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Valley Slope Sections in Jurassic Strata near Bath, Somerset [and Discussion]

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Valley slope sections in Jurassic strata near Bath, Somerset

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[Plate 7]

The valleys of the river Avon and its tributaries in the Bath area are characterized by steep slopes, up to 15°, and high relief, typically up to 160 m. The considerable downcutting of the river during the Devensian period, amounting to about 27 m, caused several large landslips, but cambering and valley-bulging appear to have been completed before the Last (Ipswichian) Interglacial, probably in the Wolstonian glacial period. Cambering is associated with disturbance of the strata to depths of 30–40 m and is present in the more gentle slopes which have been left essentially undisturbed by subsequent erosion. Conversely, the steepest and most actively eroding slopes are not cambered, the disturbed material probably having been removed by landslides and mudflows.

The slopes are mostly blanketed by colluvium or Head, ranging from 1 to 5 m in thickness. In general the Head is only marginally stable under present climatic conditions and the angle of limiting equilibrium seems to be related to the thickness of colluvium, in response to the variations of pore pressure and shear strength with depth. The observed lower bound of 9° in the Fuller's Earth clay slopes, with 5 m of Head, may well be at or close to the angle of ultimate stability.

1. Introduction

Investigations during the period 1970–4 for two road schemes in the neighbourhood of Bath provided detailed sections of slopes in the Swainswick valley and in Horsecombe Vale, respectively a few kilometres northeast and south of the city. The streams in these valleys are tributaries of the Bristol Avon which flows west to reach the Severn estuary at Avonmouth about 40 km downstream from Bath.

The sections were studied by using shell-and-auger rigs for borings in the softer strata, changing to rotary drilling at greater depths. Frequent 100 mm diameter open-drive tube samples were taken with the soft-ground rigs, while NX cores were obtained with the rotary rigs. Trial pits were dug at selected localities to depths of up to 4 m, using a small mechanical excavator, in order to examine the nature and structure of the slope deposits more comprehensively than is possible by borings alone. Piezometers of the Casagrande type were installed at various positions in order to measure pore water pressures. Aerial surveys of Swainswick valley enabled maps to be produced with contour intervals at 0.5 m, from which the slope profiles were derived, though the slope profile in Horsecombe Vale was determined by conventional survey methods.

Figure 1 shows the outline geology of the district and the locations of the main sections described in the paper. The strata are indicated in their approximate positions; no account has been taken of cambering, which is extensively developed in the area, and only some of the major landslips are included. In Swainswick valley three sections include the full, or practically the full sequence of Jurassic strata from the Great Oolite limestone at the crest of the slope down through the Fuller's Earth, the Inferior Oolite limestone, the Midford Sands, the Middle Lias and part of the Lower Lias clay. The sections are between about 120 and 160 m in vertical depth. Sections 1 and 2 show strong cambering and have average inclinations around $9\frac{1}{2}°$, while section 3, further upstream, is uncambered and exhibits a relatively steep average slope of just over 14°. The dimensions of these slopes are summarized in table 1. The section in Horsecombe Vale extends from the Great Oolite through the Fuller's Earth to the Inferior Oolite. Here the valley has a depth of 64 m and an overall slope of about $14\frac{1}{2}°$; the strata are not cambered, though the Great Oolite is much disturbed near its edge at the top of the slope.

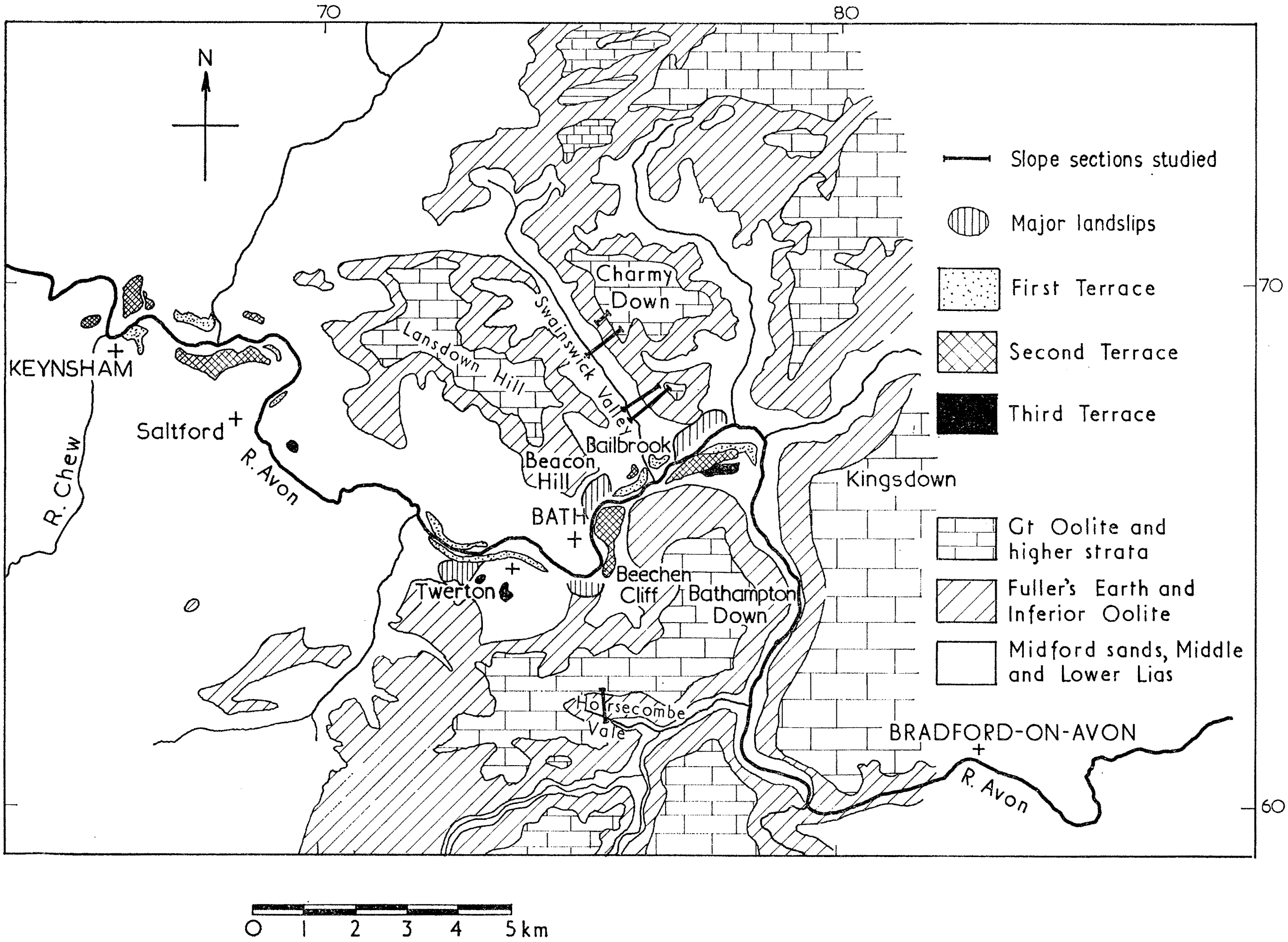

Figure 1. Outline geology of the Bath area.

The slopes are for the most part blanketed by Head or colluvium, between 1 and 5 m in thickness. Except for a few local areas the Head is either marginally stable or, on the steeper slopes, actively unstable under present climatic conditions. The mechanics of these superficial slope deposits is examined in the light of shear strength tests and pore pressure observations.

Three large landslips in the Avon valley in the vicinity of Bath, at Bailbrook, Beacon Hill and Beechen Cliff, have been described briefly by Kellaway & Taylor (1968). They vary in width from about 700 to 1200 m and in length downslope from 250 to 450 m. To these we add some information on a slip of similar dimensions at Twerton, also in the Avon valley, and a slip on section 2 in Swainswick valley. The latter has displaced the stream by about 100 m. Kellaway & Taylor (1968) concluded that the whole of Solsbury Hill had been involved in a massive landslide; but we now consider that the strata at this location have been displaced by a fault with a southerly downthrow of the order of 15 m (figure 3).

Table 1. Slope profiles

section	range of strata	depth of section m	average slope	structure
Swainswick 3	Gt Oolite to Lower Lias	158	14.2°	not cambered
Swainswick 2	Gt Oolite to Lower Lias	155	9.6°	cambered
Swainswick 1	U. Fuller's Earth to Lower Lias	122	9.4°	cambered
Horsecombe 1	Gt Oolite to Inf. Oolite	64	14.4°	not cambered

It was unfortunately not possible with the funds available to explore the bottom of Swainswick valley in sufficient detail to establish or disprove the existence of valley bulging. But this phenomenon is known to exist at Keynsham, about 8 km west of Bath (figure 1). Here the sharply folded Lias clays in the bulge are trimmed off horizontally by the gravels of no. 2 Terrace, which are themselves unfolded.

Evidently, therefore, the valley bulging at this site occurred earlier than the deposition of no. 2 Terrace. In a similar manner it can be shown that the Twerton landslip pre-dates the formation of no. 1 Terrace and post-dates the formation of no. 3. Evidence is also presented which suggests that cambering had taken place before the deposition of no. 3 Terrace. Thus at least a part of the relative chronology of the various events involved in the development of the valleys can be discerned. But clearly it is of great interest to correlate the stages of development with the basic Quaternary succession, and the key to such a correlation is provided by the river terraces. For this reason an attempt has been made to date the Avon terraces in the Bath area and so provide a time scale for the geologically recent history of the valley slopes.

2. Stratigraphy: Jurassic

From the borings the stratigraphic sequence in both valleys could be determined in some detail. A standard succession for the Swainswick valley was established by drilling borehole 15 near the southwest corner of Charmy Down (figure 3) at a site well away from any slope disturbance. The strata encountered, in downward sequence, are as follows. They all belong to the Jurassic System.

Great Oolite: a hard, massive, fine to medium grained, shell-fragmental, well jointed oolitic limestone. It forms the capping of the Lansdown Hill plateau on the west side of the valley and the Charmy Down and Solsbury Hill plateaux on the east side. The Great Oolite weathers into large slabs and angular debris.

Upper Fuller's Earth: consists of 27 m of grey fissured clays and mudstones, often rather calcareous and occasionally interbedded with thin limestone bands.

Fuller's Earth Rock: this 4 m thick bed, separating the Upper and Lower Fuller's Earth, consists of a hard, shelly, rubbly limestone with several marly seams.

Lower Fuller's Earth: a 10 m sequence of fissured and jointed clays and mudstones similar to, though rather less plastic than, the Upper Fuller's Earth. About half way up the sequence there is a thin, nodular argillaceous limestone.

Inferior Oolite: a number of subdivisions can be recognized, but for the present purpose the Inferior Oolite is best regarded as a single 12–15 m thick deposit of well jointed, and therefore pervious, oolitic limestone. Where it is involved in cambering, as described later, it may be very broken.

Midford Sands: comprise up to 31 m of yellowish-brown, homogeneous silty sand with frequent bands of hard, cemented, calcareous sandstone concretions or 'doggers'.

Junction Bed: a bed about 1 m thick of fine grained, hard, ferruginous, calcareous siltstone, locally with shelly and conglomeratic bands. In the Bath area it may be taken as defining the base of the Upper Lias.

Middle and Lower Lias: up to 80 m of Lias clays were proved in the boreholes. The uppermost 15 m consists of bluish-grey, brown-weathering slightly micaceous, frequently laminated silty clays with occasional bands of hard, calcareous siltstone. These beds are probably of Middle Lias age, and are thought to correspond to the Dyrham Silts of the South Cotswolds. They are underlain by at least 65 m of bluish-grey, stiff fissured clays and soft mudstones with occasional bands of hard, compact, argillaceous limestone and infrequent layers of ferruginous nodules. These clays are probably largely of Lower Lias age (Davoei Zone), though it has not been possible exactly to define the Middle/Lower Lias boundary.

TABLE 2. SUMMARY OF INDEX PROPERTIES

			Atterberg limits (%)		
material	site*	water content (%)	liquid limit mean (range)	plastic limit	plasticity index
Upper Fuller's Earth	S	21	51 (40–65)	20	31
	H	20	54 (40–70)	21	33
Fuller's Earth Bed	H	—	95	33	62
Lower Fuller's Earth	S	17	44 (35–55)	17	27
	H	17	44	17	27
Midford Sands	S	17	typically non-plastic		
Middle and Lower Lias	S	21	47 (35–55)	21	26
Lower Lias	S	23	52 (40–65)	22	30
Head over Fuller's Earth	S	20	47 (30–70)	19	28
	H	32	77 (45–100)	25	52
Head over Midford Sands	S	23	44 (30–60)	19	25
Head over Lias	S	26	48 (30–65)	23	25

* S, Swainswick; H, Horsecombe.

