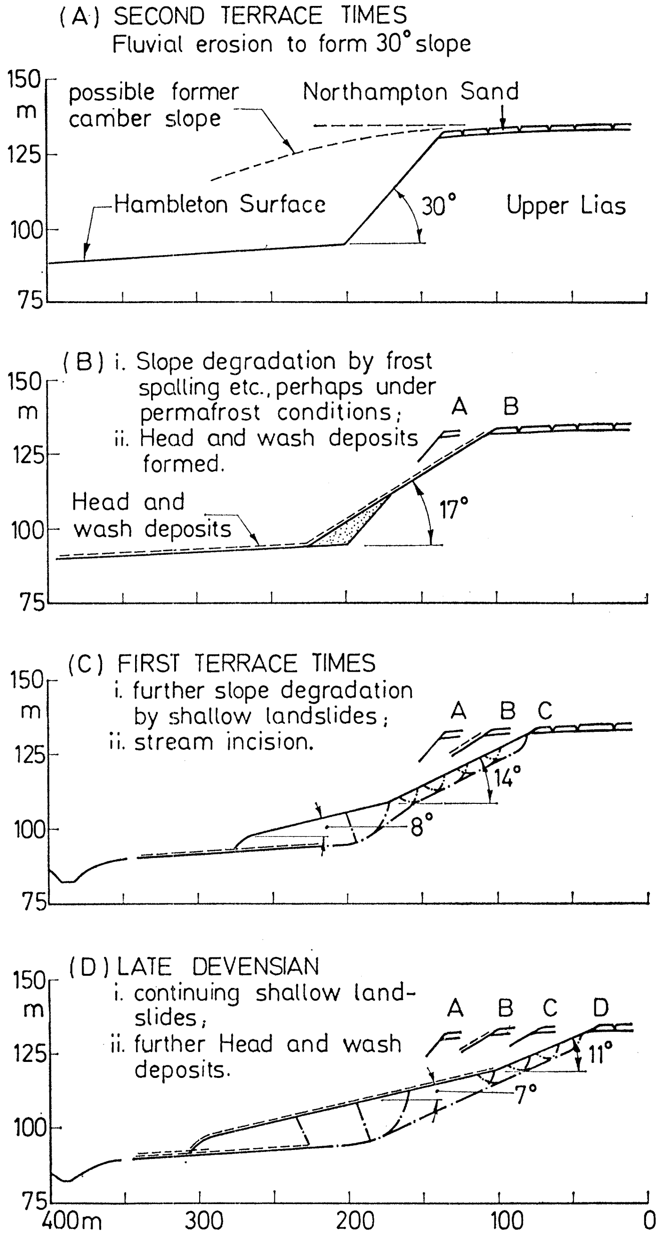

FIGURE 9. The probable stages of degradation of the Barnsdale slope. 2 × vertical exaggeration; the horizontal distances correspond to figure 7. D is based on the present-day slope section; the stream section is diagrammatic.

flanks of the embayment. As the embayment is shallow this effect is unimportant and has been ignored.

With these constraints it follows that the slope was cut fairly rapidly to a relatively steep angle, perhaps as much as 30°, figure 9*a*. To achieve this inclination there must have been more or less complete removal of debris from the base of the slope, while to maintain the short-term stability of the slope against large-scale landsliding an undrained strength of about 120 kN/m^2 is required. This is about the maximum undrained shear strength that could be expected from the unweathered Lias after the cambered and intensively brecciated material had been stripped from the slope. It is possible though that in the early Devensian the slope may have been frozen.

Once basal erosion ceased the slope commenced to decline (figure 9*b*) as a result of such processes as surface wash, frost spalling and shallow slips or falls, and clay accumulated at the slope foot. This must initially have stood at a fairly high angle, about 17–18°. This is the latest stage at which the basal Head could have been laid down.

As the upper part of the slope declined (figure 9*c*) further material was added to the accumulation zone which in the absence of frozen ground conditions would have slid forward on its base to maintain an overall inclination that was a function of the strength of the basal shear surface and of the ground water conditions within the accumulation zone. Once there has been some initial movement of the accumulation zone, the strength of the basal shear surface generated by the movement will fall to the residual value, the magnitude of which will control the slope angle of the accumulation zone. With a high groundwater table this angle will be around 9–7°, decreasing as the size of the accumulation zone increases. The predominance in the landslide mass of unweathered Lias clay still with the fabric it would have possessed *in situ*, shows that the degradation process was essentially one of landsliding rather than solifluction, and that therefore unfrozen ground conditions were required.

The Hambleton slope section

At the western end of the Hambleton outlier the slopes are relatively steep, and comparison of the edge of the Inferior Oolite outcrop with the position of the major convex break of slope, as in figure 2, suggests that there is apparently little cambering. A well record (I.G.S. 157/214), on the highest point at the west end of the outlier (figure 3) shows, however, only 1 m of Inferior Oolite over 57 m of Upper Lias. As this is several metres less than the true thickness of the Upper Lias in the area (p. 465) it is clear that there has in the past been some cambering here, in spite of the comparatively abrupt edge of the outlier. Further east, however, the slopes become less steep and cambering is more evident.

