PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Quaternary History of the Lower Greensand Escarpment and Weald Clay Vale near Sevenoaks, Kent [and Discussion]

A. W. Skempton and B. C. Worssam

Phil. Trans. R. Soc. Lond. A 1976 **283**, 493-526
doi: 10.1098/rsta.1976.0094

Phil. Trans. R. Soc. Lond. A. **283**, 493–526 (1976) [493]
Printed in Great Britain

The Quaternary history of the Lower Greensand escarpment and Weald Clay vale near Sevenoaks, Kent

By A. W. Skempton, F.R.S.
Department of Civil Engineering, Imperial College, University of London

and A. G. Weeks
A. G. Weeks & Partners, Maidstone; formerly Materials Engineer, Kent County Council

[Plates 5 and 6]

In the neighbourhood of Sevenoaks Weald many of the small hills and ridges standing up to 20 or 30 m above the streams in the clay vale south of the Lower Greensand escarpment are capped by Head deposits consisting of angular chert fragments, and other stones derived from the Greensand, set in a clay matrix. These deposits extend for a distance of at least 2 km from the escarpment, forming dissected remnants of what were originally extensive sheets, inclined at gradients of about 1.5°. The available evidence suggests they are periglacial solifluction deposits of Wolstonian age. Probably at about the same period large-scale structural disturbances occurred in what are now spurs of the escarpment; massive blocks of the Hythe Beds subsided into the underlying Atherfield and Weald Clays, and the clays were forced up at the foot of the scarp in the form of bulges.

Following this stage considerable erosion took place in the vale, accompanied by retreat of the escarpment within embayments between the spurs. On the eroded landscape solifluction debris moved up to 1 km from the scarp face during the Devensian period. This deposit again consists predominantly of clay with embedded angular chert fragments. It is about 2 m thick, with a minimum gradient of a little more than 2°, and overlies brecciated Weald Clay which typically contains several slip surfaces in its uppermost layers. Landslips in the escarpment within the embayments probably occurred at about the same time.

Not long afterwards, in the Late-Devensian Interstadial, around 12000 radiocarbon years B.P., a soil formed of which traces can be found buried beneath a lobate solifluction sheet. The lobes extend over the lower sheet for distances of 300 m from the scarp foot at an average slope of about 7°. In the subsequent Postglacial period only minor changes have taken place; some escarpment landslips have been reactivated and the streams in the vale have eroded small channels or valleys not more than 4 m deep.

Based on thaw-consolidation theory, and by using measured properties of the clays, calculations are presented which provide a reasonable explanation, in terms of soil mechanics principles, for solifluction movements of the active layer above permafrost on slopes inclined at angles as low as 1.5 or 2°. Under temperate conditions, mass movements are possible only on slopes steeper than about 8°.

The paper includes an account of the longitudinal profiles and stratigraphy of the Eden and Medway river terraces.

1. Introduction

In connection with the design of a new road (A 21) by-passing the town of Sevenoaks, in Kent, site investigations were made in the Lower Greensand escarpment and the clay vale lying to the south. During the course of these investigations the opportunity was taken of amplifying the field work to provide additional data of scientific interest. The main area of study, centred on the village of Sevenoaks Weald (National Grid Reference TQ 528509), is shown in figure 1. and further illustrated by the sections in figures 2 and 3. Most of the trial pits and borings and associated laboratory tests were carried out in the years 1965–6, but several visits have been made subsequently to examine features of the country down to the River Eden, and further information on the escarpment was obtained in 1969 from deep borings near Bayley's Hill and Ide Hill, respectively $1\frac{1}{2}$ and 4 km west of Sevenoaks Weald.

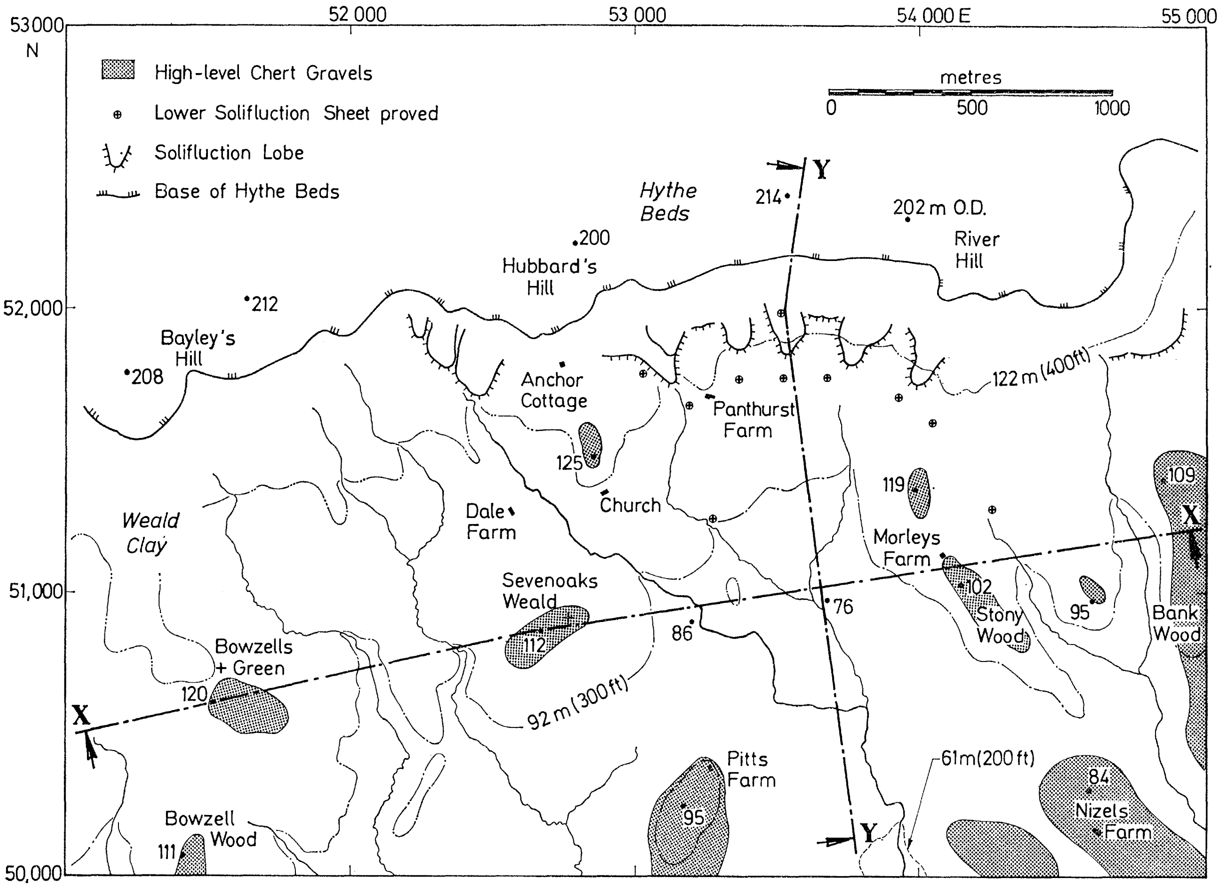


FIGURE 1. Map of the district around Sevenoaks Weald.

The regional setting is shown on the geological sketch map, figure 4. This is based on the Institute of Geological Sciences One-inch map of the country around Sevenoaks and Tonbridge (Sheet 287, first published 1950, partly revised 1971) and on the manuscript Six-inch maps (I.G.S. Library, South Kensington) modified in a few particulars by our own observations. Mr S. Buchan and the late Mr H. G. Dines surveyed the area covered by figure 4 between 1932 and 1936, and the southern part of the map was revised by Dr C. R. Bristow in 1965–6. Many details of the geology of the district are given in the Memoir accompanying Sheet 287 (Dines, Buchan, Holmes & Bristow 1969).

When mapping south of the escarpment, Dines and Buchan were impressed by the drifts of flint and chert-bearing gravels capping numerous small, isolated hills and ridges which rise above the general level of the vale and extend over a wide tract of land nearly to the northern

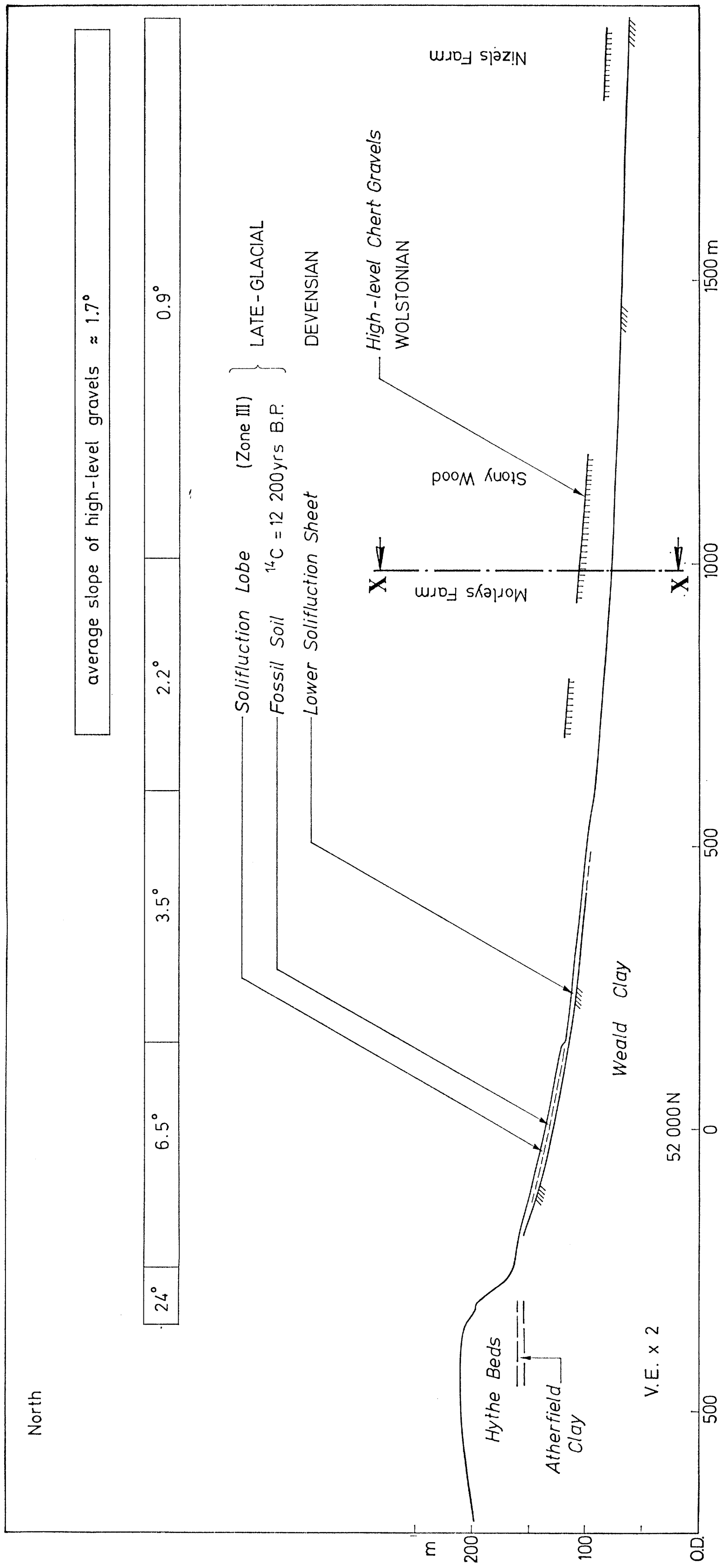


FIGURE 2. Section Y–Y through Lower Greensand Escarpment near Sevenoaks Weald.

limits of the belt of river terraces. In an important paper published jointly with other officers of the I.G.S. (Dines *et al.* 1940), on the subject of Head deposits, they identified the high-level chert gravels as the dissected remnants of a widespread sheet of debris which had been derived from the Lower Greensand and moved south by periglacial solifluction down the gentle slopes of the then existing landscape. They also recognized a dissected fan of Head, composed of flints and flint pebbles with the addition of chert, extending down to Edenbridge from gaps in the escarpment south of Limpsfield. The source of the flints and pebbles has long been attributed to gravels, of which remains still exist, near Limpsfield (Topley 1875); these gravels in turn having been derived mostly from the Chalk escarpment further north.

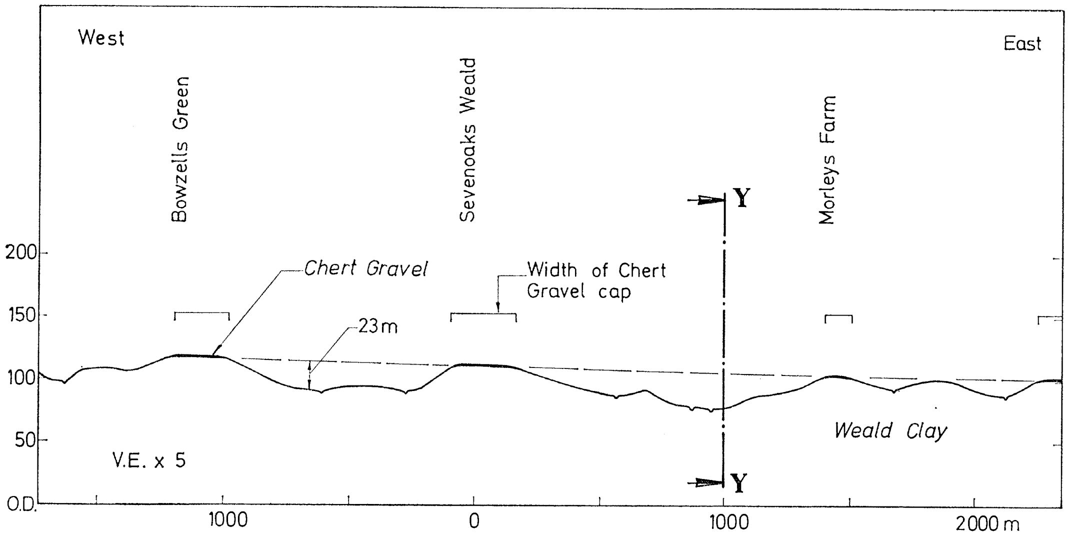


FIGURE 3. Section X–X through Sevenoaks Weald.

The Head deposits were later examined by Bird (1964), who agreed with this interpretation of the chert gravels but suggested that the flint-bearing gravels had been transported by streams, possibly fed by heavy rain or melting snow, rather than by solifluction. More recently, in the Sevenoaks Memoir, high-level flint gravels have been identified above the north bank of the Eden as far east as How Green (1.3 km north of Hever).

Dr Bird also considered the age of the high-level gravels and arrived at the tentative conclusion that they were formed after the development of a valley floor equivalent to the Boyn Hill terrace in the London Basin, which is generally accepted as being of Hoxnian Interglacial age. We have further examined the relation between these gravels and the river terraces, and while broadly agreeing with Bird's conclusion we can show that the gravels are older than the Last (Ipswichian) Interglacial. It therefore seems probable that the period of their deposition can be correlated with the Wolstonian glacial stage. Stratigraphically the high-level chert and flint gravels will be classified as Older Head deposits.