In Horsecombe Vale the stratigraphical sequence established in boreholes extends from the Great Oolite down to the Midford Sands. The beds within this range are similar in lithology and thickness to those already described from Swainswick valley, except for a $1\frac{1}{2}$–2 m thick bed of commercial fuller's earth, a highly plastic clay containing about 60 % of the clay mineral montmorillonite. This Fuller's Earth Bed lies approximately 10 m below the base of the Great Oolite.

Average values of the index properties, and the range of liquid limit, are given in table 2. They have been determined chiefly on samples taken within the top 10 m. The results call for no particular comment as the Atterberg limits are unexceptional and the natural water contents are, as usual in weathered over-consolidated clays, approximately equal to the plastic limit.

Index properties of the matrix of the Head deposits are also given in table 2. The water contents have relatively higher values than those of the parent materials, while the plasticity is slightly reduced by the inclusion of some particles from the limestones or Midford Sands. The high values of the Atterberg limits in the Head in Horsecombe Vale reflect the presence of the Fuller's Earth Bed.

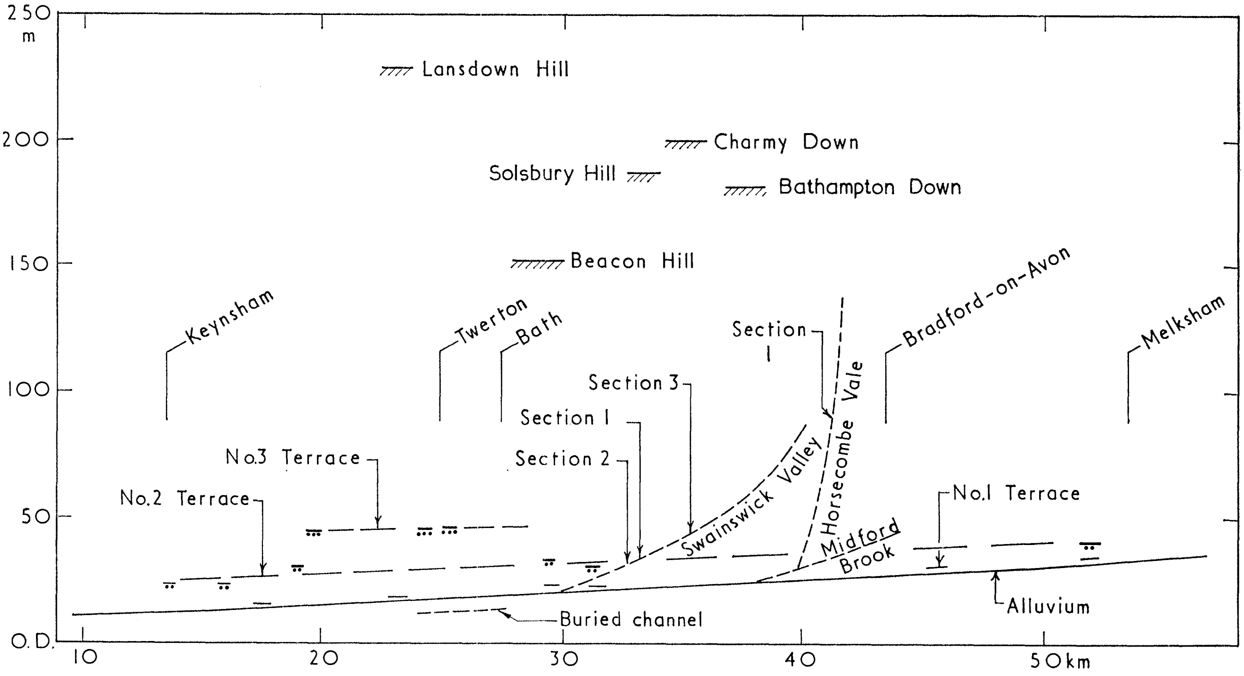

FIGURE 2. Longitudinal profile of Bristol Avon, near Bath.

3. STRATIGRAPHY OF THE RIVER GRAVELS

The oldest known drift deposits are the high-level gravels of Bathampton Down and Kingsdown. These have not yet been found north of the Avon valley, but they may mark an early stage in its evolution (Oriel 1904; Hawkins & Kellaway 1971). There is no evidence of deposits intermediate in age between the high-level drifts and the three terraces which can be recognized at relatively much lower levels in the Avon valley near Bath. These terraces are plotted on a longitudinal profile in figure 2 from which the typical heights above alluvium, given in table 3, can be obtained. There is insufficient evidence from the Avon terraces themselves to date the sequence with certainty. But Kellaway & Welch (1948) tentatively suggest correlations between Avon no. 3 and the Whitminster Terrace of the River Frome (Stroudwater), and between Avon no. 2 and the Cainscross Terrace of the Frome. These correlations are probably correct, and lead to an interpretation of the Avon terraces which is reasonable and consistent.

The River Frome, like the Bristol Avon, flows west through a steep-sided valley in Jurassic strata (ranging from the Fuller's Earth to the Lower Lias) and joins the Severn at a point about 40 km north of Avonmouth. The heights above alluvium of the Frome terraces, as given in table 3, are measured from a longitudinal profile published by Tomlinson (1940); and it is important to note that she provides clear evidence for correlating the Cainscross Terrace with the Main Terrace of the Severn and its equivalent, no. 2 Terrace of the Warwickshire Avon. This provides a firm datum in the sequence since the age of the Severn Main and Warwick Avon no. 2 (*ca.* 28000–40000 years B.P.) has been well established by radiocarbon dating (Shotton 1968) within the Middle Devensian period.

TABLE 3. PROPOSED CORRELATIONS OF THE BRISTOL AVON AND RIVER FROME TERRACES

	Bristol Avon near Bath		River Frome downstream of Stroud	
stage	terrace	height above alluvium m	terrace	height above alluvium m
Late Devensian	no. 1	3	Stroud	4
Middle Devensian	no. 2	9–15	Cainscross	7–15
Ipswichian	no. 3	27	Whitminster	25

TABLE 4. TWERTON NO. 3 TERRACE: FAUNAL LIST

mammoth	*Mammuthus primigenius*
straight-tusked elephant	*Palaeoloxodon antiquus*
horse	*Equus caballus*
woolly rhinoceros	*Coelodonta antiquitatis*
pig	*Sus scrofa*
red deer	*Cervus elephas*
bison	*Bison priscus*

No. 3 Terrace. At the Victoria quarry in Twerton, a western suburb of Bath, the surface of no. 3 Terrace lies at approximately 45 m O.D. or 27 m above alluvium. The terrace deposits, up to 3 m in thickness, consist of horizontally bedded gravels with a clay seam, overlain by clay and sand beds, covered by a thin layer of Head (figure 15). From the lower deposits a mammalian fauna has been recorded (Palmer 1931), including the species listed in table 4. This assemblage is indicative of a cool, probably late, phase of an interglacial; and as the next lowest terrace is almost certainly mid-Devensian the likelihood is that no. 3 can be correlated with the Ipswichian Interglacial. Support for this conclusion is provided by the fact that each of the species listed in table 4 can be matched in the fauna from the Aylesford Terrace of the Medway, which is of Ipswichian age (Carreck 1964) and where implements of late Acheulian type showing Levalloisian technique have been found (J. N. Carreck, personal communication). Admittedly there is a considerable difference in elevation, as the Aylesford Terrace is only 11 m above alluvium. But the strong relief and steep slopes of the Avon valley imply a comparatively rapid rate of downcutting, so it is not surprising that the Last Interglacial terrace in the Bath area (and also in the Frome valley if the correlations in table 3 are correct) lies much higher above present river level. Moreover, there is evidence to suggest a correlation between the Whitminster Terrace of the Frome and the Kidderminster Terrace of the Severn (Ackerman & Cave 1967), and the latter terrace is accepted as being of Ipswichian or very early Devensian age (Shotton 1968).

No. 2 *Terrace.* Spreads of gravel referred to the Second Terrace occur beside the Avon at Bathampton, at the mouth of the Swainswick valley (Larkhall) at Bath, at Saltford, and at Keynsham (figure 1). Their surface lies about 12 m above alluvium. No systematic record of fossils from these gravels is available. But in what appears to be the comparable terrace of the Frome, the Cainscross Terrace (table 3), a mammalian fauna characteristic of the Middle Devensian exists (Wood 1967). This differs essentially from the Twerton fauna in the absence of *Palaeoloxodon* and the presence of the musk ox, *Ovibos moschatus*. Also, as previously mentioned, Tomlinson (1940) provides evidence, both morphological and palaeontological, for correlating the Cainscross Terrace with the Main Terrace of the Severn.

Buried Channel. After the deposition of no. 2 Terrace the Avon eroded a channel which, in the Bath district, extends to a depth of about 6 m below present alluvium. This episode can with little doubt be related to the period of the main Devensian glaciation, around 15000–20000 years B.P. It will be seen that such a chronology accords with a mid-Devensian age for the Second Terrace.

No. 1 *Terrace.* Aggradation of No. 1 Terrace infilled the Buried Channel and rose to a level a few metres above the present floodplain in the neighbourhood of Bath. It is probable that the First Terrace is Late Devensian, and therefore comparable with no. 1 Terrace of the Warwickshire Avon which also is separated from the earlier no. 2 Terrace of that river by a period of downcutting corresponding to the Devensian glacial maximum (Shotton 1968).

Alluvium. The Avon valley is floored by alluvial deposits, locally up to 6 m in thickness. Bones of mammals, including horse, pig, sheep and *Bos longifrons*, are said to be common at the contact of the alluvium and the gravels filling the Buried Channel (Woodward 1876).

4. SWAINSWICK VALLEY

A simplified geological map including that part of Swainswick valley in which slope sections have been studied is shown in figure 3. The following features may be noted: the plateaux of Great Oolite forming Charmy Down and Solsbury Hill, standing at about 200 and 190 m O.D. respectively; the high col floored by Inferior Oolite at an elevation of about 120 m O.D., east of Swainswick village; the Solsbury Hill Fault running roughly east–west; and the lobes or tongues of Head, composed of Fuller's Earth clay with limestone fragments, which have moved down across the Inferior Oolite outcrop on the south and southwest slopes of Charmy Down. Not shown on the map are numerous shallow landslides in the upper slopes of Solsbury Hill, but some of them appear in sections 1 and 2. The large Bailbrook landslip is seen above the river Avon at the southeast corner of the map. Flowing at the bottom of the Swainswick valley is Lam Brook. The stream, except where it has been displaced by a landslip at the foot of section 2, runs within a narrow belt of alluvium from the edges of which the slopes ascend, in the Lias clays, at about 10°. The upper parts of the slopes are more variable in inclination but both of the two deepest sections studied (sections 2 and 3) rise to practically the same height of about 160 m above the valley floor (table 1).

Section 1

A preliminary inspection of the borehole logs from Section 1 suggested that the strata dip towards the valley: the base of the Inferior Oolite, for example, decreases in elevation from 105 m O.D. in borehole 58 to 77 m O.D. in borehole 10 (figure 4). However, detailed examination of the cores showed bedding-plane dips in the Fuller's Earth and Lias to be frequently much steeper than the overall inclination of the strata, and that the Inferior Oolite is very broken while in some borings repetition of individual beds was encountered. Moreover, the regional dip is known to be in an easterly direction, i.e. away from the valley. All these features point to the existence of cambering.