A section of the steeper western slopes, at the northwestern 'corner' of the outlier, has been investigated. This section almost directly faces the Barnsdale slope on the northern side of the valley. In profile the Hambleton slope initially descends relatively abruptly at an angle of about 15°. Below this the slope flattens to around 6°, then steepens somewhat to about 9.5°, an inclination which is maintained to a distinct concave break of slope which occurs 34 m vertically and 220 m horizontally below the crest of the slope. From this break of slope the ground sweeps in a very gentle concave profile to the Marlstone Rock Bed outcrop, a further 350 m distant.

Figure 2 shows that the foot-slope break corresponds in altitude to the back edge of the Hambleton Surface, and although the Surface does not appear on the line of section, the break of slope can be traced westward into the Hambleton Surface.

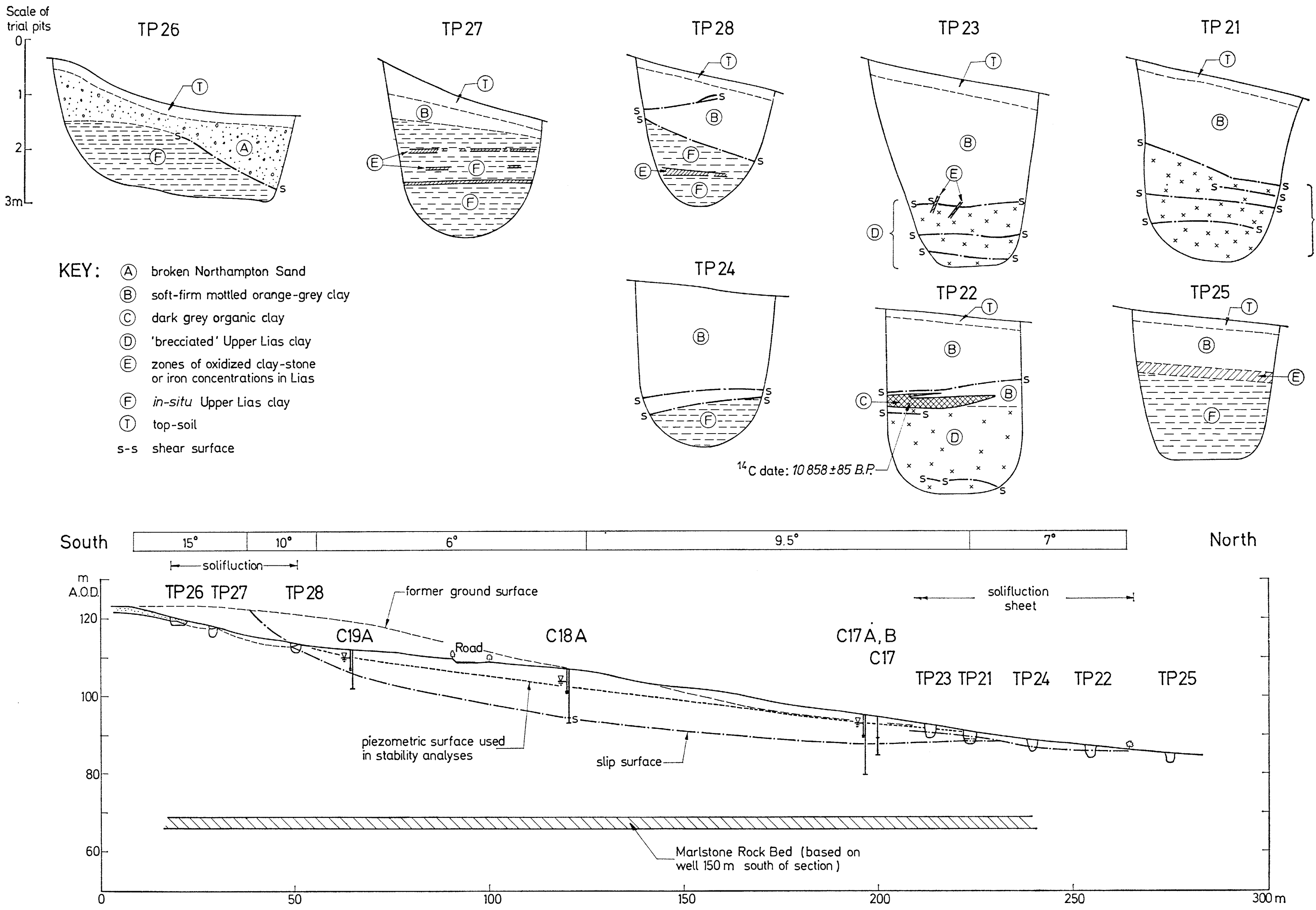

FIGURE 10. Cross-section of the Hambleton slope.

Morphologically the Hambleton slope differs from Barnsdale in having a rather different profile, for there is no clear landslip toe, and the Hambleton Surface is not developed at the foot of the slope; nor is there a 'flat' in the upper third of the slope at Barnsdale.