Before the present investigations little information had been available on periglacial solifluction deposits of the Last (Devensian) Glaciation in the area. But evidence can now be given for the existence of chert-bearing gravels, typically 2 m in thickness, spreading off the foot of the scarp face as an almost continuous sheet within the embayment between Hubbard's Hill and River Hill (figure 1) and extending at least 500 m to the south. These gravels can also be traced for considerable distances down some of the valleys. In addition there is a lobate sheet overlying the lower sheet of chert gravels; and in several places beneath the lobes a fossil soil has been found, developed in slope-wash deposits on the lower sheet. The soil is dated by radiocarbon assay to 12200 years B.P. and its formation can therefore be correlated with the Late-glacial Interstadial of the Devensian. The Lower Solifluction Sheet and the Lobes may be grouped together as the Younger Head deposits.

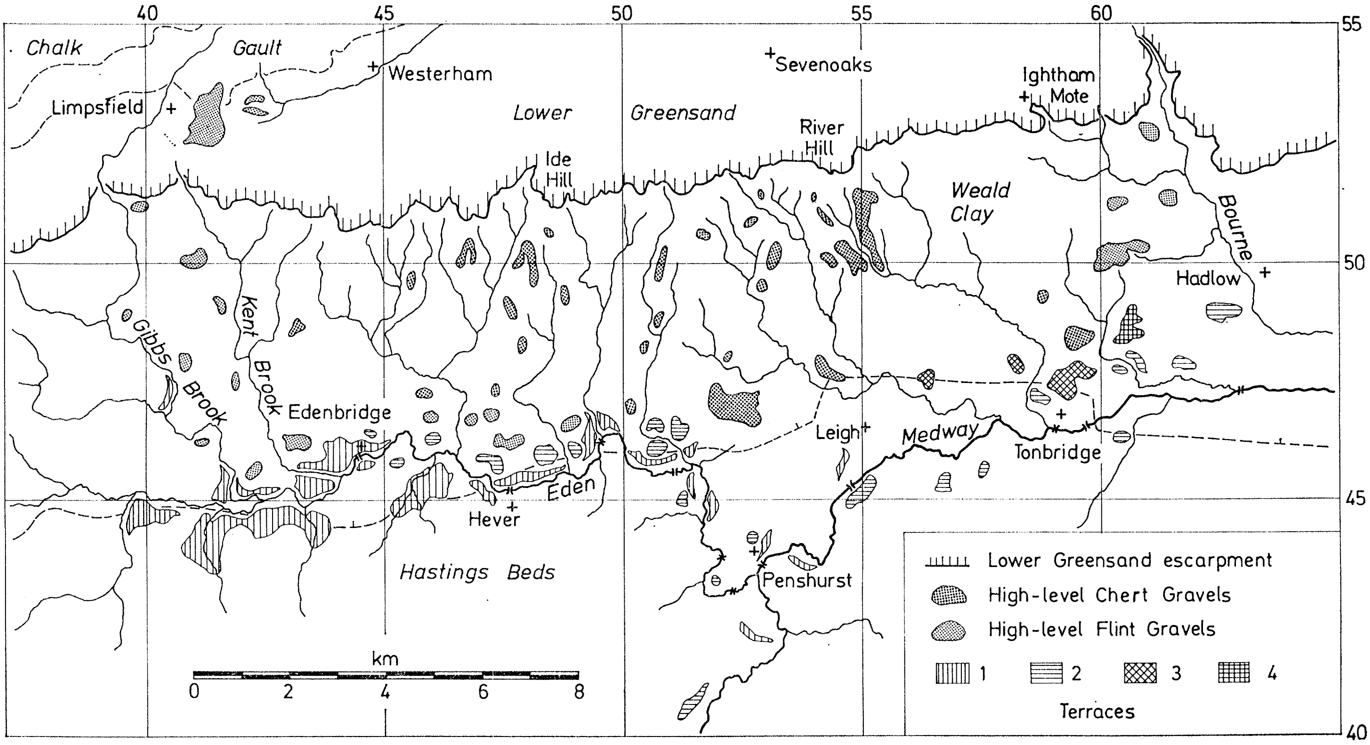


FIGURE 4. Sketch map of the Weald Clay Vale and the Eden–Medway Terraces

Our investigations have also demonstrated structural disturbances at Ide Hill and Hubbard's Hill and landslips in the scarp face within the embayment. The structural disturbances take the form of deep gulls and block subsidence in the Hythe Beds associated with bulging of the underlying clays. It is probable that the greater part of these disruptions of the strata occurred under periglacial conditions during the Wolstonian. Subsequent to that stage there has been much erosion in the clay vale, accompanied by retreat of the scarp face within the embayment. The embayment landslips may have originated in periods of excessively high ground water level brought about by melting snow in the Devensian.

Changes in the landscape of the vale during Postglacial (Flandrian) times appear to have been restricted to erosion by the streams of shallow channels cut in or through the lower solifluction gravels and the formation of small valleys in the Weald Clay, not more than 4 m in depth and floored by narrow belts of alluvium.

Preliminary accounts of the Devensian solifluction deposits and fossil soil, and also of the large-scale disturbances at Hubbard's Hill, have previously been published (Skempton & Petley 1967; Weeks 1969).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

2. Stratigraphy: Cretaceous

The general stratigraphy is set out in table 1. More detailed correlations of the Quaternary deposits will be given later, and are summarized in table 5.

(*a*) *Hythe Beds*

The Hythe Beds form a plateau at an altitude of a little over 200 m above Ordnance Datum. From the northern limit of the plateau the land falls gently in a northerly direction and the southern edge is defined by an escarpment. At intervals along the escarpment there are spurs of relatively stable ground, such as River Hill and Hubbard's Hill (figure 1), which continue to the south as ridges standing above the lower landscape of the clay vale. The old roads of the Weald ascend along these ridges. Between the spurs, or 'hills', the escarpment has been caused to retreat by erosion and takes the form of a wide embayment. Within the embayment between the two hills just mentioned the scarp face is steep, inclined at average angles of 15–25°, and has been subjected to landslipping.

Table 1. General stratigraphy

Quaternary	Alluvium Terraced River Gravels Older and Younger Head deposits	
Cretaceous	Lower Greensand	Hythe Beds Atherfield Clay
	Wealden Beds	Weald Clay Hastings Beds

The Hythe Beds have a thickness of about 45 m beneath the escarpment crest. They consist of sands and sandstones, buff or pale greenish grey in colour (known as 'Hassock'), sandy limestone (the 'Kentish Rag', much used in the past as building stone) and, in the upper parts of the formation, bands of chert up to 15 cm in thickness. The chert is extremely resistant to weathering; it is found as broken, angular or sub-angular fragments in the Head deposits and river gravels. The sandy beds are uncemented but can have a considerable clay content, especially near the base of the formation. Index properties of two representative samples are given in table 2; the clayey sand is typical Hythe Beds material between two Ragstone layers, and the other sample was taken near the base.

In logging the trial pits and borings the transition from Hythe Beds to the underlying Atherfield Clay was assumed to occur at a change from the buff or khaki coloured basal clay to a more plastic grey-brown clay. To check the validity of this and other lithological boundaries Mr D. J. Carter, of the Department of Geology at Imperial College, kindly carried out a micro-palaeontological examination of two continuous cores taken through the basal layers of the Hythe Beds down to the Weald Clay. He reports (private communication) that so far as the Hythe/Atherfield junction is concerned the true boundary is marked by an alteration from foraminifera indicating a muddy, perhaps brackish water environment in the Atherfield Clay to a fully marine fauna in the Hythe Beds. In both cores this boundary occurred about 40 cm lower than the lithological change noted above. To this extent, then, there is probably a consistent error in plotting the base of the Hythe Beds (e.g. in figures 19–21).

(*b*) *Atherfield Clay*

Where the Atherfield Clay is not greatly affected by structural disturbance or landslipping near the foot of the scarp face, borings show that it is about 8 m in thickness, reaching a maximum of 12 m at Ide Hill. Its outcrop is generally obscured by Head deposits.

Two distinct facies can be recognized: an upper clay of medium to high plasticity, and a lower silt. Both are grey in colour. The lithological difference is clear and, in the cores examined by Mr Carter, the microfauna indicate a change at this boundary from marine conditions in the silt to a muddy or brackish water environment in the clay. Index properties were determined on a number of samples from both facies; typical values are given in table 2 together with the range of liquid limit. The clay facies has a 'clay fraction' (particles smaller than 2 μm) of about 65 % of the dry mass.

Table 2. Index properties

	water content	liquid limit	plastic limit	plasticity index
Head deposits				
Slope-wash	35	65 (60–75)	28	37
Chert Gravels matrix				
Lobe	25	42 (40–45)	24	18
Lower sheet	28	52 (40–65)	26	26
Flint Gravels matrix	—	27	17	10
Hythe Beds				
clayey sand	19	31	24	7
Basal bed	28	64	24	40
Atherfield Clay				
clay	30	85 (65–95)	30	55
silt	19	35 (30–40)	18	17
Weald Clay				
brecciated	27	60 (40–80)	23	37
undisturbed	23	60 (40–80)	23	37

(*c*) *Weald Clay*

The Weald Clay is a massive deposit, up to 300 m in thickness, the outcrop of which forms the clay vale of the northern Weald of Kent. The vale extends 4–6 km from the escarpment towards the Rivers Eden and Medway. In this distance its altitude falls from about 150 to 40 m above O.D. The regional dip is northerly and varies from 2° or 3° under most of the vale to almost zero under the Hythe Beds plateau. A fault separates the Weald Clay from the outcrop of the Hastings Beds, which rise to form high land south of the rivers.

Characteristically the clays are brackish or freshwater deposits displaying fine laminations or silt partings which often show steep bedding planes and other sedimentary structures. But the laminated clays can alternate with more homogeneous, fissured clays of higher plasticity, presumably laid down in deeper water and there are occasional layers of siltstone and limestone. Ironstone modules also occur. In its unweathered and undisturbed state the Weald Clay is dark grey in colour with water contents usually at, or slightly below, the plastic limit. Where it has been exposed to weathering the clay is oxidized to a brown colour.

Beneath the solifluction gravels, for depths of several metres, the clay is brecciated. In this state it consists of small lumps of intact clay in a matrix of almost completely reworked, softer clay. At some sections the uppermost layers beneath the gravels show intense brecciation, virtually none of the original clay structure being visible. The small-scale disturbances of the clay are probably associated chiefly with the melting out of ice lenses.

Index properties from a representative selection of Weald Clay samples are given in table 2. Individual test results are plotted in figure 5 from which it will be seen that, for a given liquid limit, the water content of the brecciated clay is generally higher than in the undisturbed material. An average value for the clay fraction is about 55 % of the dry mass.

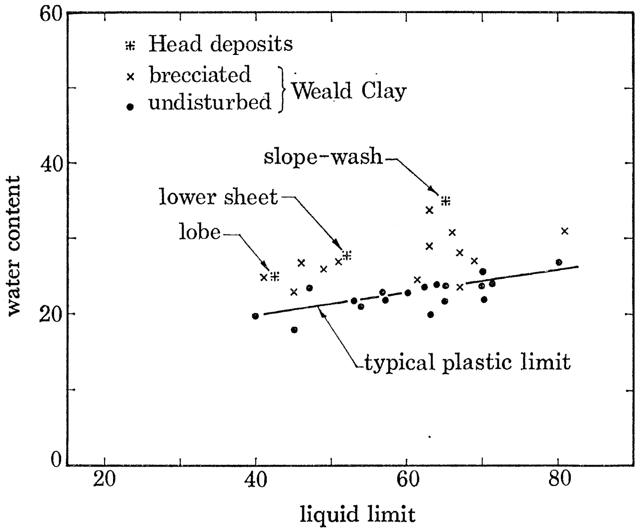


Figure 5. Index properties of Weald Clay (individual samples) and Head Deposits (average values).

3. Stratigraphy: Quaternary

(a) *Terraced river gravels*

Terrace gravels of the Rivers Eden and Medway consist of sand and sandy clay (loam) with flints, flint pebbes, cherts and pieces of sandstone. They have been mapped by the I.G.S. on the One-inch sheets of the Sevenoaks, Maidstone and Chatham districts (Sheets 287, 288 and 272), and details are given in the accompanying Memoirs. But in order to establish relations between the terraces and the high-level gravels, and to establish a stratigraphy of the terraces themselves, it is necessary to construct a longitudinal profile of the rivers with the adjacent gravels plotted in their correct positions. Altitudes of various points on the gravels, alluvium and Head deposits can be found from Ordnance Survey spot heights. To supplement this information in the critical area between Edenbridge and Tonbridge additional levels have been obtained with a surveying aneroid. In using this instrument care was taken to make frequent checks on bench marks and spot heights in the vicinity.

The longitudinal profile is given in figure 6 and the places referred to in the following discussion are shown in figure 7.

No. 1 *Terrace*

The First Terrace forms a well-defined feature 3 or 4 m above alluvium at several places between Edenbridge and Penshurst. It appears again in the neighbourhood of Yalding and Aylesford, where its height above the floodplain is about 1 m. Further downstream the terrace seems to merge with gravels at the top of the Buried Channel series containing cool-temperate

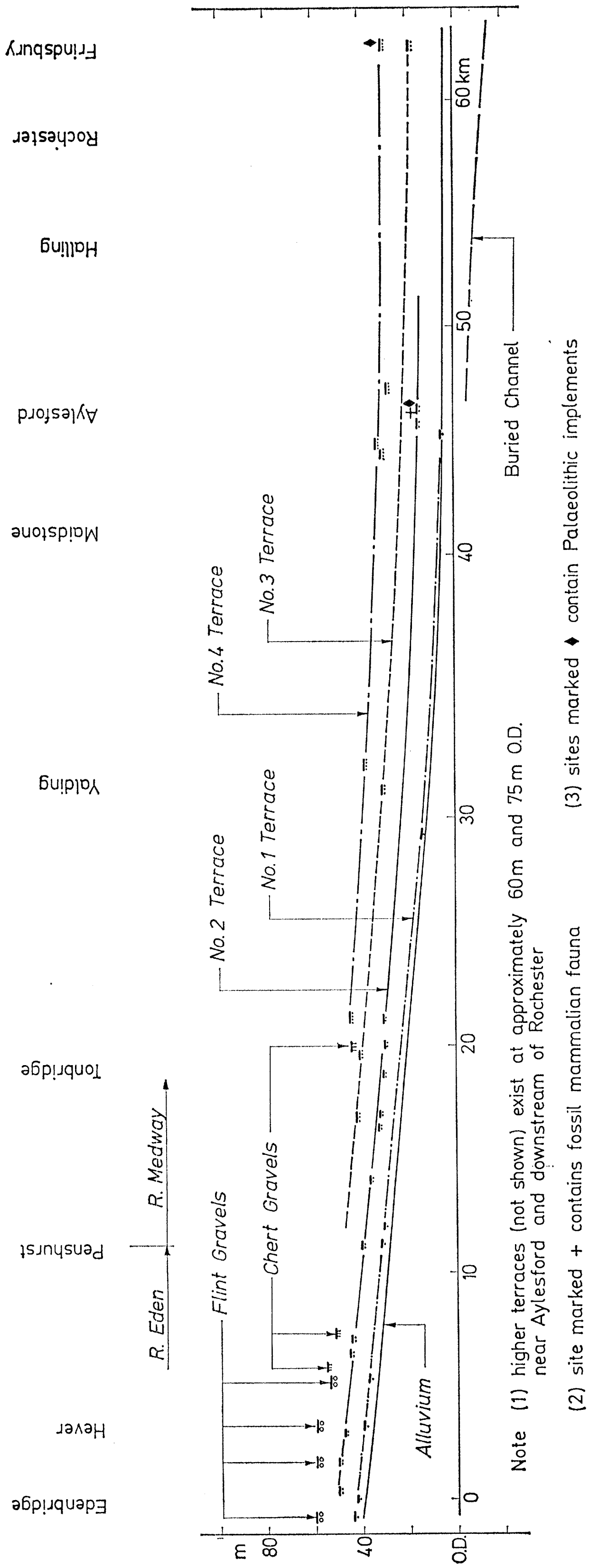


Figure 6. Longitudinal profile of the Rivers Eden and Medway.

mammalian fauna, with advanced Mousterian implements at a site near Rochester (J. N. Carreck *in lit.* 14 May 1975).