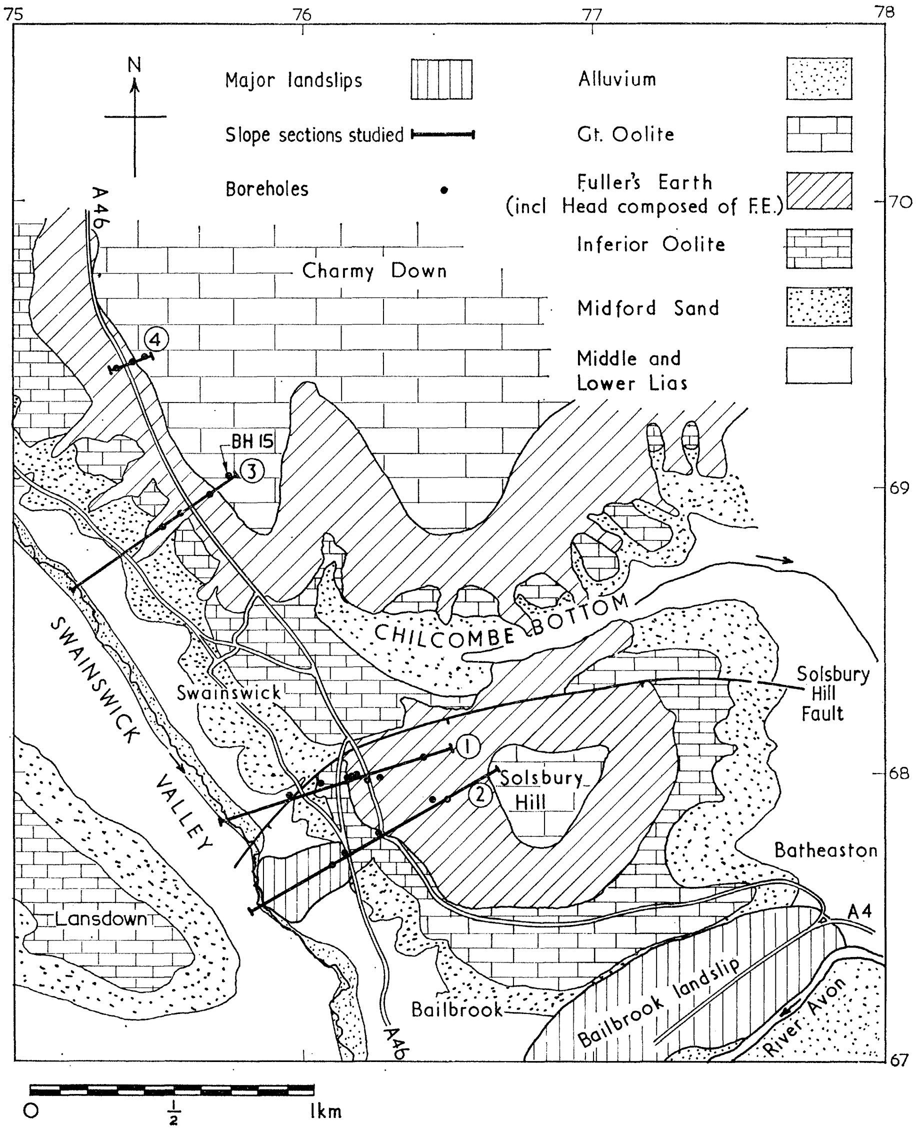

Figure 3. Swainswick valley simplified geology.

As the orientation of the cores could not be established with the equipment available it has not been demonstrated conclusively that the cambering is associated with dip-and-fault (cf. Hollingworth, Taylor & Kellaway 1944), rather than back-tilted block movements. But three closely spaced boreholes, nos. 59, 59B and 59C, carried out principally to investigate this question, support a dip-and-fault interpretation; and certainly this provides the simplest explanation of the various pieces of information from all the other boreholes. It has therefore been adopted in figure 4.

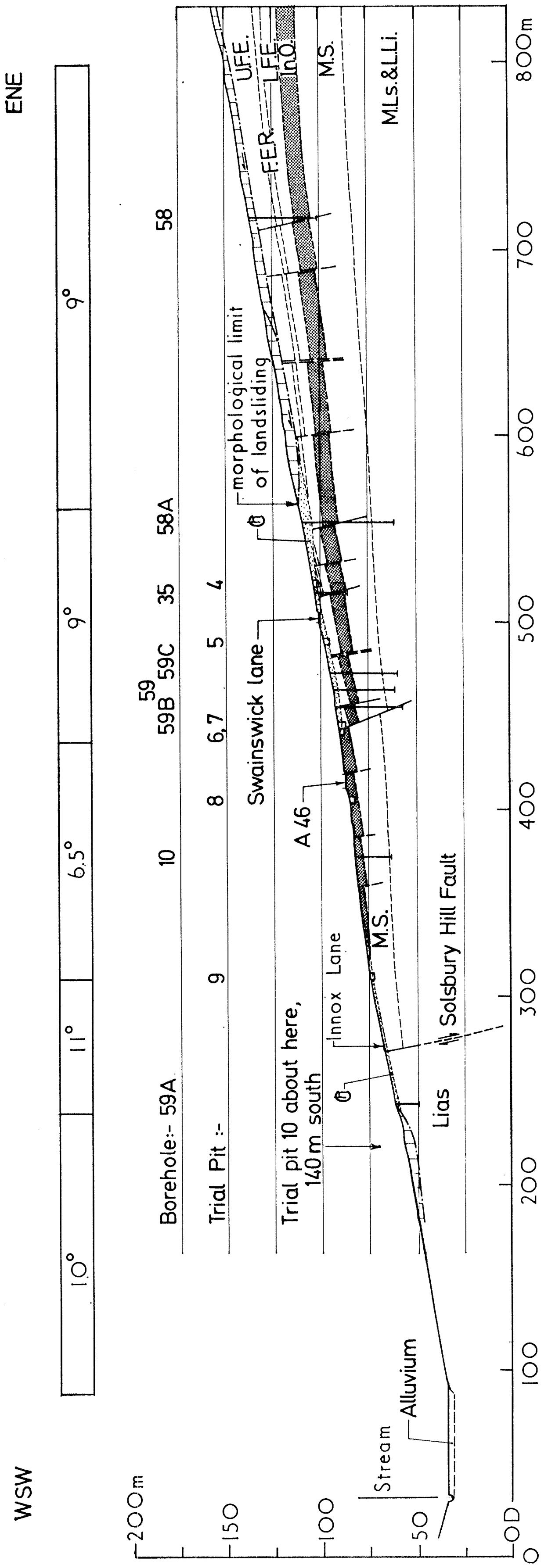

FIGURE 4. Swainswick valley, section 1.

A point of considerable interest is the depth to which the strata are disturbed. In borehole 58 the Upper Fuller's Earth was found to be brecciated to its full depth of 13 m below the surface, and a 30° dip was noted in the Lower Fuller's Earth at 20 m. In Borehole 58A, as in BH 58, the Inferior Oolite is much broken, while dips of 25–40° exist in the Lias beneath to a depth of 40 m. The group of boreholes 59, 59B and 59C also showed broken Inferior Oolite and steep dips, in some instances as high as 50°, in the Lias to the bottom of the borings about 33 m below ground level. And finally, in borehole 59A, where the Lias reaches almost up to the surface, bedding-plane dips of 20–45° were recorded between depths of 3 and 10 m, where the boring ended. In the latter case it might be possible to attribute the disturbance to the Solsbury Hill Fault, but elsewhere in this section there is no reason to invoke tectonic effects.

Turning now to the superficial deposits, the upper half of the section has a long segment sloping at 9° with a blanket of clay-rich colluvium or Head, containing many Great Oolite fragments, overlying the Fuller's Earth. Above the point marked in figure 4 as the morphological limit of landsliding there is hummocky and undulating ground, clearly indicative of a slope in a state of limiting equilibrium. Borehole 58 shows that the unstable layer is about 5 m in thickness. The lowest 100 m of the 9° segment is, by contrast, smooth and apparently stable. This area was investigated by pits 4–7, as shown in figures 4 and 5. The pits revealed up to 4 m of Head forming a layer which, at its furthest downslope extent (pits 6 and 7), is underlain by a continuous shear surface. The absence of any topographic expression of landslipping in this part of the slope suggests that the Head is a relic of former periglacial action.

The downslope limit of the Fuller's Earth Head occurs where the Inferior Oolite limestone reaches the surface. The inclination here reduces from 9 to $6\frac{1}{2}$°. Thus it seems that either the reduction in slope angle or the free-draining nature of the Inferior Oolite, or a combination of both effects, was sufficient to prevent further movement of the Head.

Below the Inferior Oolite outcrop the slope steepens again, with 11 and 10° segments down to the alluvium. The 11° segment consists chiefly of Midford Sands overlain, as shown in pit 9, by a layer of Head composed of silty clay containing fragments of Inferior Oolite (figure 5). The lowest segment, inclined at 10°, is in the Lias clays. Undulating ground indicates the presence of shallow landslides probably dating from a period when the stream was running at the foot of the slope, before deposition of the present alluvium at this section.

Pit 10

The lower slopes of Solsbury Hill have been dissected in several places by shallow gulleys. Pit 10 was excavated in one of these, 140 m south of section 1. Here there are at least 4 m of Head with fragments from the Inferior Oolite and Midford Sands, and a thin layer of organic silt at a depth of 3 m (figure 5). The silt contained many pieces of woody peat, the age of which was determined by radiocarbon assay to be

3070 ± 40 years B.P. (SRR–134).

Within and immediately above the silt numerous small molluscs were also found. Dr M. P. Kerney, who kindly examined a collection of these, reported the faunal list given in table 5 and remarked that the assemblage is post-glacial and representative of an open, marshy ground environment. Taken in conjunction with the radiocarbon date, such conditions might be a result of Neolithic forest clearance.

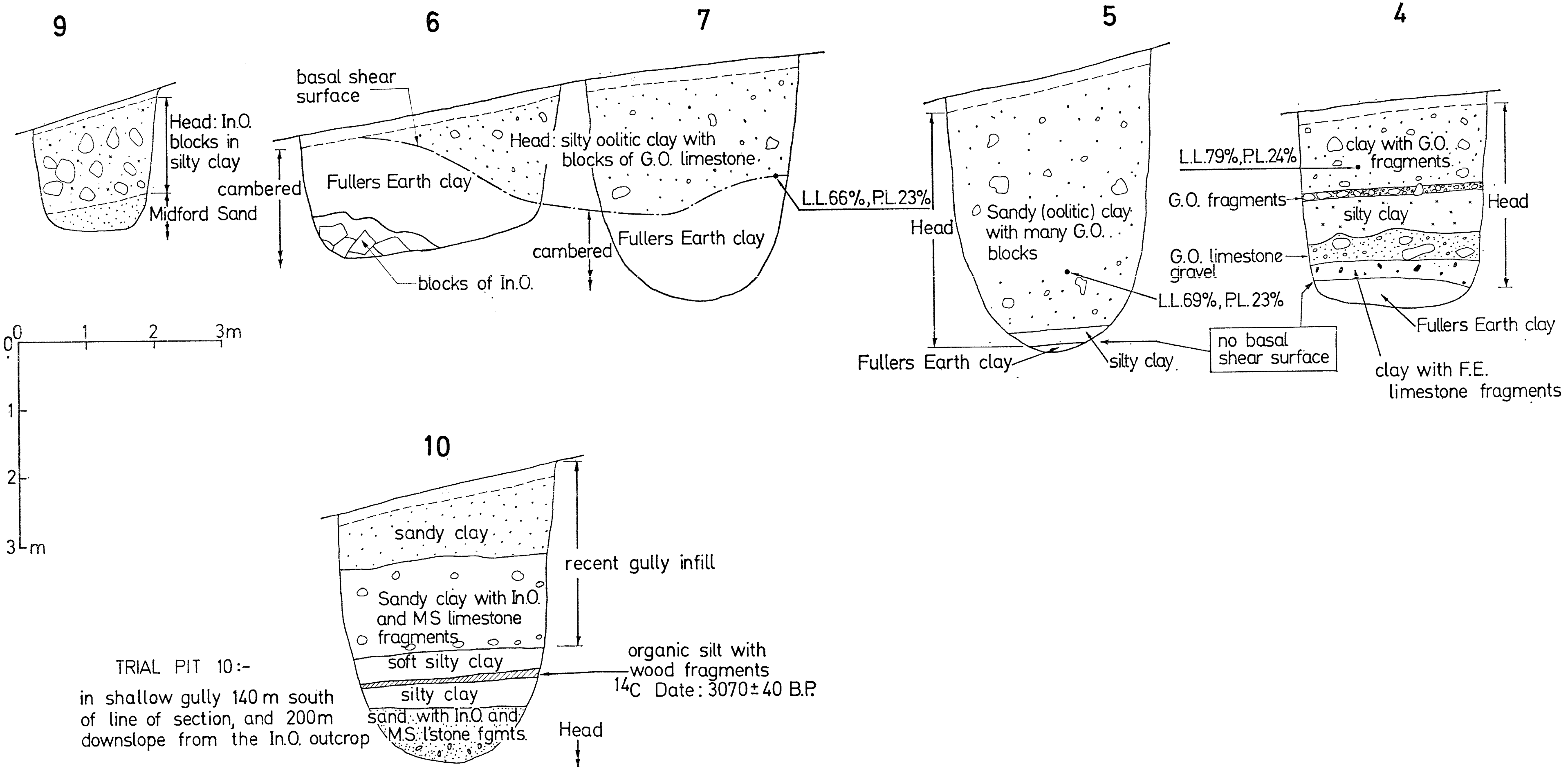

FIGURE 5. Details of selected trial pits; Swainswick valley, section 1.

Section 2

This section extends from the stream up to the edge of the Solsbury Hill plateau (figure 6). The borings again prove that as a result of cambering the base of the Inferior Oolite decreases in elevation towards the valley by at least 30 m; and in this section it can be shown that the Midford Sands decrease in thickness by not less than 15 m, also in a valleyward direction.