The subsurface investigation also showed considerable differences, as is seen from figure 10. Pits in the steep 15° segment at the crest of the slope showed only a shallow mudslide layer on *in situ*, horizontally bedded, though brecciated Lias. In the lowest of this series of pits, number 28, a shear surface dipped down slope, corresponding with the basal shear surface encountered in boring C19A. The landslide section revealed by the three borings is thus essentially that of a shallow rotational slide, with the upper boring (C19A) showing extensively brecciated Lias beneath the landslide, where in the corresponding boring (C5) at Barnsdale only limited brecciation was encountered. Head deposits do not occur under the landslide.

At the foot of the slope pits 21–25 showed a surface layer of fairly soft, completely remoulded clay underlain by a continuous shear surface. This deposit which overlies (and thus post-dates) the toe of the landslide proper, does not give rise to any surface feature, while its fabric suggests a mudslide origin. It is therefore assumed to be periglacial, of Late Devensian Zone III age, for in pit 22 it overlies a lens of organic clay, a sample of which gave a ^{14}C date of 10860 ± 85 B.P. (SRR 633).

Thus in contrast to the degraded cliff profile at Barnsdale, perhaps originally steepened to 30°, the Hambleton slope section is of a shallow rotational slide, with its rear scarp and toe subsequently eroded by solifluction. Consequently the landslide predates both the solifluction phase and the Late-glacial Interstadial, though minor reactivation of the landslide could perhaps have occurred contemporaneously with the solifluction. The cambered Inferior Oolite, the occurrence of extensively brecciated Lias beneath the landslide and the absence of the development of the Hambleton Surface show that basal erosion was limited at this locality, and that the slope was steepened overall to about 13°, as suggested in figure 10, before failure took place.

If the stability of this slope is analysed it is found that for a landslide to occur ground water conditions would have been moderately high, with average pore-water pressures in the slope such that the average ratio (r_u) of pore pressure to total overburden pressure was 0.35, which gives corresponding effective strength parameters at failure of $c' = 0$, $\phi' = 20°$. Such a strength and pore-pressures would not have been exceptional in frost-disturbed Lias clay.

STABILITY ANALYSES OF EXISTING SLOPES

The stability analyses of both the Barnsdale and Hambleton landslides have been carried out by using the method developed by Sarma (1973). This is statically equivalent to Morgenstern & Price's method (1965), and analyses carried out by both methods yield almost identical solutions. Sarma's method is, however, much more rapid and convenient to use.

The Barnsdale slope

Piezometric observations were made at weekly intervals over the period March 1972 to October 1973, and the maximum levels recorded were used for the analysis. These maxima are shown in the slope section (figure 7). The recorded levels fluctuated quite markedly on a seasonal basis, but only to a depth of about 4–5 m, deeper piezometers showing insignificant variations in water level once they had reached equilibrium. As the landslide is only about 4 m deep in the upper part of the slope this region will be affected by the seasonal water level variations. The piezometric level in this part of the slope used for the analysis is obtained from the two piezometers on the line of section, with further guidance from the behaviour of a group of ten 3.5 m deep piezometers, installed to monitor slope stabilization works on an almost identical part of the slope 60 m east of the line of section.

In the lower part of the slope the relatively permeable Head layer, which lies immediately beneath the landslide, has a marked effect on the piezometric level, which has been drawn in figure 7 on the assumption that the Head extends under the landslide for a few metres upslope of boring I1.

The unit weight used in the analysis is 19.2 kN/m³, based on the average of 17 determinations using U100 samples. With the above assumptions the stability analysis shows that the landslide is mobilizing, on its basal shear surface, an average angle of residual shearing resistance of 10.7°, taking $c'_r = 0$.

These conclusions are only slightly affected if side effects are considered. This point was examined by using the 'conventional' method of analysis (Skempton & Hutchinson 1969, pp. 317–318) assuming a constant width for the landslide, the sides of which were stressed horizontally consistent with a coefficient of earth pressure, $K = 0.75$. This is considered to be an upper limit of the likely value.

Table 4. Results of the stability analyses discussed in the text; the values of ϕ' assume that c' is zero

			side shearing				
			(a) excluded		(b) included		
	$\bar{\tau}$	$\bar{\sigma}'_n$					
	kN/m²		$\bar{\tau}/\bar{\sigma}'_n$	ϕ'	$\bar{\tau}/\bar{\sigma}'_n$	ϕ'	notes
Uppingham	3.8	12.0	0.317	17.6°	0.290	16.2°	recalculated from Chandler (1970)
Rockingham	8.7	34.0	0.256	14.4°	0.248	13.9°	Chandler (1971)
Gretton	9.2	38.0	0.242	13.6°	0.240	13.5°	Chandler *et al.* (1973)
Barnsdale	17.4	92.0	0.189	10.7°	0.189	10.4°	this paper
Hambleton	20.0	107.0	0.187	10.6°	0.182	10.3°	

It is difficult to define the average width of the portion of the Barnsdale landslide zone with which we are concerned, for much of the area is wooded and the detailed morphology towards the sides is very subdued. However, it is certainly not less than 200 m, and may be considerably wider. The landslide is thus wide compared with both its downslope length of 260 m and its maximum depth, which is 13 m. It is not surprising therefore that the inclusion of side effects in the analysis of the landslide reduced the overall ratio of shear stress to normal effective stress, τ/σ'_n, by only 3.2 %. This same reduction for side effects has been applied to the results of the analysis by using Sarma's method. This then gives $\phi'_r = 10.4°$ with $c_r = 0$; the full results are summarized in table 4. The comparative freshness of the landslide toe at Barnsdale suggests that it may be marginally unstable during particularly wet winters. Thus although the analysis underestimates the value of ϕ'_r that would be mobilized if movement occurred, it probably only does so by a very small amount.