The evidence suggests a mid-Devensian age, and it is probable that No. 1 Terrace is the equivalent of the lowest terrace in several Midland rivers, for example the Tame, Nene and Ouse, dated radiometrically to a period around 30000–40000 years B.P. (Coope & Sands 1966; Morgan 1969; Bell 1970).

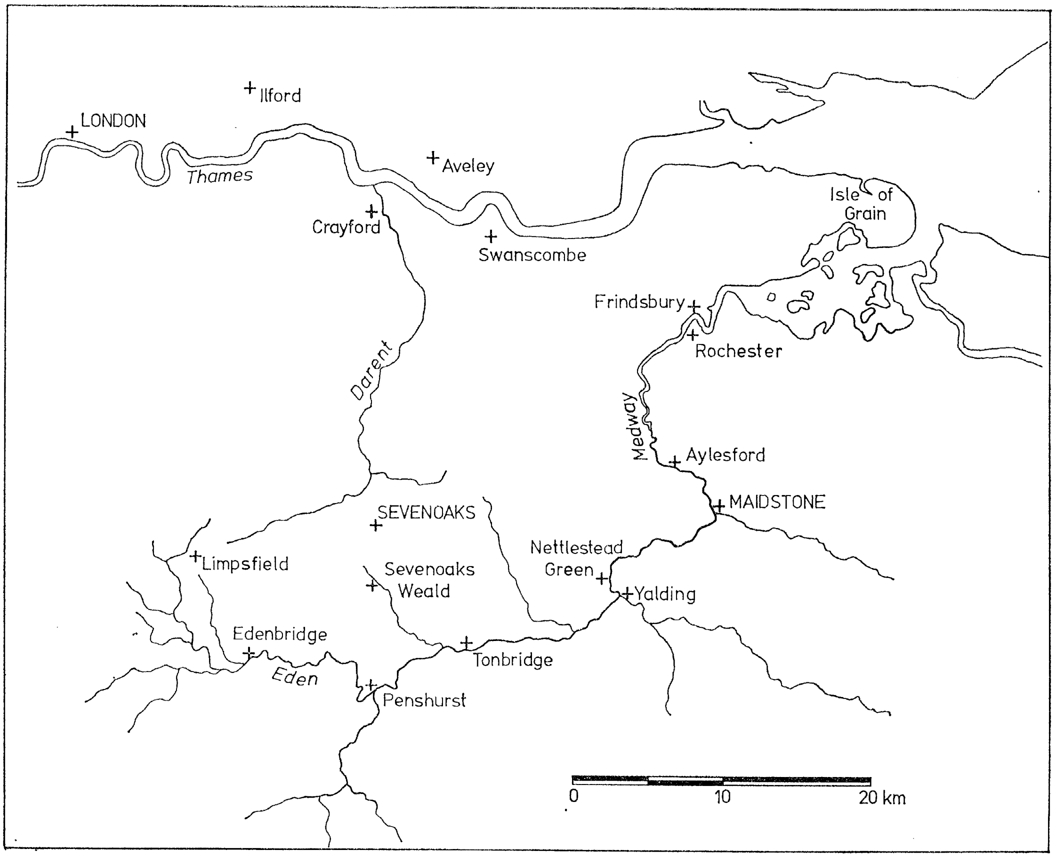


FIGURE 7. Map of the Rivers Eden and Medway.

No. 2 Terrace

The Second Terrace is seen frequently between Edenbridge and Tonbridge at heights of 10–13 m above alluvium. No exposures have been found in a long stretch of the Medway downstream of Tonbridge, but extensive deposits of sand and gravel at Aylesford with a surface 11 m above alluvium can safely be assigned to the Second Terrace. The gravels there rest on a bench at about 10 m O.D. and have a surface level around 15 m O.D. (Worssam 1963). Very probably the same terrace is represented by a spread of sandy gravel on the Isle of Grain at the mouth of the Medway, where the river joins the Thames estuary: the surface of the gravel lies at 12 to 13 m O.D., or 10 m above alluvium (Dines, Holmes & Robbie 1954).

In the Aylesford Terrace a fossil mammalian fauna has been found in association with Palaeolithic implements. The fauna, as reported by Carreck (1964), includes the species listed in table 3. This assemblage matches closely the fauna from the gravel and brickearth bordering the Thames at Crayford (Kennard 1944). The Thames brickearth, or loam, which is found also at Ilford and Aveley, has a surface elevation at approximately the same height above alluvium as no. 2 Terrace at Aylesford and dates from some part, probably towards the end, of the Ipswichian Interglacial (West, Lambert & Sparks 1964). Moreover, Mr Carreck kindly informs us that the Palaeolithic industry in the Aylesford terrace, apart from derived artefacts, is Late Acheulian showing Levalloisian technique, which agrees with an Ipswichian dating.

TABLE 3. AYLESFORD NO. 2 TERRACE: FAUNAL LIST

lion	*Panthera leo*
mammoth	*Mammuthus primigenius*
straight-tusked elephant	*Palaeoloxodon antiquus*
horse	*Equus caballus*
woolly rhinoceros	*Coelodonta antiquitatis*
pig	*Sus scrofa*
red deer	*Cervus elaphus*
giant deer	*Megaceros giganteus*
bison	*Bison priscus*
giant ox	*Bos primigenius*

No. 3 and 4 Terraces

Correlations of individual occurrences of the First and Second Terraces along the length of the rivers present little difficulty, but problems arise with the higher terraces. The interpretation shown in figure 6 is an attempt to bring the available field observations into reasonable order.

In the neighbourhood of Tonbridge and Yalding the pattern appears to be simple. No. 3 Terrace at both localities lies 18–20 m above alluvium, and no. 4 Terrace is distinctly higher: 25 m above the floodplain near Tonbridge and 27 m at Nettlestead Green. Around Aylesford there are several patches of gravel about 26 m above alluvium, and it seems evident that they should be regarded as belonging to the Fourth Terrace. They are mapped as no. 3 Terrace on the Maidstone sheet, but it is noted in the Memoir (Worssam 1963) that the Third Terrace at Yalding is appreciably lower relative to the floodplain.

At Frindsbury a large quarry exposes sections of two terraces with surface levels at approximately 18 and 30 m O.D., or 15 and 27 m above alluvium, and the gravels rest on benches cut in the Chalk at about 14 and 24 m O.D. (Cook & Killick 1924). In the Chatham Memoir (Dines *et al.* 1954) they are referred to the 2nd and 3rd Terraces respectively; but these terms are used in a very broad sense and, in the present context, it is clear that the 100 m terrace at Frindsbury can be correlated with no. 4 Terrace further upstream. The 18 m terrace is too high, both in its surface level and bench height, to be a continuation of the Aylesford Second Terrace and it may be assigned tentatively to no. 3.

On the interpretation adopted here, no. 4 Terrace has an almost constant altitude of 30 m O.D. downstream of Aylesford, in what is today the tidal reach of the Medway. This altitude immediately invites a comparison with the Boyn Hill Terrace at Swanscombe, on the south side of the Thames estuary only 14 km from Frindsbury; and the benches at both locations are almost identical in height. Studies of the fauna, flora and Palaeolithic industries at Swanscombe have shown that part, if not the whole, of the river sands and gravels date from the Hoxnian Interglacial (see Wymer 1974 for a recent summary of the evidence). It addition the Swanscombe terrace is overlain by a loam, which is covered and disturbed by solifluction gravel, containing advanced Acheulian implements of Wolstonian age, while at Frindsbury there are implements, described by Mr Carreck (personal communication) as Late Acheulian, in solifluction deposits which are later than the 30 m terrace but closely associated with it.

The suggestion can therefore be made that the Fourth Terrace of the Medway is equivalent to the Swanscombe terrace of the Thames, and broadly of Hoxnian age. Certainly it would not be easy to sustain arguments for a earlier date, while the presence of no. 3 Terrace, intermediate between no. 4 and the Ipswichian no. 2, precludes a substantially later date. The clear implication is that no. 3 Terrace can be correlated with the Wolstonian.

High terraces

Near Maidstone, and also downstream of Rochester, there are remnants of terraces (not shown in figure 6) at altitudes around 45 and 60 m O.D. There is no direct evidence of their age, though they are obviously older than no. 4.

(*b*) *Older Head deposits*

The high-level drifts always occur as deposits capping small isolated hills, ridges or spurs in the country between the escarpment and the belt of river terraces (figure 4). They fall into two groups: (i) gravels free from flints, with abundant chert fragments derived from the Hythe Beds, set in a fine-grained matrix derived partly from the sandy clays of the Hythe Beds but chiefly from the Atherfield and Weald Clays, and (ii) gravels containing flints and flint pebbles, usually with cherts as well, and typically with a more sandy or silty matrix.

It is generally agreed (following Dines *et al.* 1940) that the high-level chert gravels are Head deposits which have been transported from the escarpment and across the clay vale by periglacial solifluction. In contrast, it appears from their terrace-like distribution, northwest and east of Edenbridge, that the flint gravels were carried along pre-existing valleys of the Eden and its tributaries, Kent Brook and Gibbs Brook; and it is known (Sevenoaks Memoir 1969) that the flints were derived from the Limpsfield gravel north of the escarpment. Flint gravels which lie about 20 m above the river Bourne no doubt have an analogous origin and history.

In principle, then, the distinction between the two groups is clear. But good sections of the deposits are rare, and intensive field work, involving pits and borings, would be necessary to establish full details of the stratigraphy. The following notes are therefore provisional and may have to be modified in some respects in the light of future research.

High-level flint gravels

The main occurrences of high-level flint gravels identified by the I.G.S. on the Six-inch maps and in the Sevenoaks Memoir are shown in figure 4, together with two additional exposures in the district north of Hever. Murchison (1851), describing the gravels in this district, says they 'are spread out in what the country-people call the "plains", which are, in fact, plateaux 60 or 80 feet above the adjacent valley' of the Eden. The largest of these is at How Green (475462). Another spread of flint gravel occurs 800 m to the northwest, near Whistlers (468467). One of the new exposures is a short distance to the east (472468) near Meachlands, at the same altitude as How Green. Cherts were recorded here by the I.G.S. but in a recently cut roadside ditch we found flint pebbles mixed with the usual fragments of sandstone, ironstone and chert. The stones were closely packed with a silt filling the interstices. The silt had a liquid limit as low as 27 (table 2) and a clay fraction of only 10%. It may be noted that Bird (1964) maps chert gravels at all three sites.

The other revision applies to flint gravels at Bough Beech (489466). These were originally identified as Head and later as no. 2 Terrace. However, they lie at least 6 m higher than the Second Terrace in the locality and should be classified either as high-level flint gravels, or possibly as no. 3 Terrace. Indeed it will be seen in figure 6 that the flint gravels from this point up to Edenbridge lie between 19 and 24 m above alluvium, approximately at altitudes which might be expected for the Third Terrace, and clearly well above no. 2.

Further east, on a spur at Somerden Farm (501469), it seems that cherts merge into flint gravels, also at a level considerably higher than the Second Terrace, although towards the southern end of the same spur the gravels appear to have been moved down slope, perhaps by later solifluction, almost to the terrace level. Similarly it is reported, in the Sevenoaks Memoir, that cherts on Camp Hill (523468) merge into flint gravel on the south side of the hill, and again there has been later solifluction or down-washing. Flint pebbles have also been noted at the northwest end of Camp Hill. It may therefore be assumed that chert and flint drifts are in contact at Somerden and Camp Hill. No exact levels or boundaries can be given for the flint gravels at these sites, but their positions are not very different from the associated cherts plotted in figure 6 at 5.8 and 7.4 km downstream of Edenbridge.

The high-level flint gravels along the north side of the Eden, then, can be correlated with the Wolstonian, since they are of about the same age as the Third Terrace, or slightly older. In a different category are the gravels containing flints, flint pebbles and large angular cherts at Starvecrow (602502), 3.5 km north of Tonbridge. They are situated at an altitude around 75 m O.D., which is higher than no. 4 Terrace, to the south, and higher than the flint gravels to the north along the river Bourne. Very tentatively it may be suggested that they belong to an older drift, possibly of Anglian age.

High-level chert gravels

Characteristically the presence of these deposits is revealed by an abundance of angular chert fragments in clayey soil on hill-tops standing above the clay vale. The cherts are very obvious in freshly ploughed fields but the larger fragments can also be seen in grass. They make a striking contrast with the lower parts of the vale, where cherts are usually absent or scarce. Bird (1964) reports that cherts are sometimes found to depths of 2 m, but as a rule the deposit is less than 1 m thick. He describes a section from a pit in the middle of Camp Hill, where cherts in a matrix of silty clay to between 1 and 1.5 m were seen to be underlain by 3 m of weathered clay with contortions indicative of freeze-and-thaw action, and then unweathered Weald Clay and bedded siltstone *in situ*. Apparently there were no flints in this section but, as previously noted, flints do exist on the north and south ends of the hill.

All the high-level chert gravels identified by the I.G.S. are included in figure 4, apart from the deposit near Meachlands, now classified as a flint gravel, and with the addition of a small spread of cherts on the ridge leading from Hubbard's Hill to the church of Sevenoaks Weald (529514). There is little doubt that this gravel at one time continued up the ridge on to the slopes of the hill; indeed many cherts can be seen in a field at Anchor Cottage (figure 1), though a nearby roadside section indicates that they are confined to a thin veneer. South of the church the ridge is deeply dissected by a stream, but chert gravels appear again at Weald village and, after crossing a col, on the ridge south of Pitts Farm. From the profile shown in figure 8 it is evident that these gravels very probably form part of what was originally a continuous spread, extending southwards for a distance of 2 km, the average gradient of which is about 1.4°.