TABLE 5. SWAINSWICK VALLEY, PIT 10, DEPTH 3 m; MOLLUSC FAUNA

Aegopinella nitidula (Draparnaud)	6
A. pura (Alder)	1
Carychium minimum Müller	3
C. tridentatum (Risso)	11
Cepaea sp.	1
Cochlicopa lubrica (Müller)	12
Deroceras sp.	3
Helicella itala (L.)	1
Lymnaea truncatula (Müller)	2
Nesovitrea hammonis (Ström)	3
Pisidium personatum Malm	2
Trichia hispida (L.)	13
Vallonia costata (Müller)	19
V. excentrica Sterki	1
V. pulchella (Müller)	9
V. pulchella/excentrica	18
Vertigo pygmaea (Draparnaud)	8
Vitrea crystallina (Müller)	1
total specimens in 1 kg soil =	114

Here, as in section 1, there is abundant evidence for disturbance of the strata. The Upper Fuller's Earth in borehole 55B shows dips up to 30° and the Fuller's Earth Rock has been disturbed by a fault or gull. The Inferior Oolite is mostly very broken and fragmentary, though the Lias (at 62–65 m) is little affected. In borehole 55 dips of 25–35° are frequently recorded in the Fuller's Earth. The Inferior Oolite is again broken almost into a rubble, while the Lias at 60 m is highly disturbed. In figure 6 this has been interpreted as evidence for a deep fault in the dip-and-fault structure, though it may perhaps be of tectonic origin. Borehole 56 shows once again the broken nature of the Inferior Oolite in these cambered sections, and the Lias has dips of 15 or 20°, with some steep slickensided surfaces, down to the bottom of the boring 34 m below surface level.

A striking feature of section 2 is the presence of a topographic 'flat' nearly 200 m in length and with a rather greater width measured along the valley side. This is undoubtedly due to back-tilting of the strata in a large landslip, the basal shear of which was seen at a depth of 22 m in borehole 61 and as a zone of intense disturbance at 35 m in borehole 9. The 6 m of Lias beneath the slip surface in borehole 9 has bedding plane dips frequently up to 30–40° and at 28 m shows signs of brecciation. Below the shear zone in borehole 9 the clay is less disturbed.

Secondary slips near the foot of the slope in this section have left a steep front edge to the 'flat' and the combined effect of all these mass movements has been to displace the stream by about 100 m, as seen in figure 3.

The slopes in the Fuller's Earth are blanketed by a layer of landslide material or colluvial Head, as in section 1; but the inclination here increases, in the upper part of the slopes, from 9 to 12°. Below the limit of landsliding there is again a belt of stable Head, lying just above or directly on the Inferior Oolite. The slope in this segment is inclined at 11°, and may have been

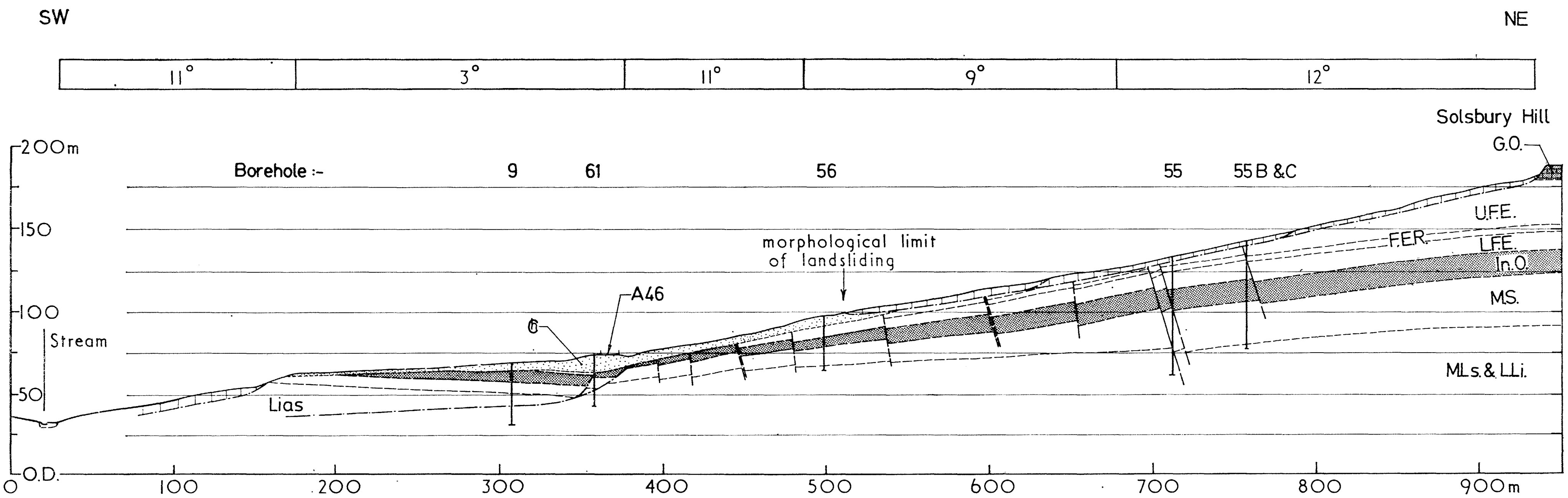

Figure 6. Swainswick valley, section 2.

steepened to this angle by local rejuvenation following the large slip. Certainly the Head has moved down into what was the back scarp of the slip, where it attains the exceptional thickness of 9 m as proved in borehole 61.

Section 3

The third section investigated is shown in figure 7. It lies about 1 km north of sections 1 and 2. Like section 2 it extends from the Lower Lias at the stream up to the Great Oolite, and the base of the Great Oolite is at an almost identical height above the stream in both sections.

Despite the close similarity in height and stratigraphy, section 3 nevertheless differs in four important respects from both sections 1 and 2. Firstly, the average slope is much steeper: just over 14° as compared with $9\frac{1}{2}$°. Secondly, the strata in section 3 show virtually no evidence of cambering except perhaps at very shallow depths. There is a slight flexure in the Junction Bed and Inferior Oolite, which is probably of depositional origin, for the Midford Sands are somewhat thicker at outcrop than in the boring (no. 15) drilled near the edge of the Charmy Down plateau; whereas the opposite would be expected were the flexure due to cambering.

Thirdly, the degree and depth of disturbance of the strata are notably less than in sections 1 and 2. In borehole 28 the Fuller's Earth shows slight disturbance throughout its depth of 18 m, though with no recorded steep dips, and in borehole 19 the Lias has bedding plane dips up to 20° or 30° to a depth of only 13 m below ground level. Otherwise, apart from some open joints, which can readily be attributed to deformations associated with stress relief, the strata appear to have been unaffected in this section.

The superficial deposits offer a fourth contrast to sections 1 and 2. Instead of 3–5 m of Head overlying the Fuller's Earth on slopes of 9–12° there is, in section 3, a deposit about 1 m in thickness on a slope inclined at $15\frac{1}{2}$°. Also, in place of a stable layer of Head on the Midford Sands, sloping at 11°, there is a steep and very unstable mudflow the partial reactivation of which, after heavy rains in July 1968, proved a hazard for the A 46 road. Moreover, the slope debris here includes material derived from the Fuller's Earth with fragments of Great Oolite, as well as Inferior Oolite; so the Head on these steep slopes has flowed down across the Inferior Oolite outcrop. There are indeed several mudflows of this type on the south-west slopes of Charmy Down and also on the southern side above Chilcombe Bottom (figure 3).

The general conclusions concerning section 3 are, therefore, that the upper parts of the slope are still degrading and either that the strata have never been substantially affected by cambering or, more probably, the disturbed material has largely been removed by subsequent erosion.

Section 4

This section lies 540 m north of section 3. Only the upper part of the slope has been investigated. Boreholes 30 and 31 show a gentle easterly dip of the Fuller's Earth, with no indications of cambering (figure 8). And in these borings apart from some open joints, occasionally lined with calcite, there appears to be no disturbance of any kind. The slope in the Fuller's Earth, above the road, is inclined at $11\frac{1}{2}$° and is blanketed by a layer of Head or colluvium, about 3 m in thickness, with an undulating and hummocky surface strongly indicative of shallow landsliding. In this particular respect the section resembles closely the uppermost segment of section 2, but more generally the slope appears to represent a further stage of development from section 3; any cambered strata have been removed by erosion and the upper segments, having been weathered to greater depths, are well advanced in the process of adjusting their inclination to an angle of ultimate equilibrium.

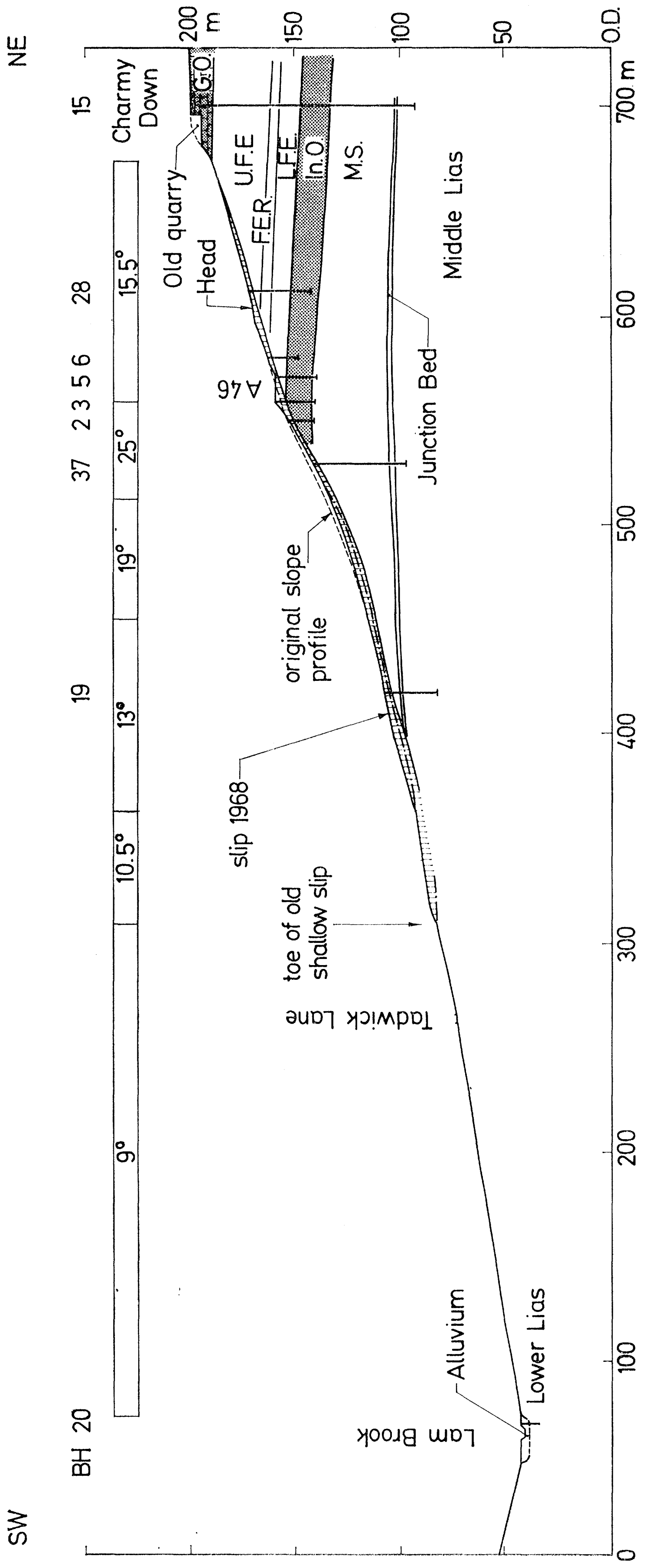

FIGURE 7. Swainswick valley, section 3.

Piezometric observations

It is convenient to express the results of piezometer observations in terms of the pore pressure ratio

$$r_u = \gamma_w h / \gamma z,$$

where h is the height of water in the piezometer, z is the depth of the piezometer tip below ground surface, and γ_w and γ are respectively the unit weights of water and soil. To a close approximation $\gamma = 2\gamma_w$.