The Hambleton slope

The analysis of the stability of this landslide is subject to some uncertainty for the pore-pressures on the shear surface are not accurately known in the deeper central portion of the landslide, as unfortunately the piezometer in boring C18A was located some distance above the shear surface. The piezometric surface used in the analysis (shown in figure 10) is based on the maximum readings obtained over the period March 1972 to October 1973. In the centre of the landslide it is assumed that there would be a component of flow vertically downwards, and hence a slightly lower piezometric surface than indicated by piezometer C18A has been used for the analyses.

Taking a soil unit weight of 19.7 kN/m^3, Sarma's method of analysis gives an average angle of residual shearing resistance, $\phi_r' = 10.6°$, with $c' = 0$. When side effects are considered, with a landslide width of 200 m and $K = 0.75$ as with the Barnsdale analysis, the ratio of τ/σ_n' is reduced by 2.7 %, equivalent to $\phi_r' = 10.3°$ (see table 4). The topography at Hambleton and the previously described investigations both indicate comparative stability compared with Barnsdale, which in turn lead one to expect a rather lower mobilized strength, instead of the identical strengths that have been obtained. This anomaly probably arises from the poor piezometric data at Hambleton.

Other Upper Lias clay stability analyses

Analyses of three case records previously reported by the author from sites at Uppingham, Gretton and Rockingham, are also summarized in table 4. The following comments are required by way of explanation.

Uppingham

The reactivation of a 2 m thick portion of a solifluction or periglacial mudslide sheet near Uppingham, Rutland (Chandler 1970), was originally analysed on the assumption that the phreatic surface coincided with the ground surface. It is now realized that although very high pore pressures were recorded this was probably on average a slight overestimate and that a water table at a depth of 0.2 m would have been more realistic. Moreover, side effects were not considered. Consequently the analyses have been recalculated, side effects being considered for overriding by the landslip toe down one side only, with an average width of the slide of 30 m.

Gretton

The Gretton case record concerns a railway embankment that became unstable only with the passage of heavily loaded freight trains (Chandler *et al.* 1973). As the embankment otherwise appears to have been stable, and is thus comparable with the other cases, it is the analysis for the stable state that is included here. A check of the influence of side effects (again taking $K = 0.75$) show them to be of no importance, reducing the ratio τ/σ_n' by only 0.8 %, the result of the plan width of the slide (225 m) being very much greater than its downslope length (24 m).

Rockingham

The third case record, the lower part of the slope of the Upper Lias escarpment at Rockingham, was considered in detail by Chandler (1971). Again this is a marginally stable slope; side effects, taking the landslide width as 150 m and $K = 0.75$, reduce the mobilized ratio of τ/σ_n' by 3.1 %, corresponding to a reduction of ϕ_r' from 14.4 to 13.9°, with $c_r' = 0$.

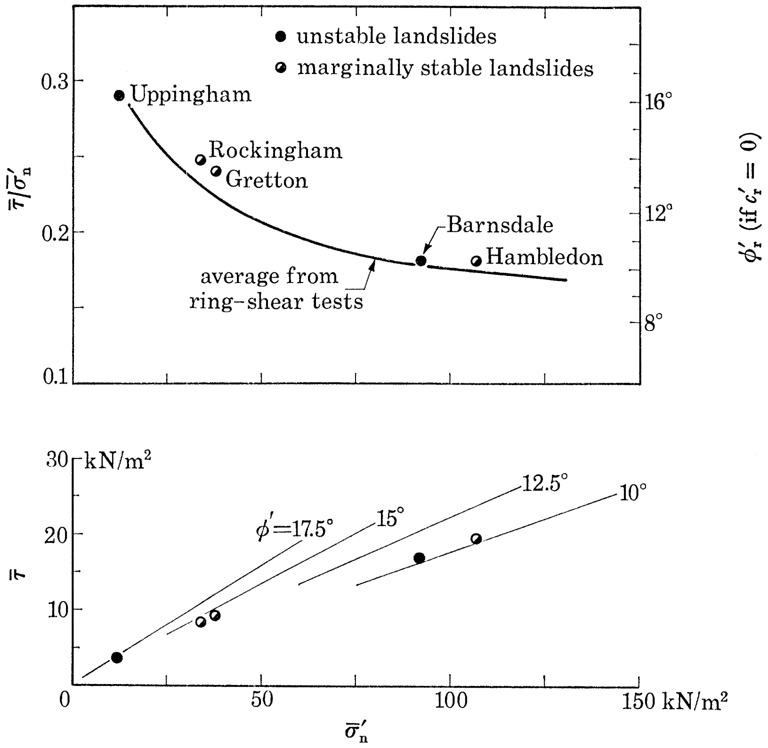

FIGURE 11. Stability analyses for Upper Lias clay landslides; side shearing included in all analyses

Field and laboratory determinations of the residual strength of Upper Lias clay

When the results of these stability analyses are compared (figure 11) it is seen that the strengths obtained are strongly stress dependent, with the Uppingham slide at an effective stress level of 12 kN/m² mobilizing $\phi_r' = 16.2°$ $(c_r' = 0)$, while the Hambleton landslide at an effective stress of 107 kN/m² gives $\phi_r' = 10.3°$. Although three of the five case records concern landslides that can be described as marginally stable, taken as a group they provide a remarkably consistent pattern of field behaviour that can usefully be compared with laboratory measurements of the residual strength of Upper Lias clay made in the ring-shear apparatus.