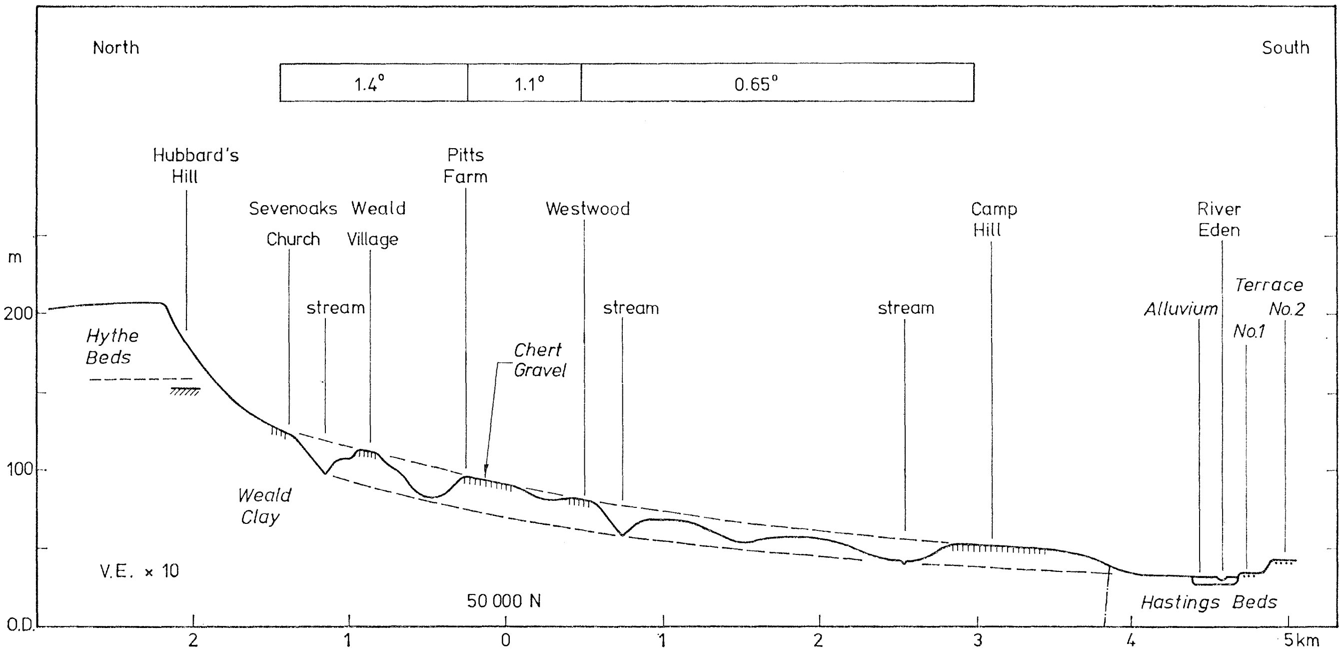


FIGURE 8. Section from Hubbard's Hill to Camp Hill and across the River Eden.

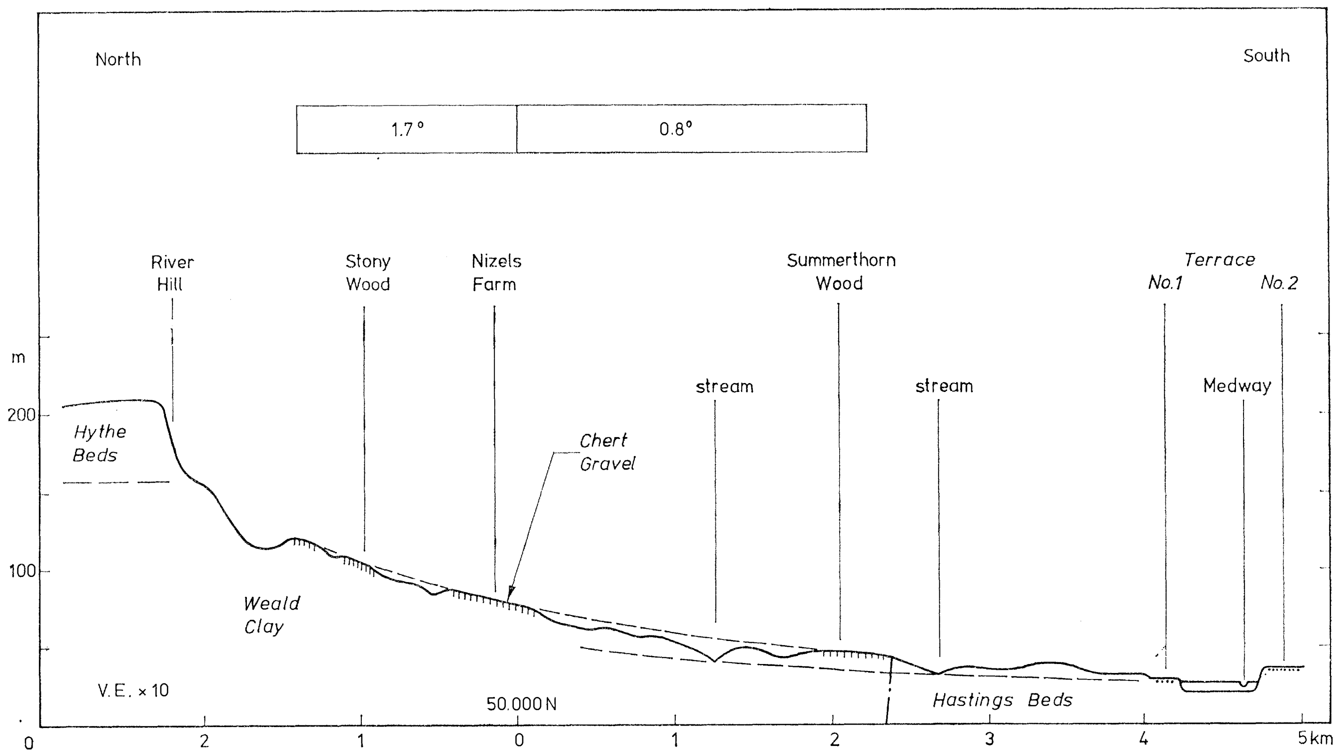


FIGURE 9. Section from River Hill to Summerthorn Wood.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Chert gravels capping the ridge below River Hill, as shown in figures 1 and 2, have a similar mode of occurrence (though they have not been traced up to the foot of the hill itself) and exhibit a gradient of about 1.7°. Cherts in the several exposures mapped in figure 1 are often up to 10 or 20 cm in length.

No process at present operating can release cherts of this size from the escarpment and transport them in a clay matrix many hundreds of metres down slopes inclined at less than 2°. Vigorous frost-shattering and periglacial solifluction clearly have to be invoked.

Between Hubbard's Hill and River Hill ridges, all traces of the high-level cherts have been removed by subsequent erosion, except for occasional fragments lying on the adjacent hill slopes well below their original position. From the sections in figures 2 and 3 it will be seen that the maximum depth of dissection is of the order 20–30 m.

Further south, exposures of high-level chert gravel become less frequent. They are found in association with flints at Somerden and Camp Hill; but there seems to be no ambiguity at Summerthorn Wood (542477), north of Leigh, where the deposit is described on the Six-inch map as clay with cherts and sandstone fragments, and at Little Trench (595485), north of Tonbridge. The gravels at all these sites lie between 4 and 5 km south of the escarpment, at heights of 10–20 m above the local streams. They appear to lie on a continuation of the same profile as the high-level gravels further north; but the gradients leading to the southerly gravels, as at Camp Hill (figure 8) and Summerthorn Wood (figure 9), are about 0.6–0.8°.

Dating the Older Head deposits

The flint gravels east of Edenbridge lie well above the Second Terrace, of Ipswichian age, and at about the same height above river alluvium as no. 3 Terrace. They were therefore deposited at some period during the Wolstonian. The most southerly chert gravels, at Somerden, Camp Hill and Little Trench, are slightly higher but, judging by the latter locality, they do not attain altitudes above no. 4 Terrace. As the Fourth Terrace is very probably not older than Hoxnian it follows that these chert gravels can also be correlated with the Wolstonian.

The high-level chert gravels further north, in the vicinity of Sevenoaks Weald, are unquestionably older than Ipswichian. This can be determined from the facts that deposits known to be of Devensian age lie at much lower altitudes in a totally different topographic situation (§ 3*c*) and, of course, that periglacial deposition could not have taken place in the temperate climate of the Ipswichian. Three hypotheses then have to be considered regarding the age of these more northerly high-level drifts.

(i) They were deposited later than the chert gravels further south. In this case, for reasons given above, they could only be of later Wolstonian age.

(ii) They were deposited at the same time. This assumption is the simplest to make; it implies that the high-level cherts were all deposited in Wolstonian times and originally formed parts of continuous sheets spreading off the escarpment (in its contemporary position) and reaching down to, or near to, the rivers in their Wolstonian locations.

(iii) They were deposited earlier than the chert gravels further south. What has to be considered here is not the question of their formation in an earlier phase of the Wolstonian, which is little more than a variant of (ii), but the radically different case for an Anglian age. In order to sustain this correlation, however, it is necessary to explain why no solifluction deposits of intermediate age (i.e. Wolstonian on the present assumption) have been found between the abundant high-level cherts around Sevenoaks Weald and the Devensian drift, while chert gravels of Wolstonian age have been preserved further south.

As no such explanation appears to be readily available the most probable conclusion is that the northerly high-level drift is Wolstonian. Bird (1964), acknowledging the 'formidable difficulties' involved, and using somewhat different lines of reasoning, arrives at basically the same result; namely that the high-level cherts were deposited during a 'solifluction episode after the development of a valley floor equivalent to the Boyn Hill terrace in the London Basin'.

Nevertheless a question remains, for it is conceivable that the most southerly cherts might have been brought down from the escarpment by solifluction in the Anglian stage and subsequently redeposited in their present positions by further solifluction in Wolstonian times. This implies the existence originally of extensive Anglian deposits which have since been lost by erosion, a possibility which cannot entirely be ruled out. Consequently it has to be admitted that although the high-level chert gravels, as shown in figure 8 for example, were formed in Wolstonian times, those nearest to the river might have been redeposited at that stage; in which case it would not be correct to deduce that solifluction had occurred on gradients as low as 0.6°.

(c) *Younger Head deposits*

The Younger Head deposits have been studied in some detail within the embayment between Hubbard's Hill and River Hill (figures 10 and 11). A complete section of the deposits was exposed in Pit F2 (535520), where the following sequence could be established (figure 15): overlying brecciated Weald Clay is the chert gravel of the Lower Solifluction Sheet, followed by slope-wash which grades up into a dark grey organic clay dated radiometrically to 12200 years B.P.; this organic horizon (fossil soil) is in turn covered by gouge clay containing a highly developed slip surface; over the gouge clay comes another layer of chert gravel (lobe F) followed again by slope-wash on which the modern topsoil has formed.

The upper and lower slope-wash deposits are practically identical materials. They consist of soft silty clays, buff or pale-grey or sometimes light reddish brown in colour, with a few very small stones. Little difference was noted in the field between the upper and lower chert gravels, but laboratory tests show that the upper gravel has a more sandy matrix. The matrix of the lower gravel, in pit F2 and in other borings and pits, is a silty clay of medium plasticity, usually brown or light grey in colour.

Index properties are summarized in table 2 and average values of the existing water contents are plotted in figure 5. The water contents are seen to be relatively high, but even so they have certainly been reduced by consolidation from still higher values at the time of deposition. Determinations of the clay fraction were made on seven samples of the chert gravels matrix; the results lay within the range 14–45% of the dry mass, mean values for the matrix of the Lower Sheet and of lobe F being 33 and 24%, respectively.

Clay particles in the chert gravel matrix of the lobes have been derived from the basal bed and clayey sands of the Hythe Beds. In the Lower Solifluction Sheet, as in the high-level chert gravels, the clay content is supplemented by material derived from the Atherfield and Weald Clays. Apart from rare ironstone fragments, in the lower gravel, which come from the Weald Clay, the stones in both the upper and lower solifluction layers consist wholly of chert, sandstone and Rag from the Hythe Beds, with chert strongly predominating.

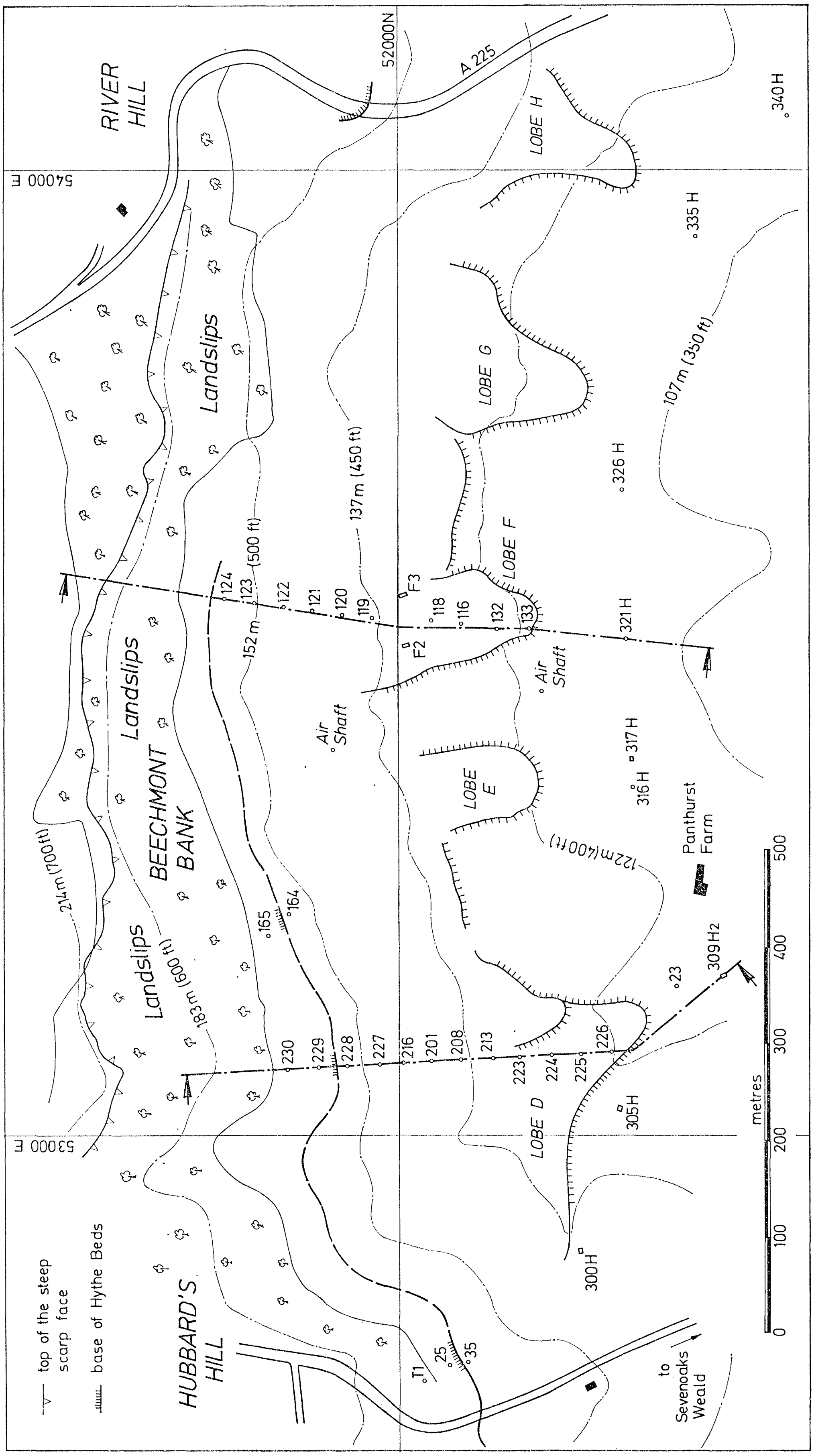


FIGURE 10. Embayment between Hubbard's Hill and River Hill.