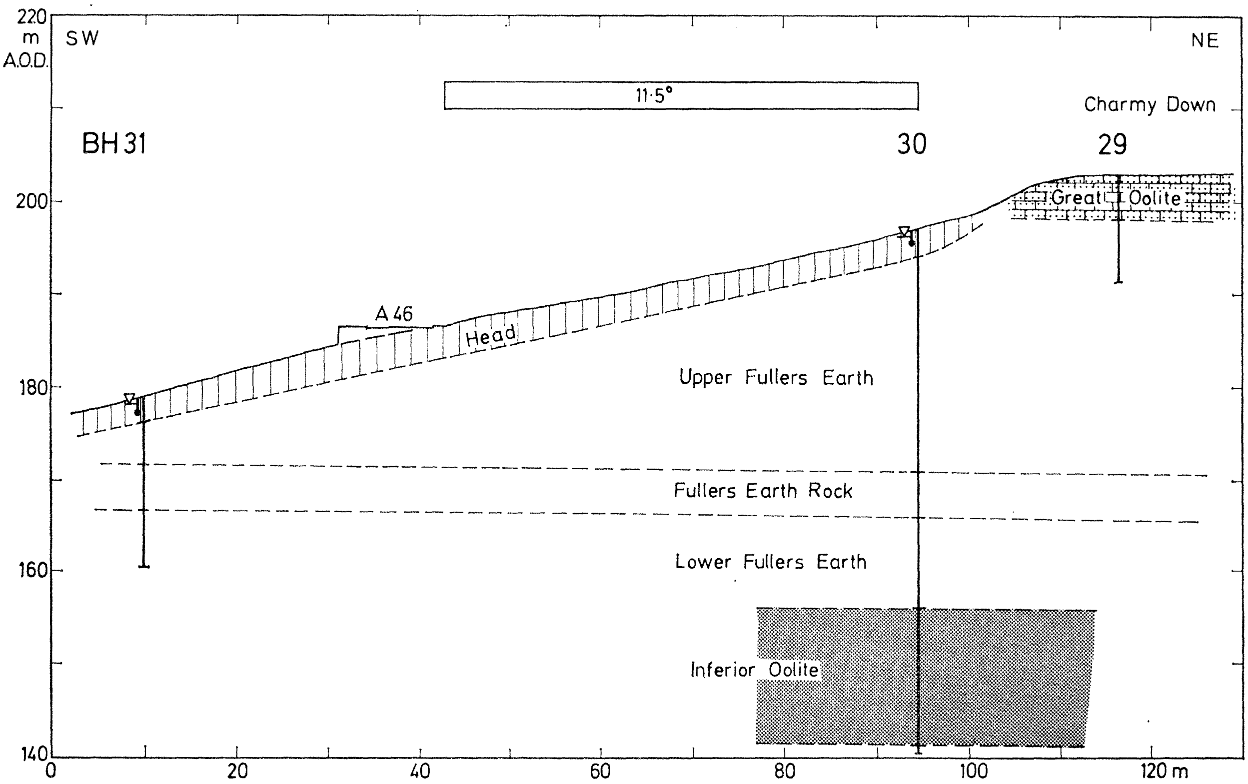

FIGURE 8. Swainswick valley, section 4.

In a temperate climate the maximum pore pressures in comparatively gentle slopes are not likely to exceed those generated by seepage parallel to the slope with ground water level at the surface. In this condition $h = z\cos^2\beta$, where β is the inclination of the slope. For values of β between 9 and 12°, and taking $\gamma = 2\gamma_w$, the maximum pore pressure ratio is therefore about 0.48.

Most of the piezometers in Swainswick valley were observed at fairly frequent intervals during the winters 1970/1 to 1973/4, and the others in 1972/3 to 1973/4. Less frequent observations were taken during the intervening summer months. All the values of r_u which will now be summarized relate to the highest readings measured. Typically the maximum winter piezometric levels were between 0.5 and 1.2 m above the lowest summer readings.

The observations can be classified into four distinct groups.

(i) Piezometers placed in or just below the Head on slopes in the Fuller's Earth or Lias clays. With one exception, to be mentioned later, the piezometric heights increase with increasing depth in a very consistent manner, as shown in figure 9, and the variation of r_u with depth may be summarized as follows:

$$\begin{array}{llll} z = & 1\text{ m} & 3\text{ m} & 5\text{ m} \\ r_u = & 0.30 & 0.33 & 0.37 \end{array}$$

The seven points in this set of observations all come from piezometers in what may be called 'uniform' slopes, i.e. slopes which, though they may be hummocky or undulating, have on a broader scale essentially parallel contours and, in particular, are not dissected into gullies and ridges. Five of these piezometers are located in the sections shown in figures 4, 6, 7 and 8: namely in BH 59A, section 1; BH 55C, section 2; BH 28, section 3; and BH 30 and BH 31, section 4.

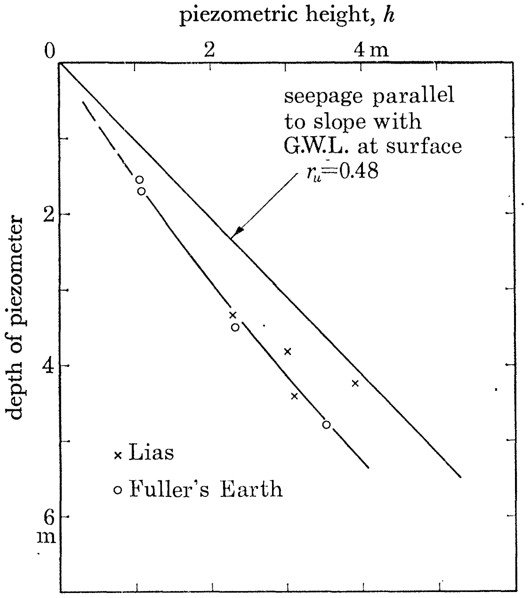

FIGURE 9. Piezometric observations in and beneath Head on Fuller's Earth and Lias clays, Swainswick valley. Maximum winter readings. $r_u = \gamma_w h/\gamma z$; $\gamma = 2\gamma_w$.

(ii) In three cases the pore pressures approached the limiting 'hydrostatic' condition. One of these, where $r_u = 0.46$, is plotted in figure 9. The piezometer here was at a depth of 4.2 m n Lias, beneath 3 m of clayey Head in a shallow gully perhaps being fed by water emerging at the base of the Midford Sands. In another instance, where the maximum recorded value of r_u was 0.44, the piezometer was located in Head near the bottom of the largest gully in the lower slopes of Solsbury Hill. The third case of unusually high pore pressures, with $r_u = 0.41$, was observed in a piezometer again in a clayey Head but on the sides of a shallow gully in the Midford Sands. The reason for such a relatively high r_u in this position is not clear.

(iii) Piezometers in the Fuller's Earth Rock, in the Inferior Oolite and in the Midford Sands invariably showed very low pore pressures, indicating that these are pervious, free-draining strata.

(iv) Three piezometers located in Head lying only a few metres above Inferior Oolite (in boreholes 59B and 59C on section 1 and BH 56 on section 2) gave values of r_u less than 0.2, averaging 0.15. These evidently reflect the fact that the Inferior Oolite limestone, in its very broken condition at these locations, is acting as an under-drain to the Head.

5. Horsecombe Vale

The stream in Horsecombe Vale is a tributary of Midford Brook which is itself a tributary of the Avon, joining the river a short distance downstream from the village of Limpley Stoke. An outline geological map of the Vale is shown in figure 10, including the location of various borings carried out in connection with the scheme for a road by-passing Bath, and showing also the position of the slope section which has been investigated in detail.

At this section the stream flows in the bottom of a V-shaped valley floored by Inferior Oolite, and the slope extends up through the Fuller's Earth to the Great Oolite, the surface of which forms a plateau 64 m above the stream (figure 11). The section is approximately parallel to the strike.

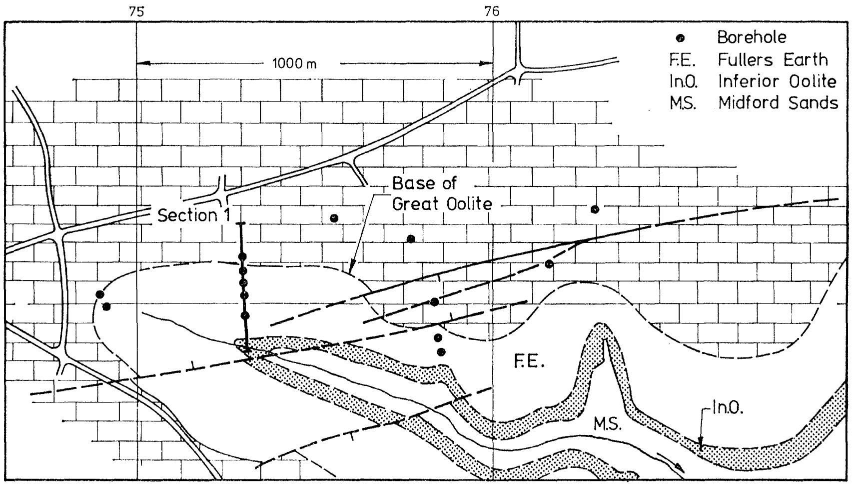

Figure 10. Horsecombe Vale: geological sketch map.

The borings reveal some slight flexures in the strata but no evidence of general cambering; nor is there any disturbance of the beds at depth. Beneath the steep, upper part of the slope, however, the Great Oolite is broken up into massive, foundered blocks in some of which the bedding planes have been tilted up to 60°. Further down the slope the blocks become increasingly disintegrated, as shown in the succession of pits 5, 6 and 3 (figure 12), and this mass of limestone rubble ends in a marked topographic feature at pit 4. In pits 3 and 6 the rubble was seen to be underlain by a thin band of clay with a well developed basal shear surface. The index properties of the clay show that it derives from the highly plastic Fuller's Earth Bed, and there can be no doubt that the foundered blocks of Great Oolite have moved by slipping on this clay.

The lower part of the slope is blanketed by a deposit, up to 3 m in thickness, chiefly composed of small limestone fragments. But pits 1 and 2 revealed that this consists of two layers separated by a buried, fossil soil containing a sparse mollusc fauna. From the position shown in figure 13 a sample of the soil was obtained and the molluscs sieved out. The species were determined and counted by Dr M. P. Kerney, to whom we are grateful for the faunal list given in table 6 and for the comment that this is a late-glacial assemblage which, from its presence in a fossil soil, can be taken as suggesting an Allerød (Zone II) Interstadial age.

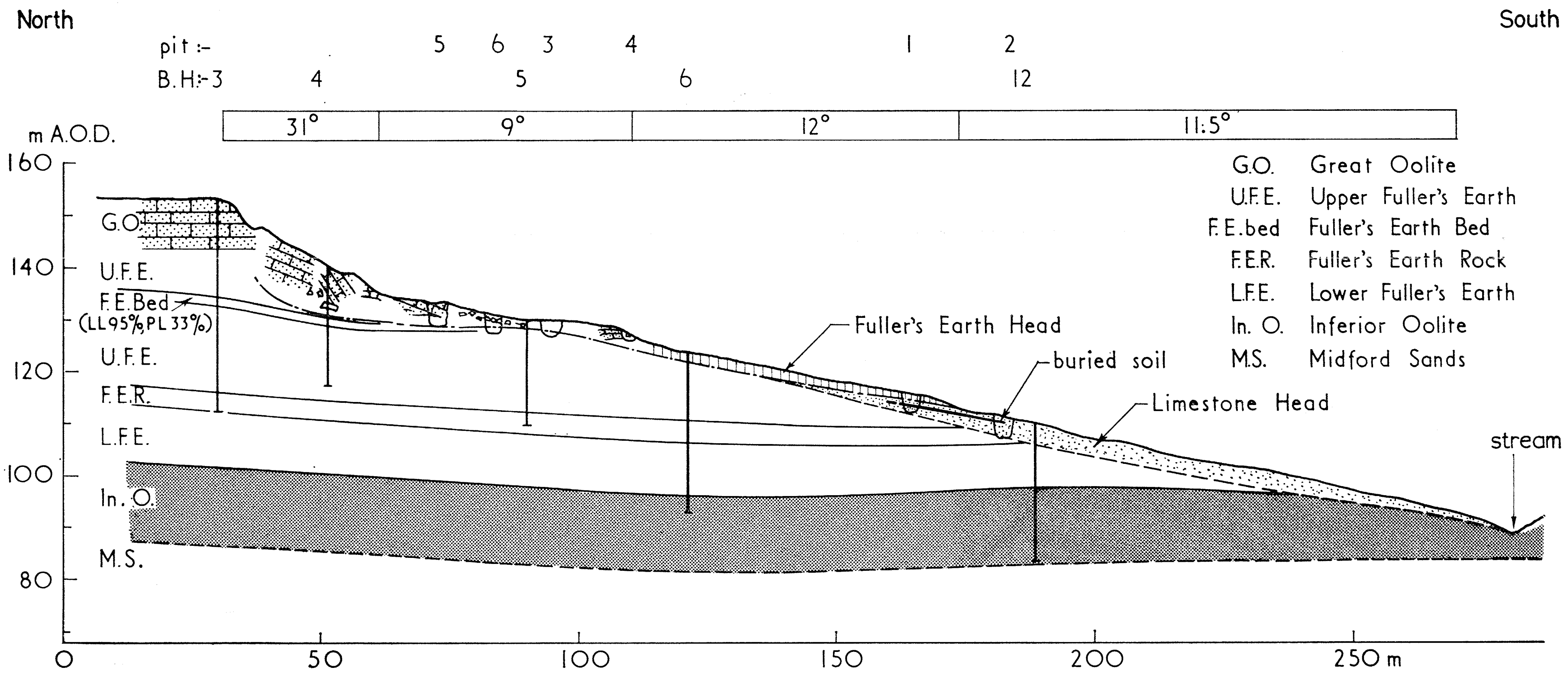

Figure 11. Horsecombe Vale, section 1.