Four ring-shear tests (Bishop *et al.* 1971) have been carried out on samples of Upper Lias clay. One of the samples was taken from the basal shear surface (depth 9.65 m) in boring I1 at Barnsdale, while of the remaining three, two came from a borrow pit close to the dam at Empingham and one from the Wansford Pumping Station excavation at the Nene abstraction point for the Empingham Scheme.

All the tests were carried out at a rate of displacement of 0.15 mm/h, and were 'multi-stage' tests with the normal stress on the specimen being changed once a constant minimum strength had been obtained at a particular normal stress.

The results of these tests and the index properties of the relevant samples are summarized in figure 12.

The range of index properties is small and all four samples are, for practical purposes, apparently identical. The residual strength of the four samples, however, varies as much as 4°, with one sample (Empingham B) having a strength 45% greater than the two samples with the lowest strengths.

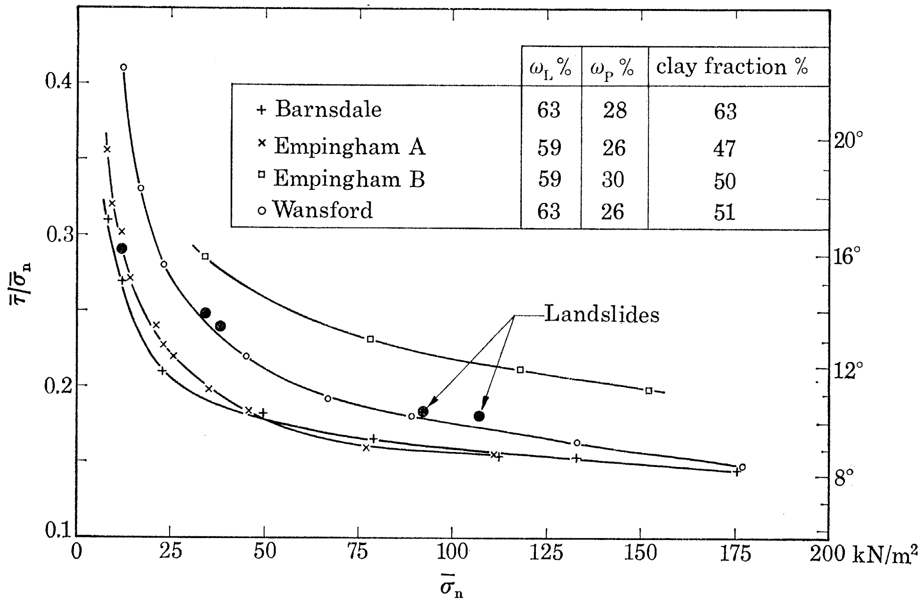

FIGURE 12. Ring shear tests on Upper Lias clay.

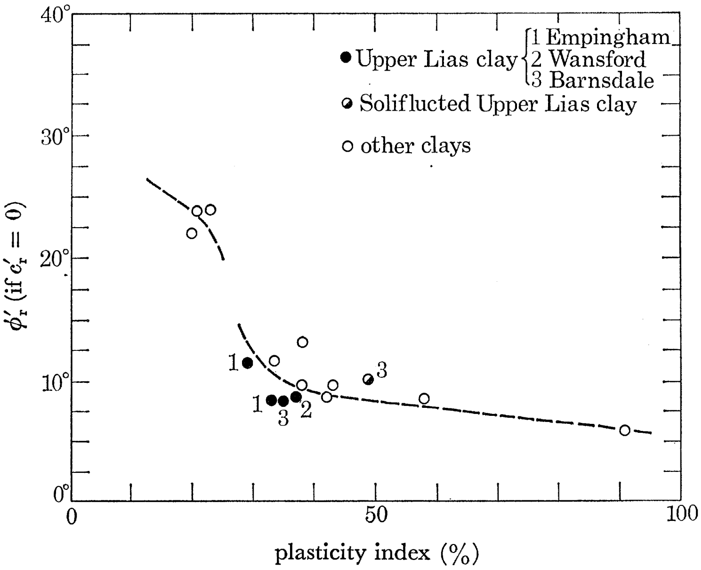

FIGURE 13. Ring-shear residual strength measurements compared with plasticity index; all results obtained at a normal effective stress of 140 kN/m². Slightly modified after Vaughan & Walbancke (1975).