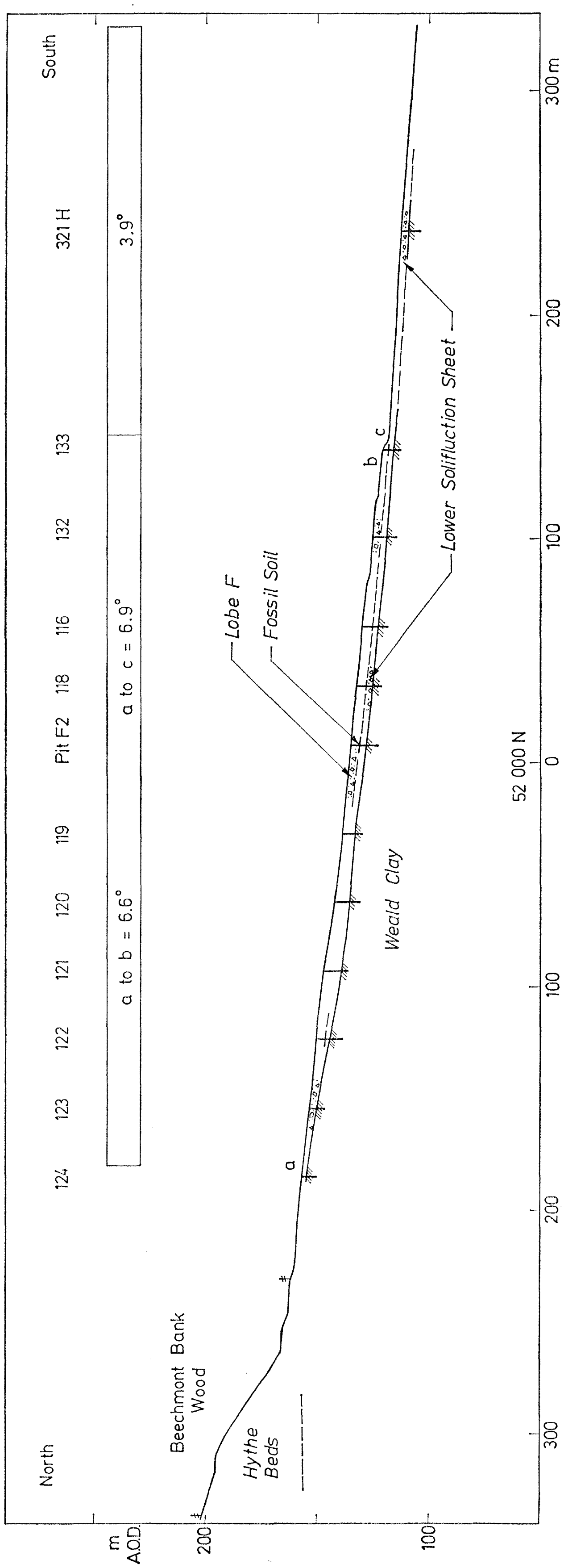


FIGURE 11. Section through lobe F.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Lower Solifluction Sheet

The Lower Solifluction Sheet has no topographic expression but its presence has been proved by borings and pits beneath the Lobes and beyond their limits for a distance of at least 500 m from the foot of the scarp face. The row of borings from 300H through 317H to 340H (figure 10) all show about 2 m of chert gravel overlying brecciated Weald Clay, on ground sloping at 3–4°, and the east–west continuity of this sheet is interrupted only by the small ridge on which Panthurst Farm is built.

The southern boundary of the sheet cannot be determined from the available evidence but there is no doubt that the gravel deposits moved for considerable distances down pre-existing valleys. Cherts embedded in silty clay to a depth of 1.5 m can be seen, for example, in the sides of a stream channel at a point (533513) 500 m east of Sevenoaks Weald church, and very probably they fan out across gently sloping land to the southeast; cherts were certainly seen in abundance in a ploughed field near the 76 m spot height shown in figure 1, almost 1 km from the escarpment.

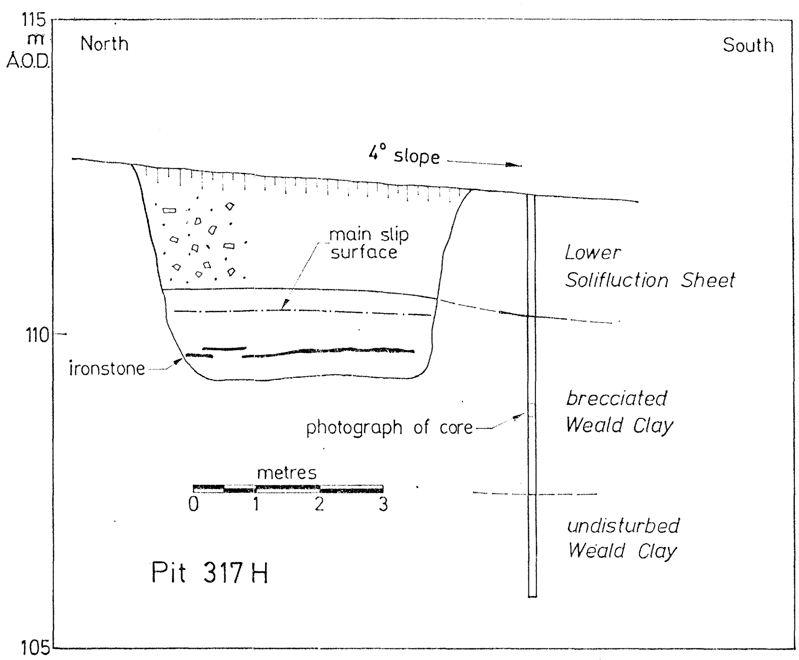


FIGURE 13. Section and borehole at pit 317H 100 m south of lobe E.

From point 533513, looking east, the Morleys Farm ridge is seen, capped by high-level chert gravels (figure 12, plate 5), and in a dry valley on the other side of the ridge cherts have been proved to a depth of 2.5 m, over Weald Clay, in a boring (543513) 250 m northeast of the farm (figure 1).

There is no reason to question the idea that the chert gravels have moved by solifluction to these positions, as the longitudinal gradient of the valley leading to point 533513 is about 2.4°, while the valley east of Morleys Farm is slightly steeper. From point 533513 down to the 76 m spot height the gradient averages 2.1°. To the south only occasional chert fragments can be seen, and it may be noted that in this area the gradient rapidly decreases, falling to 1° about 500 m to the south.

A representative section through the Lower Solifluction Sheet is shown by the pit and adjacent boring at location 317H (figure 13). Chert gravel with a silty clay matrix extends to a depth of 2 m. It is underlain by 2.7 m of brecciated Weald Clay, the upper half of which is partially weathered to a brown colour, with small lumps of intact clay in a mass of soft, reworked clay (figure 14, plate 5). The ground at this location slopes at 4°, and is completely stable under present climatic conditions. Nevertheless there are several well-defined subhorizontal slip surfaces in the brecciated Weald Clay down to 3 m below ground level (the main slip only being shown in figure 13), and it therefore seems that the solifluction movement occurred chiefly by shearing on these slip surfaces under periglacial conditions when the 'active layer' of the permafrost penetrated the top 2–3 m.

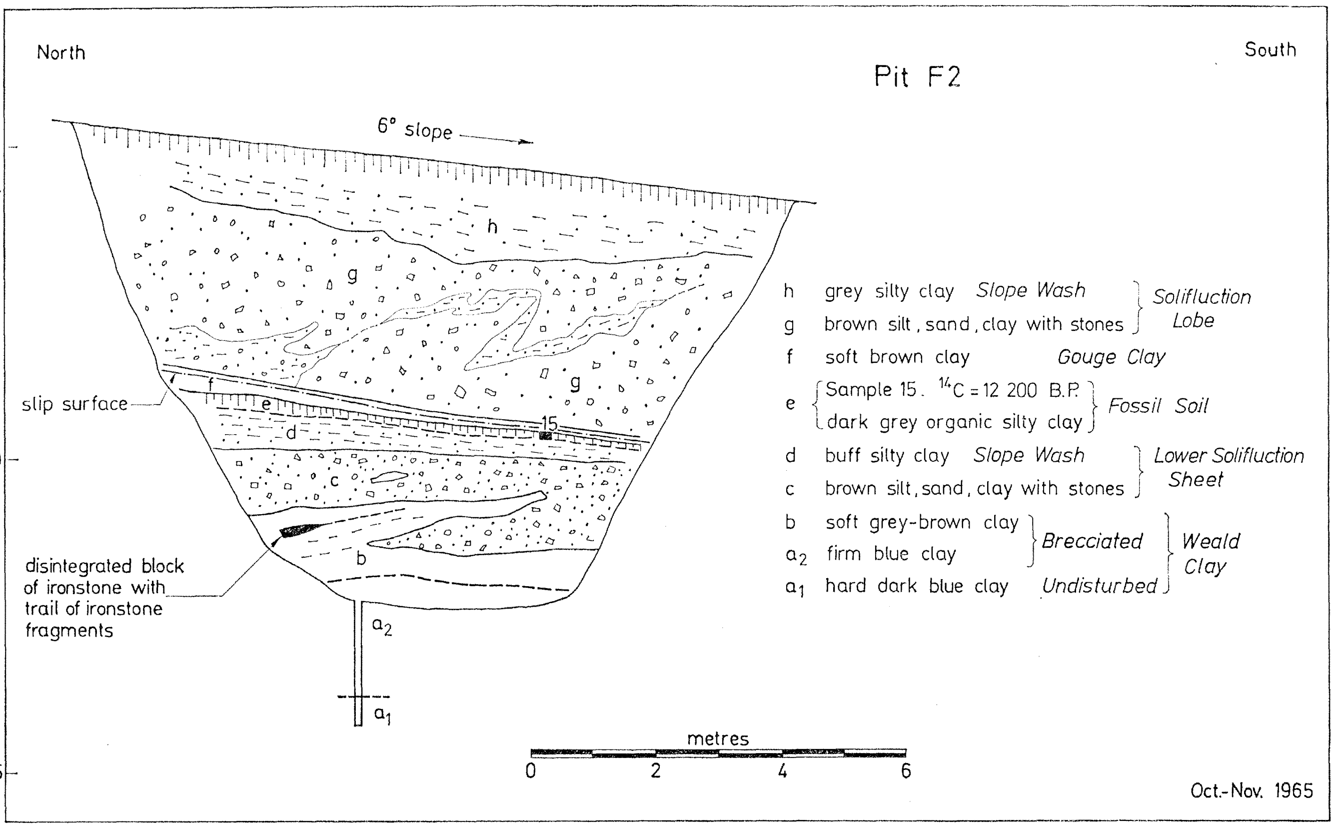
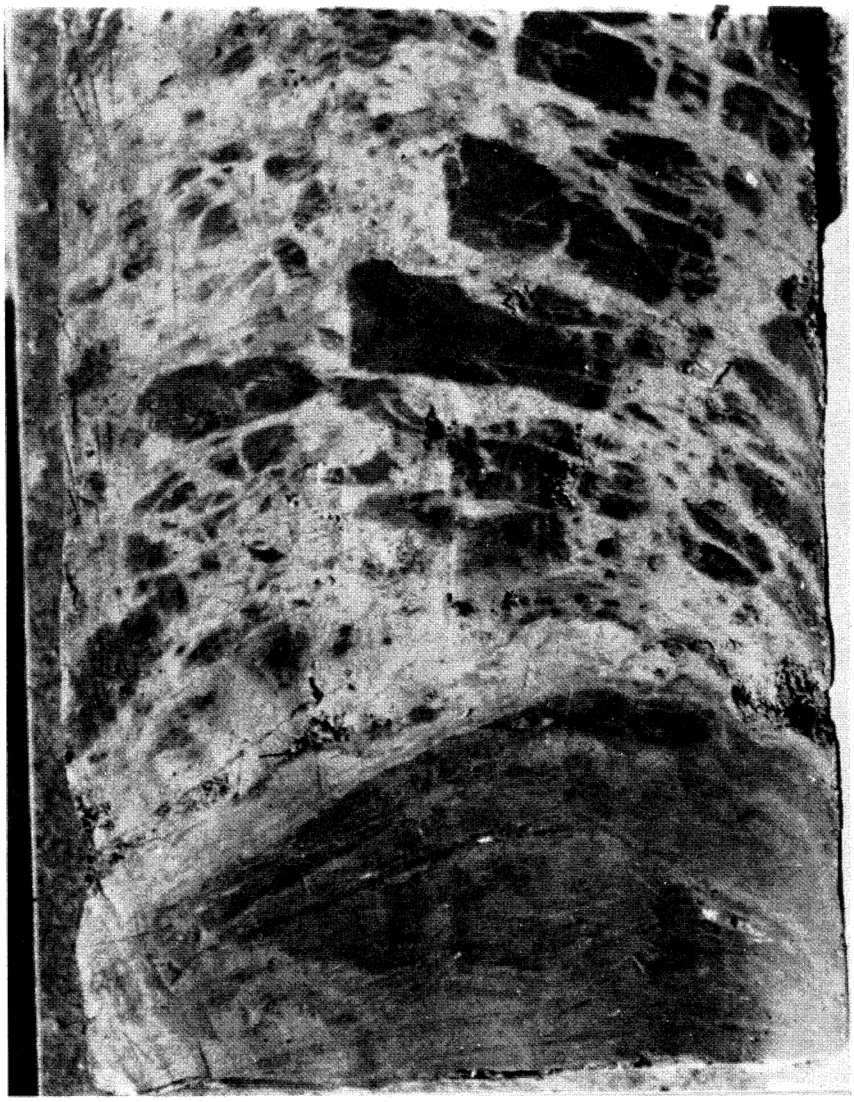


FIGURE 15. Section of pit F2 in lobe F.

Similar sections have been observed in the pits and borings at locations 300H, 305H and 309H where cherts were found to depths of 1.5–2 m, with shears in the underlying clay and, in one case, also within the chert gravel matrix.