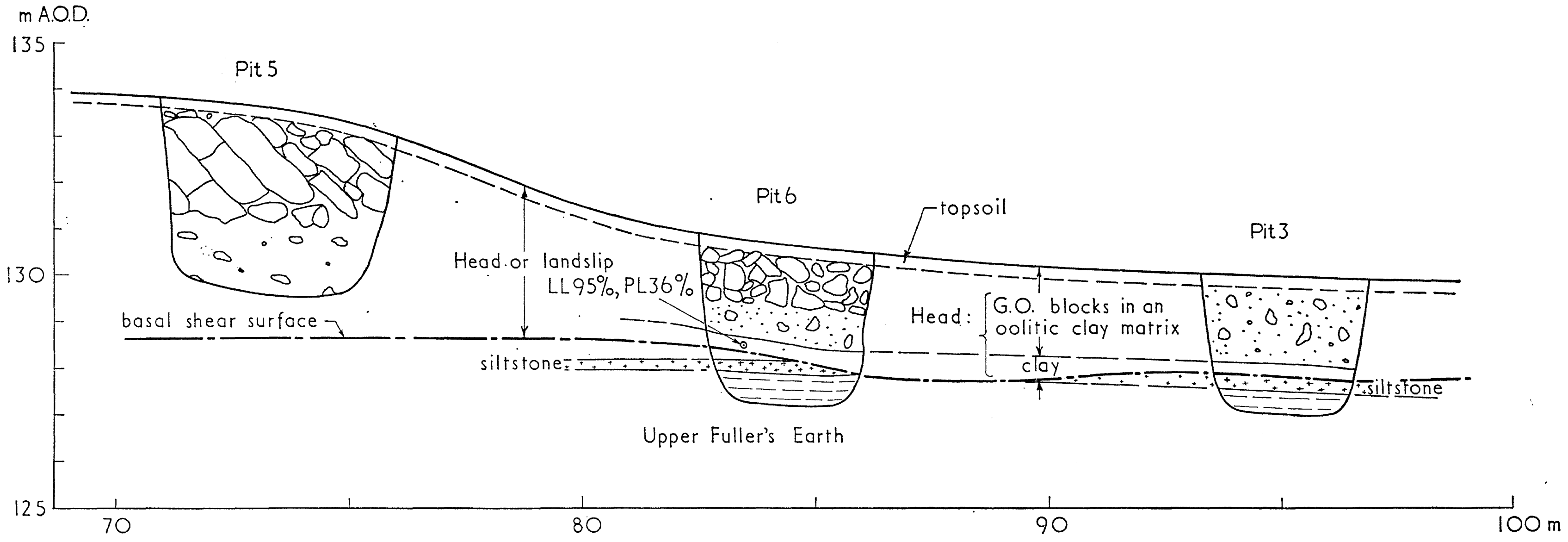

FIGURE 12. Horsecombe Vale: detail of section 1.

Overlying the limestone Head and extending up the slope apparently to join the clay beneath the Great Oolite rubble, is a layer of clay-rich Head with only a few scattered small pieces of limestone. Index properties measured in samples taken from pit 1 (figure 13) prove that most of this Head has been derived from the Fuller's Earth Bed with some additional material from the Upper Fuller's Earth. The clay Head terminates in a lobe and has a pronounced hummocky surface, from which it may be concluded that the layer is in a state of limiting equilibrium under present-day conditions.

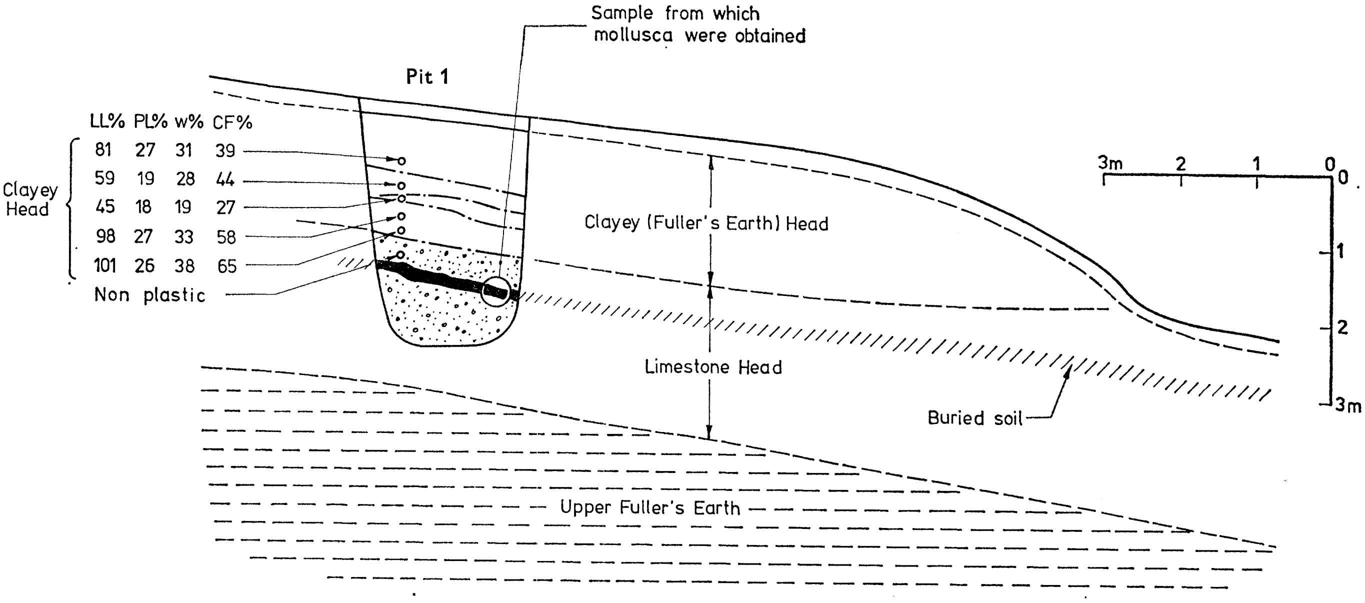

FIGURE 13. Detail of 'solifluction' lobe, Horsecombe Vale, section 1.

TABLE 6. HORSECOMBE VALE, PIT 1, DEPTH 2.4 m; MOLLUSC FAUNA

Cochlicopa sp.	1
Helicella itala (L.)	6
Hygromia hispida (L.)	11
Punctum pygmaeum (Draparnaud)	1
Pupilla muscorum (L.)	1
Vallonia costata (Müller)	8
V. pulchella (Müller)	4
total specimens in 1 kg =	32

Piezometer observations in Horsecombe Vale were made only in the autumn of 1971. They showed the limestone Head to be free-draining; and the pore pressure ratio r_u in the Fuller's Earth Head was found to be not greater than about 0.2, this relatively low value perhaps being due to underdrainage by the limestone Head. As in Swainswick valley, the Fuller's Earth Rock and the Inferior Oolite also had very small or zero pore pressures. Finally, a piezometer in BH 4 at a depth of $6\frac{1}{2}$ m in the foundered Great Oolite showed a maximum pore pressure corresponding to about $1\frac{1}{2}$ m of water, or a value of r_u equal to about 0.1.

6. SLOPE STABILITY

In virtually all the segments of the Swainswick valley slopes with which we are concerned the inclination remains essentially constant and the colluvium or Head has a more or less uniform thickness, small in comparison with the length and width of the segment. Moreover, the ground water level is at an approximately constant depth below the surface. Under these conditions slope stability can be assessed by a simple two-dimensional analysis of an element or 'slice' on the sides of which the forces are taken as being equal and opposite in magnitude and direction.

The shear stress on a plane parallel to the slope at a depth z beneath the surface is then

$$\tau = \gamma z \sin\beta\cos\beta, \tag{1}$$

where γ is the unit weight of the material and β is the slope angle. Similarly, the stress normal to this basal slip surface (actual or potential) is

$$\sigma = \gamma z \cos^2\beta.$$

And if the pore water pressure at this depth is u then the effective normal stress is

$$\sigma' = \sigma - u = \gamma z \cos^2\beta - u$$

or

$$\sigma' = \gamma z\,(\cos^2\beta - r_u),$$

where r_u is the pore pressure ratio.

On a plot representing the variations of shear strength s with effective stress normal to the shear surface the failure envelope in most clays shows some curvature at small values of σ'. But within the rather small stress range relevant to a group of slopes such as those at Swainswick, the relation can be linearized with sufficient accuracy by the Coulomb–Terzaghi equation

$$s = c' + (\sigma - u)\tan\phi',$$

where c' is the apparent cohesion and ϕ' is the angle of shearing resistance. The shear strength which can be mobilized along a plane at depth z, parallel to the slope, is therefore

$$s = c' + \gamma z\,(\cos^2\beta - r_u)\tan\phi'. \tag{2}$$

In general, the available shear resistance may be equal to, or exceed, the shear stress. In the latter case the slope can be said to have a factor of safety F, defined by the ratio

$$F = s/\tau.$$

Substituting the foregoing expressions for τ and s, and rewriting the resulting equation in non-dimensional terms, we have

$$\sin\beta\cos\beta = \frac{1}{F}\left[\frac{c'}{\gamma z} + (\cos^2\beta - r_u)\tan\phi'\right]. \tag{3}$$

Clearly if the slope is in a state of limiting equilibrium, $F = 1.0$. In stable slopes, i.e. those with a reserve of strength, F is greater than 1.0.

Back-analysis of unstable (limiting equilibrium) colluvial slopes and reactivated landslides has shown that the appropriate strength parameters c' and ϕ' are those corresponding to the residual strength as measured on pre-existing shear surfaces (Skempton 1964). To determine the residual strength parameters drained shear box tests were carried out on samples in which a plane had previously been cut (figure 14). Each test was repeated several times. Within the range of effective stress relevant to the Swainswick slopes ($\sigma' = 15$ to $60\,\mathrm{kN/m^2}$) the parameters for Fuller's Earth Head are found to be

$$c' = 2\,\mathrm{kN/m^2}, \quad \phi' = 13.5°.$$

Similar tests on the Lias clay, taken in conjunction with results from back-analysis of slopes in the Lias clays of the East Midlands (Chandler 1976), give the following slightly lower strength parameters:

$$c' = 1.5\,\mathrm{kN/m^2}, \quad \phi' = 12.5°.$$

The unit weight of the clayey Head deposits varies little from $20\,\mathrm{kN/m^3}$, which, as previously noted, is almost exactly twice the unit weight of water ($9.8\,\mathrm{kN/m^3}$).

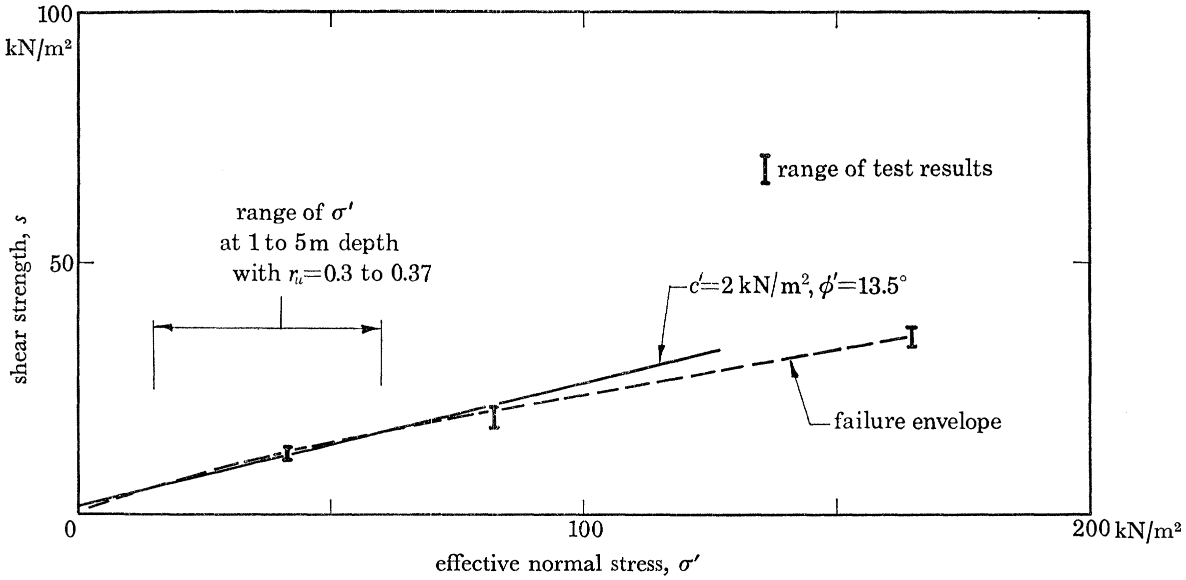

FIGURE 14. Tests to determine the residual strength of Fuller's Earth Head.