Vaughan & Walbancke (1975) have compared ring-shear residual strengths of various soils, at a constant effective normal stress of 140 kN/m^2, and their plot of ϕ'_r against plasticity index is shown in figure 13. This shows that at this stress level the variation of strength of the Lias clay samples is similar to that of other soils, and may in part be a function of the plasticity of the soil. Since a normal stress level of 140 kN/m^2 is not high enough in some of the tests shown in figure 12 for a constant minimum strength to have been reached, it is likely that some of the scatter of figure 13 may also be in part a function of stress level. Moreover, the Vaughan–Walbancke curve shows an abrupt upturn at a plasticity index of about 30%, close to the typical value for the Upper Lias. Consequently the Upper Lias may be sensitive to small changes in plasticity, and hence ill-conditioned for comparison of field and laboratory measurements of residual strength.

When the results of the stability analyses are compared with the average of the four sets of data for the *in situ* Lias (figure 11) then the ring-shear strengths slightly underestimate, by up to 6%, the residual strengths mobilized in the field. The effect must be slightly greater than indicated in figure 11, for the evidence suggests that three of the landslides are at least marginally stable and if movement occurred a slightly higher angle of shearing resistance would be mobilized.

A similar conclusion is reached if the Barnsdale landslip analysis is compared with the ring-shear test on the sample specifically obtained from that landslide, the ring-shear strength in this case being less by 11.5%.

SUMMARY AND CONCLUSIONS

History of the landslipped slopes in the Gwash valley

The chronology of the development of present day slopes in so far as it can be inferred from the available evidence is given in table 5. The earliest event of which a clear record remains is the deposition of the Chalky Boulder Clay; this was followed by an extensive phase of erosion during which the River Gwash cut down some 45 m, and cambering and valley bulging were

TABLE 5. THE CHRONOLOGY OF SLOPE DEVELOPMENT IN THE GWASH VALLEY. DASHED LINES DENOTE UNCERTAINTY

			GWASH/WELLAND	BARNSDALE SLOPE	HAMBLETON SLOPE
FLANDRIAN			Alluvium		
DEVENSIAN	Late	Zone III		HEAD	HEAD
		L-g Inst.		organic soil 11 800 B.P.	organic soil 10 900 B.P.
				HEAD	HEAD
	Middle		FIRST TERRACE	MAJOR DEGRADATION PHASE stream downcutting	LANDSLIDE
	Early		HEAD on Hambleton surface	HEAD on Hambleton surface slope degradation	
IPSWICHIAN			SECOND TERRACE HAMBLETON SURFACE	slope over-steepened	slope steepened
(earlier)			cambering and bulging	slope cambered	slope cambered
			CHALKY BOULDER CLAY		

developed. Towards the end of this phase of erosion the Gwash and its tributaries cut laterally into the relatively easily eroded Lias clay slopes, broadened the Vale of Catmose to approximately its present form and in so doing locally stripped the cambered Inferior Oolite from the valley sides, producing comparatively steep slopes.

The present-day remnants of this former valley floor, the Hambleton Surface, now form benches below which erosion has subsequently continued for a further 12 m or so. This altitude suggests that the Hambleton Surface can be correlated with the Second Terraces of the Gwash and of the Welland, which in turn broadly suggests an Ipswichian date for both the Hambleton Surface and the formation of the steeper slopes in the Vale of Catmose.

At Barnsdale the slopes must have stood at about 30° after the erosion phase, and after a limited amount of fairly superficial spalling and slumping, a spread of Head developed on both the slope and the Hambleton Surface at its foot, where locally it was reworked by fluvial action. The included flora and fauna show that the Head formed under cold conditions, while its extent beneath the subsequent landslide debris implies that it was formed at a time when no major degradation of the slope had occurred. Although a delay in degradation may be expected due to the relatively slow rate of softening (Vaughan & Walbancke 1973) and weathering of the Lias clay, the major cause of the delayed degradation seems to be that the slope was affected by permafrost, for if extensive degradation of the slope had occurred during permafrost conditions the landslip debris would have been composed of mudslide material, which is not the case. Looking at what is known of the history of the Devensian it seems probable that permafrost would have disappeared briefly during the Chelford Interstadial (*ca.* 60000 B.P.) and again around 43000 B.P., at the beginning of the Upton Warren Interstadial when the insect fauna shows the climate to have been warmer than at the present day (Coope 1975), but there may well have been at least discontinuous permafrost during much of the ensuing Interstadial complex which lasted to 26000 B.P. Much later, about 13000 B.P., there would have been further thawing of permafrost (Coope 1975). Following this line of argument it is concluded that phases of degradation of the Barnsdale slope could have occurred about 60000 B.P., at 43000 B.P. and again at around 13000 B.P. Landsliding during a comparatively warmer period is hinted at by an upward increase in pollen in the basal Head in boring I1 to the point where it was overwhelemd by the overlying landslide.

The organic horizon at the toe of the landslide shows that further Head in the form of slope wash and mud-slides (solifluction) occurred subsequent to 11800 B.P., presumably during the Zone III cold period. There is no direct evidence of movement of the landslide mass at this time, but no doubt at least small movements occurred, which to judge from the comparative freshness of the toe of the landslide, have probably continued in a minor way up to the present day.