In pit F2 the Weald Clay was seen to be dragged up into the chert gravel as a tongue, about 2 m in length, containing a trail of ironstone fragments (figure 15). Contortions of the same type, though smaller in scale, were also observed in pit F3, nearby. No slip surfaces in the Weald Clay could be detected in these pits. But when an excavation was made through lobe G a large mass of material on the uphill side began sliding on a shear surface in the Weald Clay, below the chert gravel, and calculations showed the strength to be at its residual value. In other

12



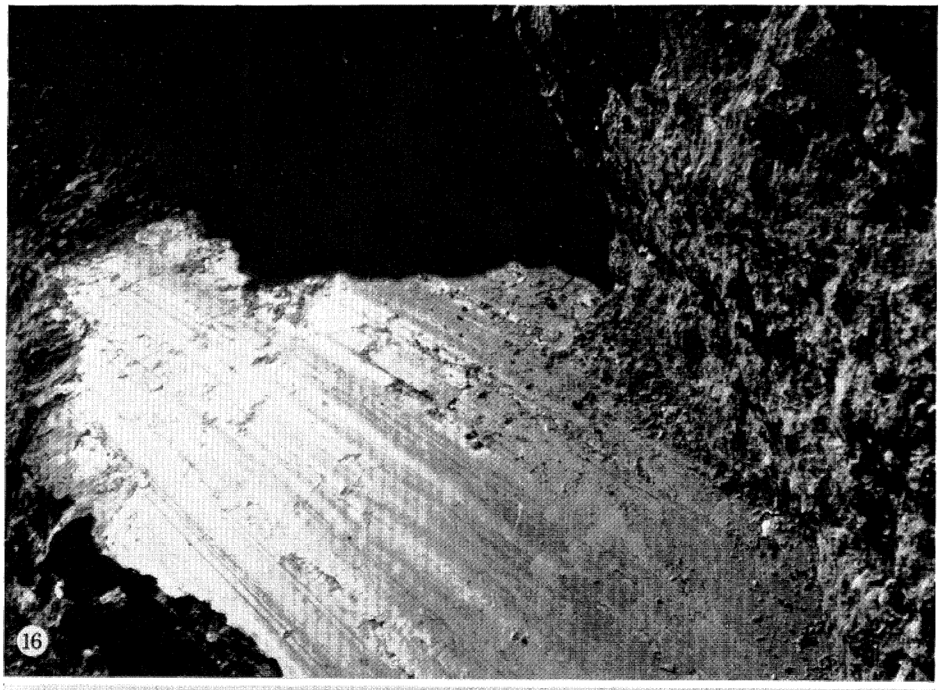
14

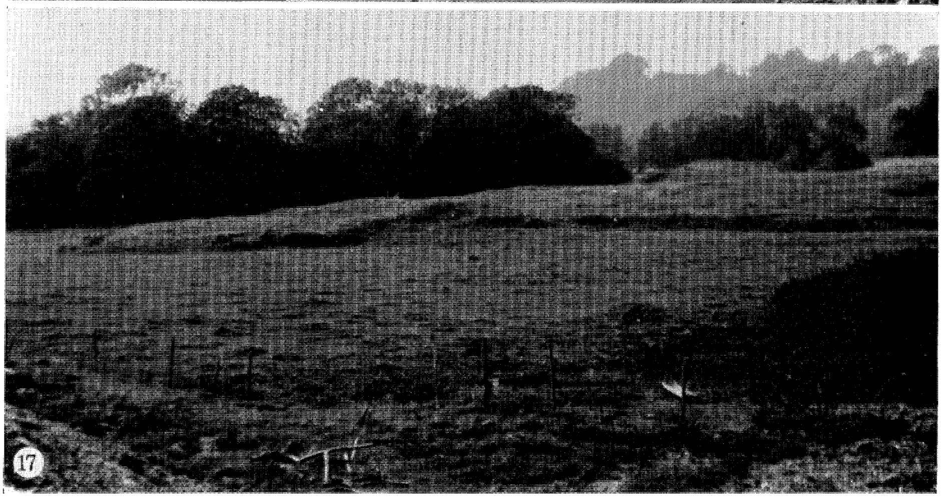
FIGURE 12. View from point 533513 looking towards the ridge north of Morleys Farm. Devensian chert gravel is exposed in a stream channel just behind the view point and high-level (Wolstonian) gravel caps the ridge.

FIGURE 14. Section of core from a depth of 3.5 m in borehole 317H, showing brecciated Weald Clay. The core diameter is 10 cm.

(*Facing p.* 512)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES





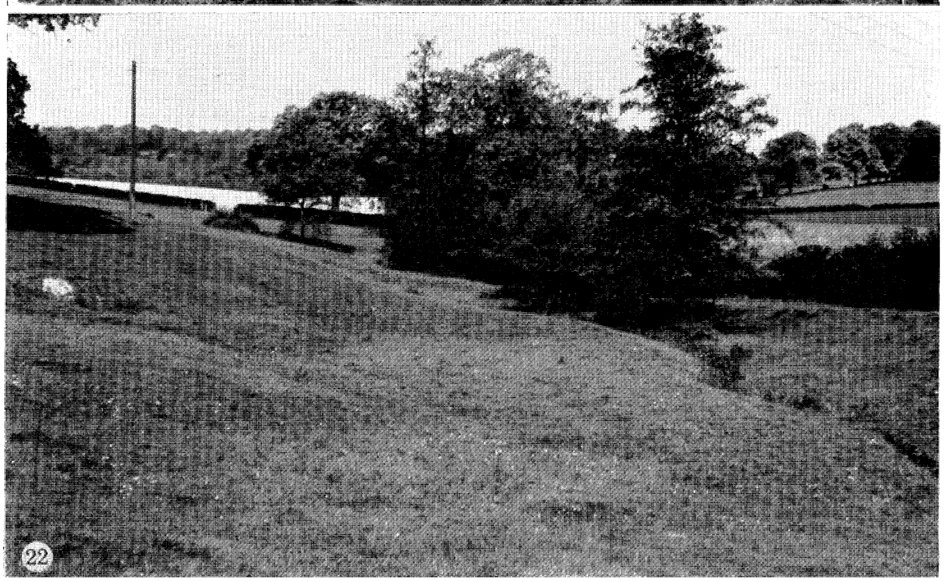


FIGURE 16. Pit F2. Slip surface in gouge clay beneath the upper chert gravel and overlying Late Devensian interstadial fossil soil.

FIGURE 17. Lobe F, looking northwest. The Lower Solifluction Sheet extends beyond the edge of the lobe, in the foreground.

FIGURE 22. Postglacial stream erosion in the valley east of Dale Farm.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

words, the excavation led to reactivation of movement on a pre-existing slip surface at the base of the lower sheet.

The largest chert fragment encountered in the investigations was found in the lower sheet in pit F2. It is drawn to scale in figure 15, and has a length of 60 cm. The other stones were frequently up to 10 cm and occasionally 20 cm in size.

The amount of slope-wash recorded in pit F2, overlying the lower chert gravel, appears to be exceptional and may have been deposited, and preserved, in a local depression or furrow. In pit F3 it was seen only as a pocket of clay beneath the organic horizon, while in the pits further south, beyond the lobes, this material if it exists at all is no thicker than the modern topsoil.

Fossil soil

As seen in pit F2 the lower slope-wash grades up into a dark grey silty organic clay rich in humus. Sample 15, taken in this soil at the position shown in figure 15, was submitted to Geochron Laboratories for radiocarbon assay. The sample was inspected for rootlet contamination and digested in hot HCl to remove carbonates. The age proved to be 12250 ± 280 radiocarbon years B.P. (GX 0793). This dates the soil firmly within the Late-glacial Interstadial of the Devensian as defined by Coope (1975). Calculations of the radiocarbon age were based upon the Libby half-life (5570 years) for ^{14}C, using as a standard 95% of the activity of N.B.S. oxalic acid (Geochron Laboratories Report 21 October 1966).

Table 4. Pollen analysis of fossil soil, pit F2

Betula	25	
Pinus	11	
		36 AP total
Gramineae	17	
Cyperaceae	6	
Artemisia	23	
Compositae	8	
Epilobium	13	
Rubiceae	4	
Thalictrum	5	
Umbelliferae	4	
		80 NAP total
Botrychium	4	
Lycopodium	1	
Ophioglossum	1	
		6 spore total

A block of the soil taken immediately adjacent to sample 15 was sent to Dr R. G. West, F.R.S., at the Botany School, Cambridge, and we are very grateful to him for carrying out a pollen analysis. The results (West *in lit.* 15 Aug. 1966) are given in table 4. Dr West commented that the pollen was scarce (33 × 2 cm traverses), and the spectrum is of a type which may well be Late Devensian. This conclusion is of course in agreement with the radiocarbon date.

The organic clay horizon was found also in pit F3 and in several of the borings such as nos. 118 and 122 in figure 11. But these borings through the lobes, made in a routine fashion, for the installation of piezometers, were not logged in detail and the absence of any record of the soil is not necessarily significant.

Upper Lobate Sheet

The upper layer of chert gravel spreads off the escarpment over the Lower Solifluction Sheet. Characteristically it takes the form of lobes, but these appear to be extensions, perhaps in a slightly later stage of development, from a more continuous sheet. The bench forming the margin of this sheet can be seen between lobes D and E and between lobes F and G (figure 10). Engineering works prior to the investigations may have removed evidence for the sheet elsewhere, just as subsequent works have obliterated almost all traces of lobes D, G and H. The southern parts of lobes E and F remain, however, and stand out as conspicuous features of the landscape north of the new by-pass road (figure 17, plate 6). They extend about 300 m from the scarp foot. Similar lobes have been mapped to the west of Hubbard's Hill and on the east of River Hill (figure 1), and no doubt others could be found further afield.

A section through lobe F is shown in figure 11, with a detailed profile in figure 15. There is some evidence of flow structure within the chert gravel, indicating very low strengths at the time of formation, but clearly the main component of downhill movement has taken place by shearing on a polished and striated slip surface within a thin layer of gouge clay beneath the gravel (figure 16, plate 6).

The surface inclination of the lobes is about 6 or 7° on average, with a tendency in some cases to show a slight concave profile ranging in slope from 9° near the scarp face to 5° at the toe. The edges of the lobes are quite steep in places and exhibit signs of recent instability.

Where the thickness of the lobe material, above the organic horizon, could be determined in borings and pits F2 and F3 it varied from 3 to 5 m; the upper metre, approximately, being slope-wash clay. The stones, all derived from the Hythe Beds, were found to be often up to 10 cm in size and occasionally as large as 20 cm, embedded in a matrix of sandy clay.

Dating the Younger Head deposits

It is evident that the lower chert gravels were deposited on a landscape which has changed little since the time of their deposition; in marked contrast to the high-level gravels. This fact, coupled with their obviously periglacial origin, strongly suggests a Devensian age. Moreover, there are no signs of weathering beween the gravel and the overlying slope-wash which, in-turn, grades up into the fossil soil proved to be of Late-glacial Interstadial age. Thus there is no difficulty in correlating the Lower Solifluction Sheet with the Devensian.

From the abundance of large chert fragments in the Lobes, these too are judged to have a periglacial origin and can therefore be correlated with the Late-glacial Zone III period (10800–10000 years B.P.): the only periglacial phase following the Interstadial and preceding the return to temperate conditions in Postglacial times. The upper slope-wash is later than the chert gravel of the Lobes, but no exact date can be given for its formation.

4. The mechanics of periglacial mudflows

The solifluction sheets can best be described as periglacial mudflows or mudslides (following the terminology of Chandler 1972), in which a clayey gravel moves down slope principally by shearing on a slip surface at or near the top of the underlying Weald Clay. In temperate conditions such a mechanism would not be possible at slopes of less than about 8°. But it can be hown that during seasonal thawing of the active layer above permafrost sufficiently high pores pressures may be developed at the base of the layer for movement to take place on slopes of less than 2°.

To outline the mechanics of this problem, consider a layer of material of depth z sliding on a plane parallel to the slope and inclined at an angle β. The unit weight of the material is γ. It will be assumed that the length of the sliding mass is large compared to its depth and, further, that the shear strength on the slip plane can be represented in terms of the effective stress $\sigma' = (\sigma - u)$ by the Coulomb-Terzaghi expression

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

where c' and ϕ' are the apparent cohesion and angle of shearing resistance of the clay, σ is the total stress normal to the plane and u is the pore water pressure acting at depth z.

For limiting equilibrium, when movement is just possible, the shear stress on the plane is equal to the shear strength, or

$$\gamma z \sin \beta \cos \beta = c' + (\gamma z \cos^2 \beta - u) \tan \phi'. \tag{1}$$

If the piezometric height is h, then $u = \gamma_w h$, where γ_w is the unit weight of water (9.8 kN/m^3); and it is convenient to express the pore pressure in terms of the ratio

$$r_u = u/\gamma z = \gamma_w h/\gamma z.$$

Equation (1) can then be rewritten in the form

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

Under temperate conditions the highest pore pressures will exist when groundwater level is at the surface. This is the full 'hydrostatic' case; and as γ is usually about $2\gamma_w$ the corresponding value of r_u is approximately 0.5. The extreme upper limit is the 'geostatic' value $r_u = 1.0$, which implies a piezometric level rising above the slope to a height approximately equal to the depth z; a state clearly impossible under ordinary conditions, but theoretically possible if frozen soil is thawed so rapidly that the entire weight of overburden is transferred to the pore water, without any of the water being able to escape.

The time required for thawing to proceed from the surface to a depth of, say, 2 m is several months (McRoberts 1975). In a sandy material much consolidation could occur in this period, but in a clay the rate of consolidation may be sufficiently low to prevent any substantial dissipation of pore pressure at the depth of the slip plane. It is therefore of significance in the present context to note (i) that sliding occurred chiefly within the brecciated Weald Clay and (ii) that the overlying chert gravel has a clay matrix, and is a matrix dominated material.

Morgenstern & Nixon (1971) have presented an analysis of the problem of calculating the excess pore pressure at a depth D in soil having a coefficient of consolidation c_v, when t is the time required for thawing to penetrate to this depth. The results are expressed as a function of the thaw-consolidation ratio

$$R = D/(2\sqrt{(c_v t)}).$$

Laboratory tests on samples of brecciated Weald Clay and of the chert gravel matrix, from a boring adjacent to Pit 309H, show a coefficient of consolidation virtually identical for both materials and equal to about 2.5 m^2/year. It will be assumed that thawing reached a depth of 2 m, the typical depth of slip surfaces beneath the Lower Solifluction Sheet, in a period of 3 months, which seems to be a reasonable time from the annual temperature curve deduced by

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Williams (1975) for the colder parts of the Devensian. With these assumptions the thaw-consolidation ratio has a value of 1.3; and from the numerical solution given by Morgenstern & Nixon this corresponds to 22 % dissipation of excess pore pressure, or $r_u = 0.89$.

It must be emphasized that the calculation is approximate as t is not known precisely and the tests were carried out on the clays as they exist today; c_v may have been rather different when the soil had just thawed out. To make some allowance for these uncertainties R will be varied by ± 25 %, in which case the upper and lower limits of r_u are 0.93 and 0.83.

The next step is to determine the shear strength parameters. Tests have been made to measure the strength on slip surfaces in samples taken from pits 300H and 317H (Skempton & Petley 1967), while the residual strength of brecciated Weald Clay with similar index properties, from Arlington in Sussex, has been measured in ring shear tests (Bishop *et al.* 1971). The failure envelope is slightly curved but can with little error be linearized over a moderately wide range of effective stress. Thus for values of σ' between 20 and 50 kN/m², which is a typical range for shallow landslides in temperate climates,

$$c' = 1\ \mathrm{kN/m^2}, \quad \phi' = 14°.$$

Extrapolating the failure envelope back towards zero effective stress we find that for values of σ' between 5 and 20 kN/m²

$$c' = 0.2\ \mathrm{kN/m^2}, \quad \phi' = 16°,$$

but for effective stresses less than 5 kN/m² there is some uncertainty. The above set of parameters might also apply, or if the true cohesion is zero the appropriate parameters would be

$$c' = 0, \quad \phi' = 18°.$$

It is now possible to find from equation (2) the minimum or limiting slope β for any given value of r_u assuming the thickness of the sliding mass to be $z = 2$ m and taking the unit weight $\gamma = 20$ kN/m³.