With the foregoing data on shear strength, and by using the piezometric observations of pore pressure, it is now possible to calculate the factor of safety for several representative slope segments; and where the field evidence suggests that these are in, or close to, a state of limiting equilibrium under present climatic conditions the correct value of F should be around 1.0. Three segments in the Fuller's Earth slopes will first be considered.

(i) The $15\frac{1}{2}°$ slope in the upper part of section 3. Here the Head or colluvium is about 1 m in thickness, and the slope appears to be only marginally stable. Certainly there is active instability just below the Inferior Oolite outcrop (figure 7) and the $15\frac{1}{2}°$ segment above the outcrop is probably standing at its steepest possible angle. It has a length, measured downslope, of about 100 m.

(ii) The $11\frac{1}{2}°$ segment of section 4 (figure 8). In stratigraphy and in the absence of cambering this is similar to the comparable segment of section 3, but the slope appears to be more 'mature', with a greater thickness of Head (3 m) and a less steep inclination. The hummocky and undulating topography provides strong evidence, nevertheless, that landsliding has occurred in comparatively recent times and the factor of safety under present day conditions cannot be appreciably greater than 1.0. The downslope length of this segment is about 60 m.

(iii) The upper part of section 1 (figure 4). For a length of more than 200 m the ground is hummocky and undulating but maintains a constant overall inclination of 9°. The Head in this segment is about 5 m in thickness.

The factors of safety calculated from equation (3) and using values of r_u derived from figure 9 are given in table 7. They differ from a value of 1.0 by amounts which are considered to be insignificant in view of the limited data available, and therefore provide independent evidence that each of the three slope segments are only marginally stable despite the considerable range of inclinations.

TABLE 7. SLOPE STABILITY ANALYSIS

case	section*	substratum	slope β	depth of colluvium, z/m	pore pressure ratio r_u	shear strength parameters c' kN/m²	ϕ'	calculated factor of safety F
(i)	S 3	Fuller's Earth	$15\frac{1}{2}^\circ$	1	0.30	2	$13\frac{1}{2}^\circ$	0.97
(ii)	S 4	Fuller's Earth	$11\frac{1}{2}^\circ$	3	0.33	2	$13\frac{1}{2}^\circ$	0.95
(iii)	S 1	Fuller's Earth	9°	5	0.37	2	$13\frac{1}{2}^\circ$	1.07
(iv)	S 1	Fuller's Earth over In. O.	9°	3	0.15	2	$13\frac{1}{2}^\circ$	1.50
(v)	S 1	Lias clay	10°	3	0.33	$1\frac{1}{2}$	$12\frac{1}{2}^\circ$	0.98
(vi)	H 1	Fuller's Earth	12°	2	0.20	1	12°	0.92

* S, Swainswick valley; H, Horsecombe Vale.

Thus it appears that the limiting or critical slope angle is related to the thickness of colluvium or Head, becoming smaller as the thickness is greater; and this follows directly from the facts that with increasing depth the strength ratio s/σ' decreases while the pore pressure ratio r_u increases. Numerous field observations have shown, however, that for any particular clay stratum there is a rather well defined lower bound to the angle of slope on which relatively shallow landslide movements can occur under present conditions: e.g. 9° in Lias clays (Chandler 1970) or 8° in London Clay (Hutchinson 1967). From the Swainswick slopes it now seems that these 'angles of ultimate stability' (Skempton & Hutchinson 1969) are found where the depth of weathering, or thickness of colluvium, has reached its maximum extent.

(iv) The fourth case to be analysed is that of the lower 9° segment in section 1, which is about 100 m in length. Here the Head has an average thickness of about 3 m and lies only a few metres above the cambered Inferior Oolite. The observed pore pressure ratio is around 0.15, which leads to a factor of safety of 1.5 (table 7); a result in accordance with the completely stable appearance of this segment. But the Head has evidently moved downslope at some time in its history, and it can readily be shown that this could have happened only if the pore pressures rose to the full 'hydrostatic' value, corresponding to $r_u = 0.48$. Such a condition might obtain in a period of prolonged and exceptionally heavy rainfall, but more probably it was due to temporary increases in pore pressure consequent upon the melting out of ice lenses during a phase of periglacial activity.

(v) The last of the Swainswick slopes to be considered is the 10° segment in the Lias clays near the foot of section 1. This has a length of about 150 m and exhibits subdued undulation indicating the presence of shallow landsliding which has probably not been active in the recent past. The depth of sliding or thickness of the colluvium is not known with certainty in this segment, but from pits and borings in the vicinity a figure of 3 m is reasonable. The calculated factor of safety (table 7) is approximately 1.0, as would be expected.

Brief consideration may finally be given to the Horsecombe Vale section. The limestone Head slopes at $11\frac{1}{2}°$ and is a granular, free-draining material which must be stable under present conditions. There can be little doubt that it is a periglacial solifluction deposit and, indeed, it contains a fossil soil of Late-glacial age.

(vi) The Fuller's Earth Head has an average inclination of 12° and is 2 m in thickness (figure 11). It is obviously in a state of limiting equilibrium. The piezometric observations were not continued for a sufficient time properly to establish maximum values, but the indication is that the pore pressures are lower than in comparable segments of the Swainswick slopes, with a value of r_u not exceeding 0.2. Cut-plane tests on a sample of this Head deposit gave the following residual strength parameters at the relevant effective stress level ($\sigma' = 30\ \text{kN/m}^2$):

$$c' = 1\ \text{kN/m}^2, \quad \phi' = 12°.$$

The calculated factor of safety is 0.92 (table 7); a result which is rather less than the expected value of about 1.0, probably as a consequence of the exceptionally high plasticity (liquid limit = 98, plastic limit = 29) of the sample tested.

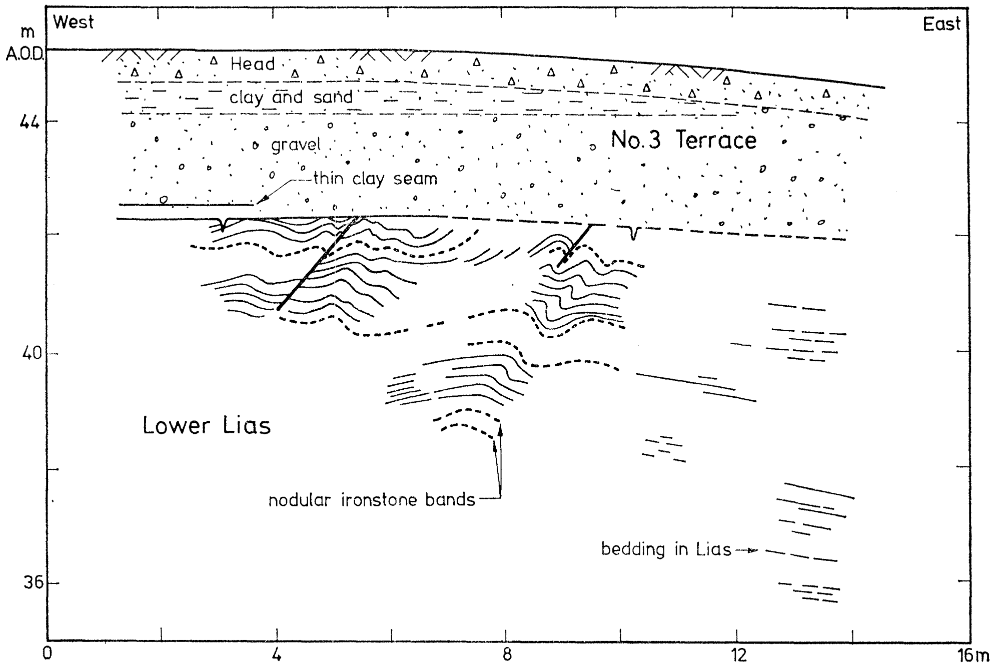

FIGURE 15. Section at Victoria Pit, Twerton, near Bath (1948).

7. STAGES OF SLOPE DEVELOPMENT

It is evident that the slopes in the Bath area are not the products of a uniform set of processes acting under climatic conditions similar to those of the present day. A complete reconstruction of the stages of slope developmet is not possible. However, we can elucidate part of the history of the Avon valley by relating several independent lines of evidence to the chronology of the river terraces. The results are shown in table 8.

Cambering

The Victoria Pit at Twerton is now completely degraded but about twenty-six years ago the section sketched in figure 15 could be seen. This shows contortions and minor faults in the Lower Lias clay beneath undisturbed deposits of no. 3 Terrace. The disturbances in the Lias are very probably associated with cambering, and may well be dip-and-fault structures. If this is correct, cambering must have occurred before the deposition of no. 3 Terrace, and therefore at a stage earlier than the Ipswichian Interglacial when the River Avon was flowing at a height about 27 m above its present level. This suggests that the disturbances were formed during the Wolstonian (or the preceding Anglian) Glaciation. Moreover, subsequent deepening of the valley in post-Ipswichian times has caused no further disturbances at the Twerton site.

In the Swainswick valley, as at Limpley Stoke and Bathampton Down (Hawkins & Kellaway 1971), there are also strong indications that cambering must have been largely if not entirely completed in a comparatively remote epoch. Thus the most severe cambering occurs in the relatively gentle slopes of sections 1 and 2, where the strata are disturbed to depths of 30–40 m; but cambering is virtually absent and disturbance is far less pronounced in the steeper and actively degrading slopes in section 3. The clear implications are that cambering is not taking place under present, or more generally under Postglacial, climatic conditions; and that sections 1 and 2 are to a significant degree 'fossil' slopes, the upper parts of which have been left with only superficial changes since their formation in pre-Ipswichian times.

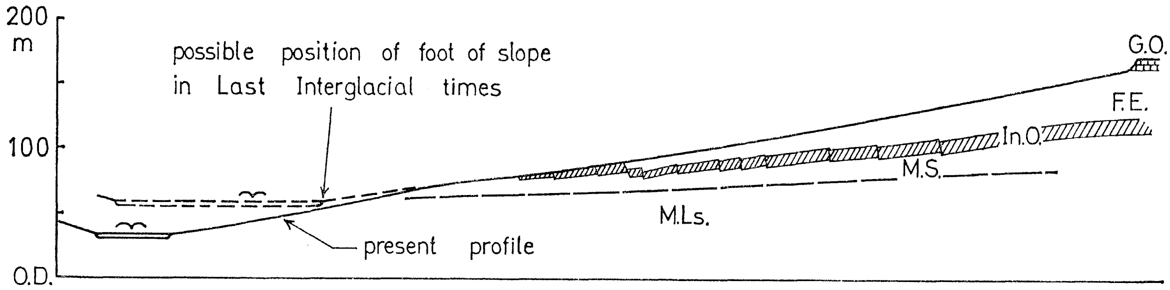

FIGURE 16. Diagram indicating manner by which a cambered slope can be left almost undisturbed by subsequent stream erosion; based on Swainswick section 1.

Figure 16 illustrates the manner in which such a state of affairs might be brought about. By the end of the Ipswichian Interglacial the stream is assumed to have formed a valley floor at about the same height above present alluvium as no. 3 Terrace of the Avon, and the slope, already cambered, rises up from the valley floor at an inclination not very different from that existing today. Subsequent erosion at this section is presumed to have been accompanied by a movement of the stream in a direction away from the slope, thereby leaving the upper, cambered part substantially unaffected in post-Ipswichian times. If, by contrast, the stream had undercut the slope much of the cambering could have been removed by landslipping, as may have happened at section 3.

Valley bulging

At a site about 1 km northwest of Keynsham at the confluence of the Rivers Chew and Avon (figure 1) sharply folded Lias clays, first described by Tutcher (1923) and shown in figure 17, plate 7, were found to be planed off by the bench of Avon no. 2 Terrace, and the overlying

FIGURE 17. Valley-bulge structure in Lias clay near Keynsham. Undisturbed gravels of the overlying no. 2 Terrace had been removed by excavation before the photograph was taken (photo by J. W. Tutcher *ca.* 1922). The section is $6\frac{1}{2}$ m high.

gravels (which had been removed by excavation when the photograph was taken) were horizontally bedded; though with some shallow involutions, presumably due to Devensian cryoturbation. The structures in the Lias are typical of valley bulging (Leese, Ross & Vernon 1959) and do not conform with the tectonic 'style' of the Jurassic strata in this region, characterized by simple concentric folds.