The Barnsdale slope is thus a fluvially eroded 'cliff', formed at about the time of the Ipswichian Interglacial, the degradation of which largely occurred rather intermittently in response to climatic changes during the Devensian, though with some minor movements up to the present day. Thus even after about 100000 years of degradation the slope is still at or slightly above the threshold slope for landsliding. The reconstruction of the pattern of slope degradation (figure 9) suggests that at the centre of the shallow embayment occupied by the landslipped mass, the crest of the slope has retreated about 190 m in this time.

The Hambleton landslide occurred in response to the steepening of the northwesterly slopes of the Hambleton outlier at the time of the formation of the Barnsdale cliff, though at Hambleton the erosion was much less severe. This erosion steepened the Hambleton slope by only a limited amount, to around 13°, left most of the frost disturbed, brecciated Lias clay in place, and a shallow rotational landslide occurred in this weakened clay. Both the rear scarp and the toe of this landslide were degraded by mudslides (solifluction), which at the toe overlie an organic horizon dated 10850 B.P. It thus appears that as at Barnsdale the latest phase of solifluction was of Zone III date, though there may have been earlier solifluction phases. The date of the landslide cannot be determined with any precision, though it must have occurred within the Devensian.

Landslipped slopes in the Welland valley

The extraordinarily close similarity between the Barnsdale slope and a section of the main Upper Lias escarpment in the Welland valley at Rockingham (Chandler 1971) suggests a common origin for many of the landslipped slopes in both the Gwash and Welland valleys.

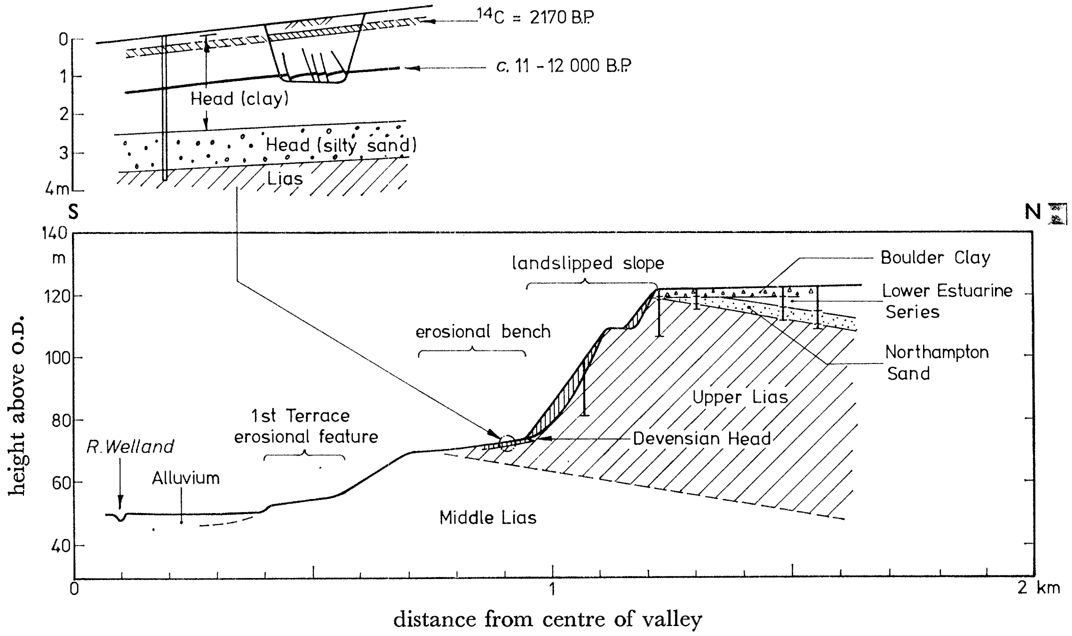

FIGURE 14. The Jurassic escarpment in the Welland valley 2 km north of Rockingham. Vertical exaggeration × 6.5.

The following points of similarity occur at both Barnsdale and Rockingham:

(1) Absence of camber (though nearby slopes are cambered).

(2) Brecciation of the Lias clay is minimal or absent.

(3) There is a bench at the foot of the landslipped slope.

(4) Head, comprising a lower relatively coarse member with overlying clay lies on the bench and passes under the landslide mass.

(5) The upper, clayey Head contains a very dark coloured organic horizon which is disturbed by minor faulting.

The Rockingham section is shown in figure 14. The conclusion (Chandler 1971) that the Rockingham slope was steeped by fluvial erosion prior to degradation by landsliding is confirmed by the Barnsdale studies, though it now appears that the original interpretation of the Rockingham section was in error in one respect. At the foot of the Rockingham slope, just beyond the landslide toe and hence forming the surface of the bench, a series of layered deposits was encountered (Chandler 1971, Figures 6 and 7). These were largely composed of light grey, mottled orange clay about 2.5 m thick with occasional ironstone and flint fragments in the upper part and apparently stone-free beneath, with a 75 mm dark grey clay horizon at a depth of about 2 m. This clay sequence is underlain by a layer of silty sand. As these layers are continuous, nearly horizontal and extend back into the slope beneath the landslide mass, it was suggested that they formed part of the Upper Lias sequence. It is now clear, however, in view of the similarity to the Barnsdale Head deposits, both in lithology and position, that these deposits are also an accumulation of Devensian material, the base of which, by correlation with Barnsdale, is tentatively placed at the base of the relatively granular lower Head, here a silty sand.