In the first place we note that under temperate conditions, with a maximum r_u equal to 0.5 (and therefore with $\sigma' \geqslant 20$ kN/m²), sliding can occur only on slopes steeper than about 8°. And the same result applies in a thaw-consolidation process with 100 % dissipation of excess pore pressures.

Under periglacial conditions and in a clay soil, however, it has just been shown that r_u might be as high as 0.93, in which case $\sigma' \approx 3$ kN/m² and the limiting slopes is 1.3° ($c' = 0$, $\phi' = 18°$) or 1.4° ($c' = 0.2$, $\phi' = 16°$). By using the calculated value of $r_u = 0.89$ the effective stress is about 4.5 kN/m² and the limiting slope is 2.0° (with either set of strength parameters), while for a lower bound of $r_u = 0.83$ the slope is 3.0° ($\sigma' \approx 7$ kN/m², $c' = 0.2$, $\phi' = 16°$).

The Devensian lower solifluction gravels moved on a minimum gradient of just over 2°, while the high-level drift moved on slopes of about 1.5°. These field observations can readily be explained on the basis of the foregoing calculations; but in order to account for movements on slopes of 0.6° or 0.8°, as in the profiles down to Camp Hill and Summerthorn Wood, values of r_u around 0.97 or 0.96 have to be invoked. These correspond to about 6 % dissipation of excess pore pressure, an extremely low value though not impossible if c_v is less than 1 m²/year.

It is also of interest, following Hutchinson (1974), to estimate the water contents of the clays at the time when movements were taking place. The shear strength at the base of a sheet 2 m thick moving on a slope of 2°, for example, is about 1.5 kN/m². Now, to a first approximation, the strength of remoulded clays is uniquely related to the liquidity index, as defined by the expression

$$\mathrm{LI} = \frac{w - \mathrm{PL}}{\mathrm{LL} - \mathrm{PL}},$$

and for a strength of 1.5 kN/m² the value of LI is around 0.9 (Skempton & Northey 1952). For Weald Clay, with liquid and plastic limits of 60 and 23 respectively (table 2), the corresponding water content is about 55. Similarly the water content of the chert gravel clay matrix would be approximately 50. These water contents are of course much higher than the present values. They refer to the state of the clays just after thawing, when the effective stresses were very small.

So far as the lobes are concerned, analyses based on measured shear strength parameters of the slip surface from samples taken in pit F2, and on observed piezometric levels, show that they are marginally stable under present-day conditions. An increase in pore water pressure up to the full hydrostatic value might be sufficient to cause movement. Thus the existence of permafrost is not necessarily implied. On the other hand severe frost-shattering must have been active in order to release the large fragments of chert and other stones from the Hythe Beds; and the material in the lobes may well have been softened by freezing and thawing, with the development of some excess pore pressures.

5. The escarpment

Studies have been made at four sites in the Lower Greensand escarpment between River Hill and Ide Hill. They indicate that large-scale structural disturbance, in the form of block subsidence in the Hythe Beds accompanied by bulging in the Atherfield and Weald Clays, is confined to older parts of the escarpment now left as 'hills' or spurs; while mass movements within the embayments are characterized by landslips.

(a) *Hubbard's Hill*

A plan of this locality is shown in figure 18. Section I (figure 19) records the investigations made at the site of Weald Bridge. The southern part of pit WB1 showed Weald Clay at a higher elevation than had been expected, and also a 'pinching out' of the Atherfield silt. These observations suggested the presence of a bulge at the foot of the escarpment, somewhat analogous to the well known 'valley bulges'. To check this hypothesis borehole 25 was drilled. It proved the Weald Clay at a level 5 m lower than the exposure in pit WB1, and also revealed two siltstone layers. As the siltstones could act as excellent marker bands, additional borings were made below the pit, and beyond; and pit WB4 was excavated to provide further information. The results, as shown in figure 19, confirmed the existence of a sharp bulge in the Weald Clay, rising 5 m and continuing, with some minor distortions, at least 20 m to the south. The new borings and pit also confirmed the almost total absence of Atherfield silt above the bulge.

Throughout the length of the pits a slip surface, with many secondary shears, was traced in the Atherfield clay. At the northern end of pit WB1 the slip surface appears to be associated with minor landslip movements in the Hythe Beds, but at other sites subhorizontal shears have been found in the Atherfield clay well behind the scarp face. Although the slip surface was not specifically noted in borehole 25 it may continue northwards under the Hythe Beds, and has merely been involved in, not caused by, the landslips at the scarp toe.

A sheet of Head sweeps down the slope, with a smooth surface profile and an approximately uniform thickness of about 2 m. It is entirely unaffected by the bulging and truncates the small landslips. Possibly this sheet is the upper part of lobe D or, more probably, it continues as the Lower Solifluction Sheet proved in pits 300H and 305H (figure 18).

Two other sections through the escarpment at Hubbard's Hill are shown in figures 20 and 21. The Weald Clay bulge is seen again. It has much the same amplitude as in section I, but is less sharply defined.

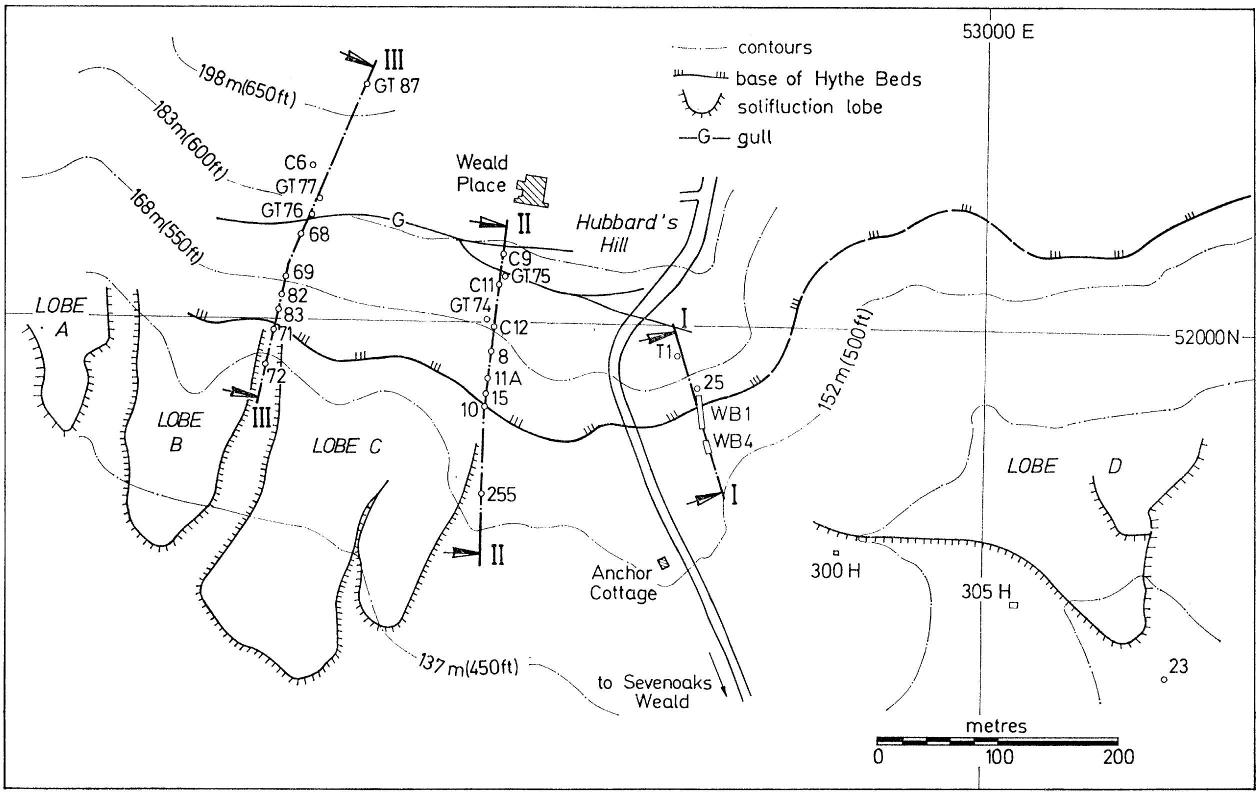


FIGURE 18. Hubbard's Hill: plan.

An important feature in sections II and III is the presence of deep fissures or gulls. The gulls are filled with silt and stones, but they can be discerned as depressions in the ground surface. When first observed they were taken as indicating that the Hythe Beds had been cambered. Certainly the Hythe Beds are disturbed, with many minor faults, but the evidence now available from the borings and pit 283/A (figure 21) shows that a large block up to 25 m thick has subsided and moved forward, essentially without rotation. It should be noted, however, that the toe of this mass of rock has been forced upwards, as indicated by the section between boreholes 15 and 10 in figure 20, and confirmed by a pit excavated nearby.

Observations at Ide Hill, shortly to be described, leave little doubt that block subsidence and bulging in the clays at the foot of the scarp are closely related. Further, it is very unlikely that such disturbances could take place under temperate conditions. Deep freezing and thawing seem to have been necessary to reduce the strength of the clays, and the most readily acceptable explanation of the forward thrusting invokes ice-wedges acting in joints within the Hythe Beds.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

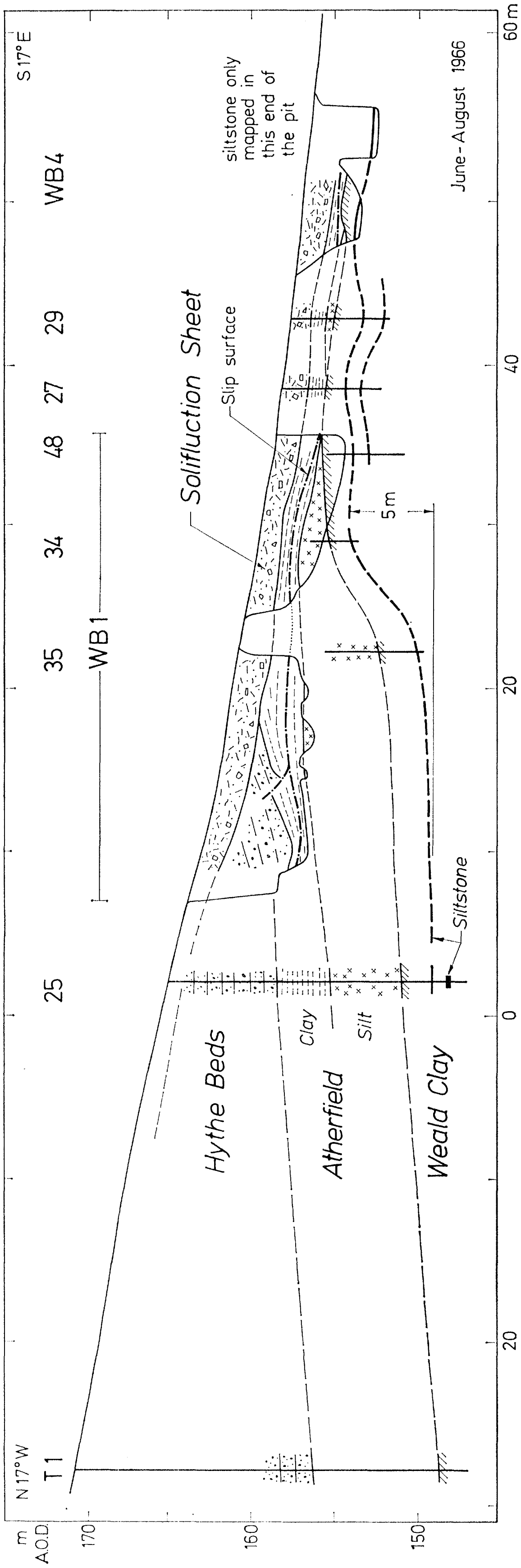


Figure 19. Hubbard's Hill: section I.

To put the various events at Hubbard's Hill into a chronological sequence, the first point to recall is that high-level cherts were found near Sevenoaks Weald church on the ridge which runs south from the hill. Subsequent to the deposition of this gravel widespread erosion has taken place, though the central part of the hill and the land now forming the ridge have remained with little change; and it is on the slopes of this eroded landscape that the Devensian solifluction sheets and lobes have been formed. Clearly the bulging of the Weald Clay, as seen in sections I–III, pre-dates the solifluction material and the slopes over which it flowed. The conclusion can therefore be drawn that block subsidence in the Hythe Beds and bulging of the Weald Clay occurred during a periglacial stage earlier than the Devensian; though the gulls may have been widened, at least in their upper parts, during this period.

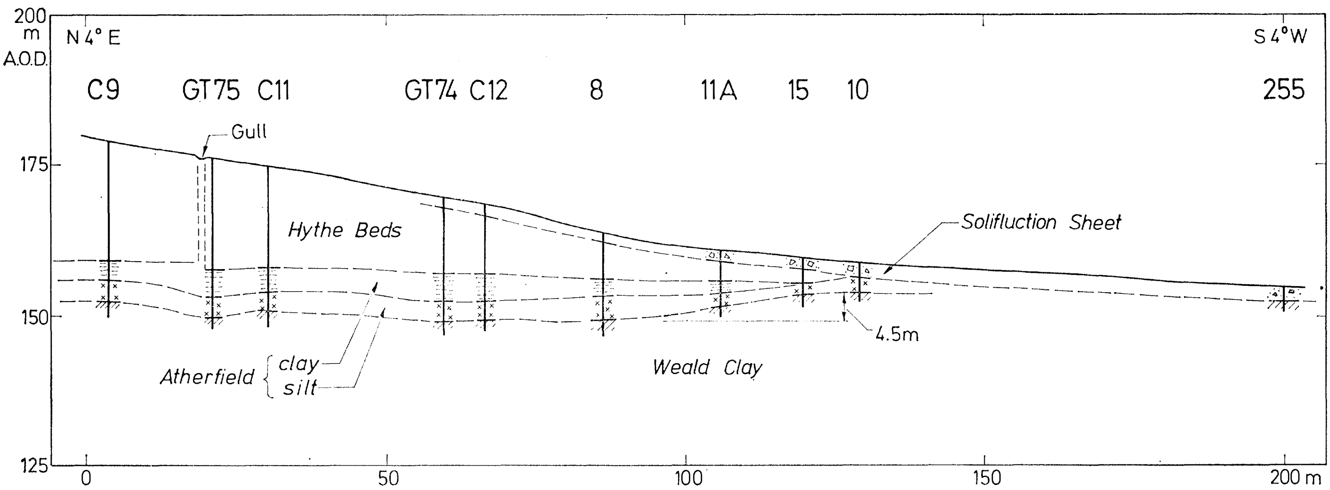


FIGURE 20. Hubbard's Hill: section II.

(*b*) *Ide Hill*

Further evidence on the phenomenon of 'block subsidence' in the Hythe Beds escarpment is provided by two groups of borings near the village of Ide Hill. In this area there is a large re-entrant, or coombe like feature, in which several landslides occurred following exceptionally heavy rainfall in the winter 1968–9. The borings about to be described were made, among others, in connection with works to stabilize the slopes.