Now no. 2 Terrace is almost certainly of mid-Devensian age. If this correlation is correct, the valley bulging at Keynsham preceded the main cold phase of the Devensian. We are therefore again led to the conclusion that the intense subsurface disturbances in the valley of the Avon and its major tributaries took place during the Wolstonian or some earlier glacial period (Hawkins & Kellaway 1971; Kellaway 1972).

Landslips

It is possible that landslips may have taken place at periods when the Avon was at a higher level than it is today; but the large landslips which can still be seen in the Bath area, such as those at Bailbrook, Beacon Hill and Beechen Cliff, are closely related to recent positions of the river. A landslip west of the Victoria Pit at Twerton is of particular interest as field mapping shows that it pre-dates the aggradation of no. 1 Terrace, but involves a slope in the Lias clays which clearly post-dates the deposition of no. 3 Terrace. The slip, in plan, has a width of about 700 m and extends more than 300 m up the slope above no. 1 Terrace. The depth of the basal shear surface has not been determined, though the relation of the slip to no. 1 Terrace suggests that it occurred when the Buried Channel was being eroded. Kellaway & Taylor (1968) consider the Beacon Hill and Beechen Cliff slides also to be of this age. Moreover, it may be noted that Ackermann & Cave (1967) mention several large slips in the Frome valley which have displaced the Cainscross Terrace, and are therefore later than Middle Devensian.

Landsliding has continued until modern times in the Bath region, though apparently not on the same scale as these Late Devensian movements. The topography of the upper slopes of Solsbury Hill, for example, is characteristic of shallow landslides probably reactivated in Late-glacial times and not yet in a state of permanent stability. Part of the Beacon Hill slip moved again in 1790 (Kellaway & Taylor 1968); several slides occurred in the exceptionally wet winter of 1799–1800 (Phillips 1844); and numerous mudflows have been reported in the Bath–Bristol area following very heavy rainfall in July 1968 (Hawkins 1973).

Head

There can be little doubt that the slopes, as they existed at the end of the Wolstonian period, were covered with Head formed by periglacial solifluction processes, but to what degree any of these deposits have survived subsequent erosion of the valleys is not known. However, it seems probable that at least some of the Head still blanketing the slopes can be tentatively correlated with the Early or Middle Devensian. This conclusion is based upon analogy with extensive solifluction gravels on the southern slope of Bredon Hill, near Tewkesbury, which grade into the basal deposits of the Beckford Terrace of Carrant Brook, a tributary stream of the Warwickshire Avon. The Beckford Terrace must be of Middle Devensian age, as an organic silt layer within fluvial sands overlying the basal gravels has been dated by radio-carbon assay to 27600 years B.P. (Briggs, Coope & Gilbertson 1975). In a similar manner Devensian periglacial solifluction gravels, which certainly pre-date the Late-glacial Interstadial (*ca.* 12000 years B.P.), lie on the slopes of the clay vale south of the Lower Greensand escarpment near Sevenoaks, in

Kent, and have been subjected to little subsequent erosion (Skempton & Weeks 1976). It therefore seems reasonable to suppose that much of the Head on slopes such as those in sections 1 and 2 in Swainswick valley, which are not being actively eroded, may have been formed at about the same time.

It is clear, nevertheless, that the Fuller's Earth Head and a small amount of the limestone Head in Horsecombe Vale have been deposited later than the Late-glacial Interstadial, since they lie stratigraphically above a fossil soil which, from its mollusc fauna, can be dated to this stage. In all probability these Head deposits were formed during Zone III of the Devensian Late-glacial, a short but important phase of periglacial activity which has been dated by radiocarbon assay to the period from about 10800 to 10000 years B.P. A more recent episode of Head formation, on a much smaller scale, is recorded by the material which has partially infilled a gully on the lower slopes near section 1 and in so doing has buried an organic silt layer dated 3070 years B.P. (figure 5).

Table 8. Quaternary correlations

				River Avon at Bath	
stage			valleys		height above alluvium (m)
Flandrian			minor landslips	Alluvium	
Devensian	Late	III	Head	no. 1 Terrace	3
		L-g Inst.	fossil soil		
			large landslips	Buried Channel	
	Middle		Terrace at Keynsham trims off valley bulge	no. 2 Terrace	12
	Early		Head		
Ipswichian			Terrace at Twerton on cambered strata	no. 3 Terrace	27
Wolstonian and earlier			major period(s) of downcutting, cambering and valley bulging	—	

8. Conclusions

(1) There is evidence to suggest that cambering in the valley slopes of the Avon and its tributaries occurred prior to the Last (Ipswichian) Interglacial. A similar conclusion applies to the valley-bulging near Keynsham.

(2) During the Devensian period the river lowered its valley floor by about 27 m in the Bath area. This downcutting appears to have been associated with little if any cambering, but it caused several large landslips. At least one of these, at Twerton, can be dated with high probability to the Buried Channel phase corresponding to the main glacial stage of the Late Devensian.

(3) At sections 1 and 2 in the Swainswick valley the cambered slopes have been influenced only slightly by post-Ipswichian erosion. Disturbances of the strata in these sections penetrate to depths of 30 or 40 m.

(4) At section 3 in Swainswick valley, where the stratigraphy and topographic relief are almost identical to sections 1 and 2, but the slope angle is steeper, there is less disturbance and

virtually no cambering. It seems probable that the disturbed strata have largely been removed by subsequent erosion. The upper, very steep slopes of this section are still subject to shallow landsliding or mudflows.

(5) The slopes in the Swainswick valley and Horsecombe Vale are blanketed by colluvium or Head varying in thickness from 1 to 5 m. The upper part of the Head in the latter valley includes a fossil soil of Late Devensian age, and more generally it is probable that much of the colluvium was formed in Devensian times. At some localities, however, Head has been deposited more recently; for instance in a gully in the lower slopes of Solsbury Hill, perhaps as a consequence of forest clearance since Neolithic times. The process continues intermittently up to the present day.

(6) Field evidence and stability analyses indicate that the angle of limiting equilibrium in slopes in the Fuller's Earth tends to become smaller as the thickness of colluvium is greater. This is due to the facts that the pore pressure ratio increases with depth and the strength ratio decreases. Thus it is possible to have slopes at 15° with 1 m of colluvium, at 11° with 3 m, and at 9° with 5 m; all in a state of limiting equilibrium under present climatic conditions. The lowest of these slope inclinations may represent the angle of ultimate stability for this material.

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Discussion

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The overall strategy of the day's discussion, as I have understood it, seems to be (i) to establish the character of the failure; (ii) from knowledge both of the failure and surrounding environment to establish the approximate time of the initial event; (iii) by inference from climate to generate a causal explanation for the failure. Only the professional engineer is competent to deal with the first stage, but some comments on (ii) and (iii) may be in order. There seem to be three weaknesses in the overall line of reasoning which need fresh investigation. The first of these is the use, without supplementary information, of river terraces and similar morphogenetic forms for dating. River terraces are notoriously inadequate on the grounds of (*a*) improper knowledge of characteristic long profiles, (*b*) problems of height correlation and (*c*) problems of changes of profile and regime which are completely unrelated to climatic changes, notwithstanding the difficulty of spatial correlation of sediment types, which have not been applied today. The second is the use of various inferences concerning climate from sediments. Once again the term 'Head' is used both in a genetic and generic sense. The climatic circumstances in which chert gravels can be carried 5 km across surfaces of low inclination certainly bear more investigation. Thirdly, even if we accept the grouping in time of initial failures, the climatic association is likely to be much more complicated than has been suggested. I note, by way of illustration, that in the October 1973 intense floods of southeast Spain massive failures took place over an area about four times the size of the English Weald in a single storm. Here many of the slopes had been oversteepened by high-frequency but relatively low-magnitude events, including, for example, winter frosts. Presumably the slopes are being maintained at a steep angle by virtue of strong pore-water tensions. Is it not equally possible that a few high magnitude, infrequent events in southern Britain during the Late Glacial could have comparable effects, especially if it could be shown that they were preceded by long dry spells? Certainly there is need, if we are to follow this overall induction, for a much better appreciation of the magnitude and frequency problem. Finally, I repeat the point about spatial variability. In seeking causative links one has to remember that 20 m of gravelly slope deposit in one place may be a very poor climatic indicator unless the possibility of local causative factors can be discounted. Not surprisingly, the incidence of erosion is also spatially varied, so that its appearance in one or two sections is of doubtful utility. In modelling the controls on hillslope form spatial variations in the probability of particular events, such as the occurrence of high positive pressures, must be taken into account.

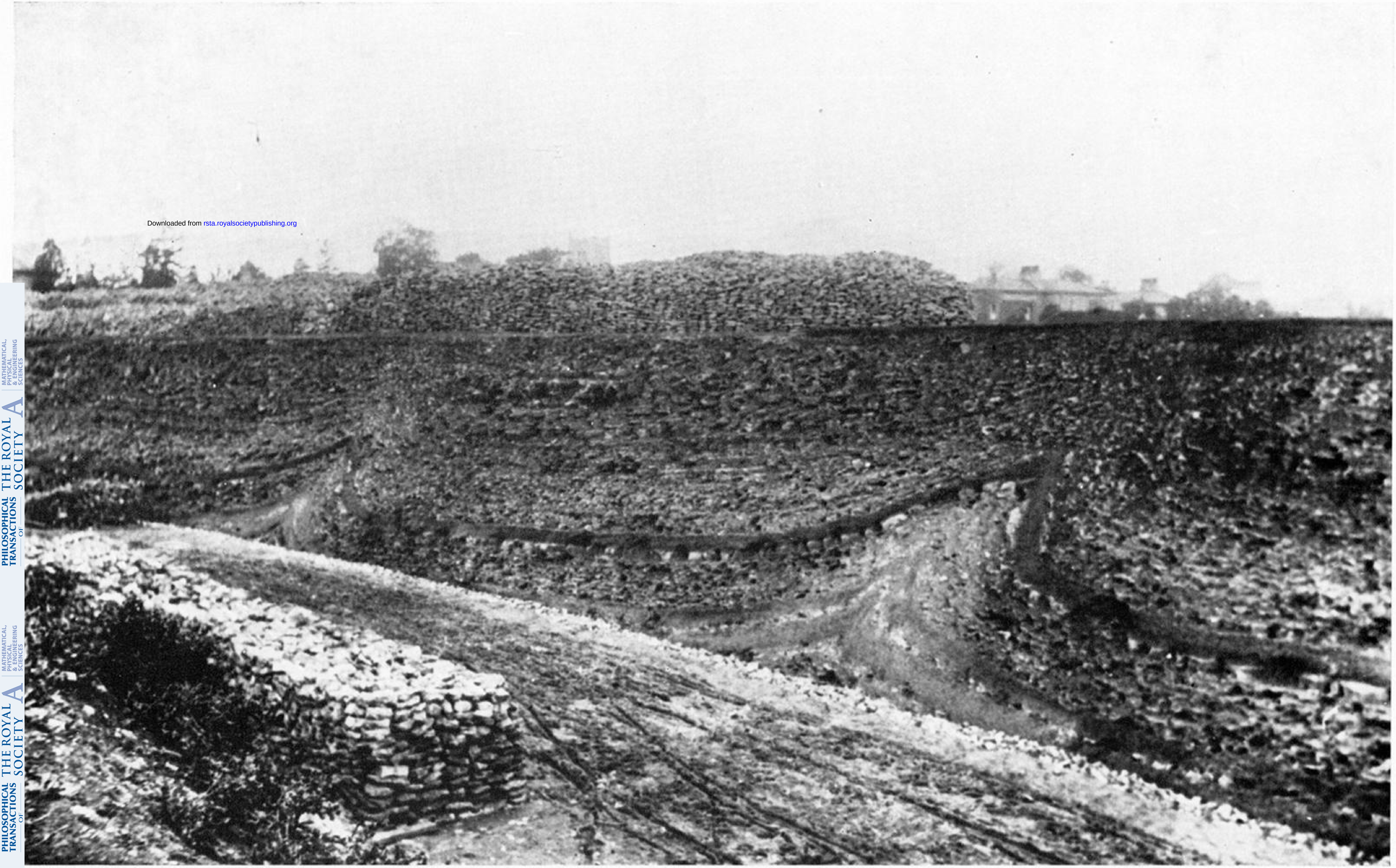

FIGURE 17. Valley-bulge structure in Lias clay near Keynsham. Undisturbed gravels of the overlying no. 2 Terrace had been removed by excavation before the photograph was taken (photo by J. W. Tutcher *ca.* 1922). The section is $6\frac{1}{2}$ m high.