Direct evidence of comparatively recent landslide activity, inferred from the freshness of the landslide toe at Barnsdale, is provided at Rockingham by disturbance of 16th century ridge-and-furrow strip-fields and by a trial pit that showed the landslip toe at one point to override a soil horizon containing charcoal which gave a ^{14}C date of 2170 B.P. Other landslipped slopes backing bench-like features also occur in the Welland valley, notably at Drayton (SP 828924) and at Slawston (SP 780930), both upstream from Rockingham.

The results of the investigations of the A 606 and Hambleton Access road diversions are published by permission of the Anglian Water Authority. Discussions with Professor A. W. Skempton, Professor A. Straw, Mr A. Horton, Dr J. N. Hutchinson and Mr P. Horswill are gratefully acknowledged; moreover, the latter rendered invaluable assistance with many aspects of the work.

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Appendix. Pollen analyses, boring I1, Barnsdale

Details of the lithology at the depth at which the samples were obtained are given on page 474. Analyses by Mr A. Hall, University of Cambridge.

depth/m		
9.79–9.82	traverses counted	93
	Pinus	18
	Betula-Corylus-Myrica	1
	Cf. *Salix*	1
	Gramineae	5
	Cyperaceae	4
	Compositae (Tubuliflorae)	21
	Compositae (Liguliflorae)	2
	Filipendula	1
	Cf. Gentianaceae	7
	Polemonium	1
	Cf. Umbelliferae	1
	Selaginella	1 (a single microspore)
	Pre-Quaternary microfossils	1128

sum AP 19; sum NAP 43; sum pollen 62

depth/m		
9.82–9.85	traverses counted	47
	Pinus	3½
	Cf. Gramineae	1
	Compositae (Tubuliflorae)	9
	Compositae (Liguliflorae)	2
	Pre-Quaternary microfossils	477
	sum AP 3½; sum NAP 12; sum pollen 15½	
9.87–9.90	traverses counted	47
	Pinus	2½
	Compositae (Tubuliflorae)	1
	Chenopodiaceae	1
	Pre-Quaternary microfossils	215
	sum AP 2½; sum NAP 2; sum pollen 4½	
9.95–9.98	traverses counted	47
	Pinus	5
	Gramineae	1
	Compositae (Rubuliflorae)	1
	sum AP 5; sum NAP 2; sum pollen 7	
	Pre-Quaternary microfossils	364
10.05–10.10	traverses counted	23
	No pollen	
	Pre-Quaternary microfossils	499
10.30–10.35	Traverses counted	24
	Pinus	2½
	Ilex	1
	Pre-Quaternary microfossils	426

Discussion

Dr R. H. Johnson (*University of Manchester*)

In his paper Dr Chandler has demonstrated some slope movements that occurred later than 11800 years B.P. and were probably of Late Glacial (Zone III) age. In the Longdendale valley of the South Pennines, Dr Tallis, Mr S. Walthall and I have been using pollen analytical dating methods to determine the age of peat which is found in slump depressions where it obviously accumulated after slumping took place.

From our preliminary studies we find that peat was forming in the slump 'troughs' at the back of the slump and at the foot of the landslide scars sometime during the pollen Zone VI period. Movements were taking place at different times in Zone VI, for at Lawrence Edge (SK 084988) the basal peats are early Zone VI; at Rakes Rocks (SE 059005) in the Crowden valley, the peats date from at least mid-Zone VI, and at Hollins Clough (SK 052997), the earliest peat layers date from the Zone VI/VII transition period. In at least two landslide localities slump debris overlies boulder-clay of Devensian age which was deposited on the lower valley slopes and so we have established a lower as well as an upper time limit for these slide movements.

Further to this, in one locality – Bradwell Stich (SK 083988) below the Lawrence Edge scar – we have recognized several successive slip movements. The first and major slide took place before 9000 years B.P. (early Zone VI) and later slip movements were *before* 5500 years B.P. (Zone VII a) and *after* 5000 years B.P. (Zone VII b). These pollen analytical datings are of course approximate and in using them we have related our chronology to the chronozone limits as given by Smith & Pilcher (1973). Fortunately, we can also date the final movement in this particular landslide as in the toe area a mudflow moved forward and overwhelmed a small birch wood, and a macro fragment taken from the flow debris was ^{14}C dated (B. 481) as 1970 ± 100 years B.P.

We hope in time to obtain other ^{14}C determinations, but first it will be necessary to complete our surveys of the floors of the depressions so that the oldest peat of each basin is examined. Given that such peats probably form within a few decades of the actual slip movements, this method of using pollen analysis seems useful when palaeosols or other specific stratigraphic datum points have not been found.

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Figure 4. Head on the Hambleton Surface. This locality is just east of section 1, figure 2, where the Hambleton Surface is cut across the Marlstone Rock Bed which here underlies the Head.

FIGURE 8. Chalky Boulder Clay infilled gulls in the Northampton Sand Ironstone in the plateau beyond the crest of the Barnsdale slope.