In the first group, centred on location 486515, three borings were carried down through the Hythe Beds and the Atherfield Clay into the Weald Clay; they were situated between 200 and 300 m behind the main, south-facing escarpment, and proved a thickness of the Atherfield clay and silt varying from 8 to 12 m.

In the second group one boring was located at the crest of the scarp and another about 40 m behind. After penetrating 20 m of Hythe Beds both showed only 2 m of Atherfield deposits over the Weald Clay. But a third boring in this group, drilled beyond the toe of the Hythe Beds, proved 10 m of Atherfield clay and silt, underlying Head deposits. It is remarkable that, at this location, the upper surface of the Weald Clay remained at a practically constant elevation (154 m O.D.).

The conclusion is inescapable that a vast block of Hythe Beds, 20 m thick and more than 40 m wide, has subsided into the Atherfield Clay and in doing so has squeezed this material out

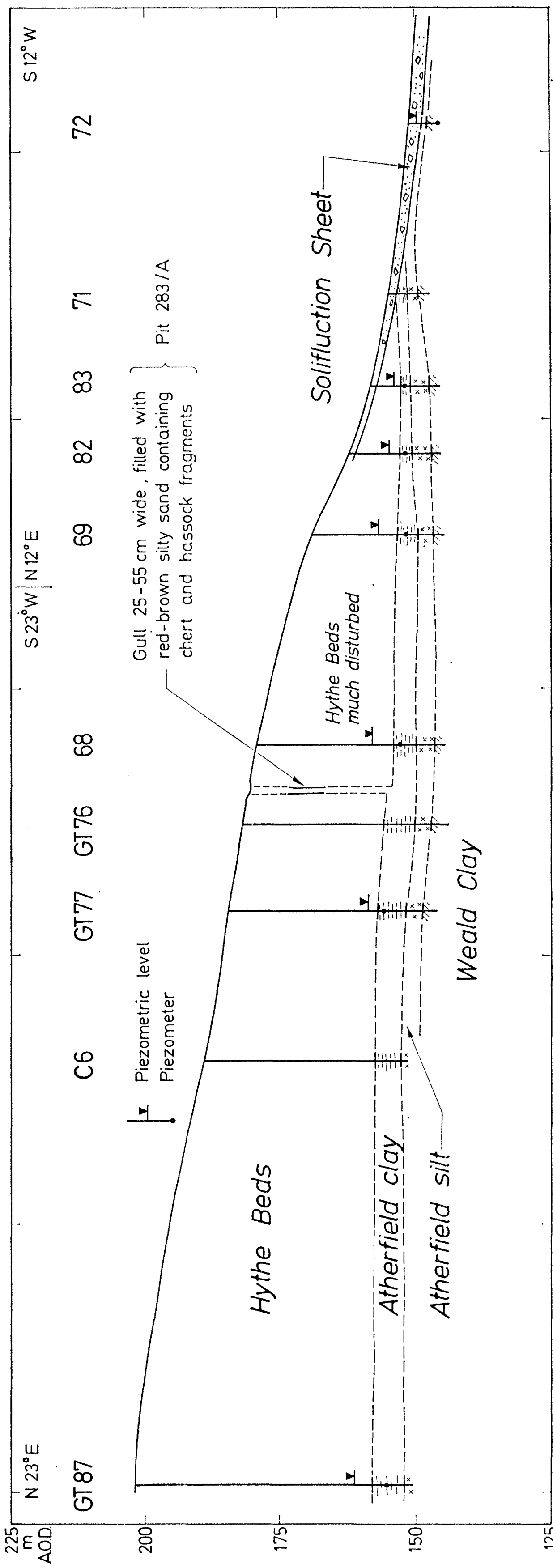


FIGURE 21. Hubbard's Hill: section III.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

beyond the foot of the scarp face in the form of a 'bulge'. The vertical component of subsidence is probably at least 6 m.

The recent landslide at this site took place entirely within the solifluction deposits.

It is further to be noted that two of the borings in the first group were drilled through the scarp face within the re-entrant; but they revealed no sign of disturbance in the Atherfield or Weald Clays, and the slope movements in 1969 simply reactivated an older landslip in the toe of the escarpment beyond these two borings. Thus, despite the steepness of the scarp (averaging 25°) and the great thickness of Hythe Beds (42 m below the scarp crest), there is no evidence here of block subsidence or other types of deformation, except landslipping.

The marked difference between the two sites may perhaps be explained on the assumptions (i) that the re-entrant has been formed, or enlarged and deepened, by erosion subsequent to the (Wolstonian) period when block subsidence occurred in the main escarpment, and (ii) that periglacial conditions during the Devensian stage, though capable of producing the Head deposits which blanket the slopes within the re-entrant, and also capable of initiating large landslips, were not sufficiently severe to cause major structural disturbances.

(*c*) *Bayley's Hill*

At the head of a small embayment east of Bayley's Hill (515518) there is an old landslip the reactivation of which in 1969 caused considerable damage. The slip involves most of the scarp face and the slip surface passes through the Atherfield Clay. The scarp is again fairly steep and the Hythe Beds have a thickness of about 35 m.

Borings through the scarp face show no disturbances in the Atherfield or Weald Clays, apart from those associated with the landslip.

(*d*) *Embayment between Hubbard's Hill and River Hill*

Geomorphological mapping, carried out at the request of the senior author by Mr R. P. Martin, under the direction of Dr Denys Brunsden, has revealed three areas of major land-slipping in the escarpment between Hubbard's Hill and River Hill. These are in the thickly wooded slopes of Beechmont Bank, at the positions indicated in figure 10. The degraded toes of the landslip masses can just be discerned beyond the southern boundary of the wood, and their very subdued topographic expression suggests that they have been modified by solifluction. Indeed they may have provided a source of material for the upper lobate sheet. It therefore seems probable that the landslips were initiated in Devensian times before, and possibly during, Zone III. A Wolstonian date cannot be postulated, owing to the retreat of the embayment escarpment subsequent to that period.

Unfortunately it was not possible to make borings through the escarpment in Beechmont Bank and only three boreholes were taken through the Hythe Beds south of the scarp foot (figure 10). These show nothing abnormal, however, and there is no reason to suppose that conditions in the embayment differ essentially from those observed near Bayley's Hill.

6. Postglacial changes in the landscape

In Postglacial times only slight changes have occurred in the escarpment and in the clay vale. At several places old landslips have been reactivated, both in the escarpment proper and in the solifluction material blanketing the steeper slopes beneath the scarp foot. The streams have eroded channels, typically up to 2 m in depth, in or through the Lower Solifluction Sheet, and in the Weald Clay they have excavated new, small valleys the sides of which sometimes show signs of continued instability. A view of one of these little valleys, to the east of Dale Farm (figure 1), is shown in figure 22, plate 6. Further downstream, narrow bands of alluvium have been deposited and the maximum depth of incision is about 3–4 m. The present floodplains of the Rivers Eden and Medway have been formed during this period by the deposition of alluvium.

7. Summary and conclusions

The Quaternary correlations are set out in table 5 and the main conclusions may be summarized as follows:

(i) South of the Lower Greensand escarpment in the vicinity of Sevenoaks Weald many of the small hills and ridges, standing up to 20 or 30 m above the streams of the clay vale, are capped by deposits consisting of chert fragments, and other stones derived from the Greensand, set in a clay matrix. These deposits are the dissected remnants of originally continuous sheets which spread off the escarpment and moved down the gentle slopes of the then existing landscape for distances of at least 2 km at an average gradient of about 1.5°. The cherts are angular and often up to 20 cm in length. For stones of this size to be released from the Greensand in large quantities and transported in a clay matrix for such distances on slopes of less than 2°, intense frost shattering and periglacial solifluction have to be invoked. There is reason to believe that the formation of these high-level chert gravels very probably occurred during the Wolstonian stage.

(ii) In some cases the solifluction debris may have moved as far as 4 km from the escarpment on gradients falling to about 0.8°.

(iii) Bordering the northern limits of the belt of river terraces of the Eden and Medway, at distances of 4–5 km from the escarpment, there are several exposures of high-level chert gravel of Wolstonian age. If in primary positions they would represent the most southerly limits of the solifluction sheets, and near the limits the gradients would have been not more than about 0.6°. But it is possible that these gravels were brought down from the escarpment in Anglian times and redeposited in their present situations during the Wolstonian.

Table 5. Quaternary correlations

		vale	escarpment	rivers
Flandrian		—	—	alluvium
Devensian	Zone III	Upper lobate sheet		
	L-g Inst.	fossil soil		
		Lower Solifluction Sheet	landslips in embayments	no. 1 Terrace
Ipswichian		—	—	no. 2 Terrace
Wolstonian		high-level chert gravels	block subsidence and and bulging	no. 3 Terrace

(iv) Following deposition of the Wolstonian gravels considerable erosion took place in the clay vale, accompanied by retreat of the escarpment within embayments between spurs.

(v) On this eroded landscape, in Devensian times, sheets of solifluction debris spread off the escarpment within the embayments and moved at least 500 m, while streams of the debris extended down valleys for a total distance of about 1 km from the foot of the scarp face. The typical gradient on which movement occurred is 3 or 4°, falling to a minimum value of just over 2°. This lower solifluction sheet is about 2 m in thickness, consisting of clay with embedded angular chert fragments, overlying brecciated Weald Clay in the upper layers of which there are several slip surfaces. Brecciation of the clay is attributed to disturbance caused by the melt-out of ice lenses.

(vi) During the Late Devensian Interstadial (*ca.* 12000 radiocarbon years B.P.) a soil formed on slope-wash clay covering the lower solifluction sheet.

(vii) Soon afterwards, in Zone III of the Late-glacial sequence, the soil was buried beneath a lobate sheet of solifluction debris spreading for a distance of up to 300 m from the scarp foot. The lobes have an average slope of about 7°.

(viii) Based on thaw-consolidation theory, and on measured properties of the Weald Clay and the clay matrix of the chert gravels, a rational explanation in terms of soil mechanics principles can be established for the movement of the active layer above permafrost on gradients as low as 1.5° or 2°. Under temperate conditions such slopes are completely stable; movement could occur only on gradients steeper than about 8°.

(ix) In the spurs of the escarpment there are large-scale structural disturbances; massive blocks of the Hythe Beds subsided into the underlying Atherfield and Weald Clays, and the clays were forced up at the foot of the scarp in the form of bulges. These disturbances probably occurred in the Wolstonian stage.

(x) Large landslips are present in the escarpment within the embayments. Field evidence suggests that they took place in the Devensian before and perhaps during the final phase of solifluction which produced the upper lobate sheet.

(xi) In Postglacial times some landslips have been reactivated, and the streams in the clay vale have eroded small channels or valleys not more than 4 m in depth.

(xii) Finally it may be noted that in the region of Haslemere, 50–60 km west of Sevenoaks Weald, three groups of solifluction deposits can be recognized south of the Lower Greensand escarpment: a younger Head of Devensian age; an older Head capping small hills and interfluves; and the earliest Head existing as a few remnants at still higher altitudes (Thurrell, Worssam & Edmonds 1968). Originally the older Head was correlated with the Wolstonian and the earliest Head assigned tentatively to the Anglian. But according to Kellaway, Worssam, Holmes & Kerney (1973) all the high-level drifts in the Haslemere area may be of Anglian age (i.e. pre-Hoxnian). This view reflects a major uncertainty concerning the status of the Wolstonian stage; a question which pervades Quaternary studies in England today. The present investigations support the more traditional interpretation, namely that the Wolstonian includes a period or periods of intense glacial and periglacial activity.

The results of borings, trial pits and laboratory tests are published by permission of Kent County Council. Assistance in the field work by Professor N. R. Morgenstern, Dr D. J. Petley and Dr D. J. Shearman is very gratefully acknowledged. We thank Dr R. G. West, F.R.S., for the pollen analysis, Mr D. J. Carter for micropalaeontological studies and Dr J. N. Carreck for information on the fauna and Palaeolothic implements of the river terraces. In discussions and field visits we have been greatly helped by Mr B. C. Worssam, Dr D. Brunsden, Mr R. P. Martin, Dr J. N. Hutchinson and Dr R. J. Chandler.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

References (Skempton & Weeks)

Bell, F. G. 1970 Late Pleistocene floras from Earith, Huntingdonshire. *Phil. Trans. R. Soc. Lond.* B **258**, 347–378.

Bird, E. C. F. 1964 Denudation of the Weald Clay vale in West Kent. *Proc. Geol. Ass.* **74**, 445–455.

Bishop, A. W., Green, G. E., Garga, V. K., Andresen, A. & Brown, J. D. 1971 A new ring shear apparatus and its application to the measurement of residual strength. *Géotechnique* **21**, 273–328.

Carreck, J. N. 1964 Field meeting to the Medway valley, Kent from Maidstone to Rochester. *Proc. Geol. Ass.* **75**, 357–360.

Chandler, R. J. 1972 Periglacial mudslides in Vestspitsbergen and their bearing on the origin of fossil solifluction shears in low angled clay slopes. *Q. J. Eng. Geol.* **5**, 223–241.

Cook, W. H. & Killick, J. R. 1924 On the discovery of a flint-working site of Palaeolithic date in the Medway valley at Rochester. *Proc. Prehist. Soc. East Anglia* **4**, 133–154.

Coope, G. R. & Sands, C. H. S. 1966 Insect faunas of the last glaciation from the Tame Valley, Warwickshire. *Proc. R. Soc. Lond.* B **165**, 389–412.

Coope, G. R. 1975 Climatic fluctuations in northwest Europe since the Last Interglacial. *Ice Ages: Ancient and Modern. Geol. J. Spec. Issue No.* 6, pp. 153–168.

Dines, H. G., Hollingworth, S. E., Edwards, W., Buchan, S. & Welch, F. B. A. 1940 The mapping of head deposits. *Geol. Mag.* **77**, 198–226.

Dines, H. G., Buchan, S., Holmes, S. C. A. & Bristow, C. R. 1969 *Geology of the country around Sevenoaks and Tonbridge.* London: H.M.S.O.

Dines, H. G., Holmes, S. C. A. & Robbie, J. A. 1954 *Geology of the country around Chatham.* London: H.M.S.O.

Hutchinson, J. N. 1974 Periglacial solifluction: an approximate mechanism for clayey soils. *Géotechnique* **24**, 438–443.

Kellaway, G. A., Worssam, B. C., Holmes, S. C. A., Kerney, M. P. & Shephard-Thorn, E. R. 1973 South-east England. In Mitchell *et al.* A correlation of Quaternary deposits in the British Isles. *Geol. Soc. Spec. Rep. No.* 4.

Kennard, A. S. 1944 The Crayford brickearths. *Proc. Geol. Ass.* **55**, 121–167.

McRoberts, E. C. 1975 Field observations of thawing in soils. *Can. Geotech. J.* **12**, 126–130.

Morgan, M. A. 1969 A Pleistocene fauna and flora from Great Billing, Northamptonshire. *Opuscula Entom.* **34**, 109–129.

Morgenstern, N. R. & Nixon, J. F. 1971 One-dimensional consolidation of thawing soils. *Can. Geotech. J.* **8**, 558–565.

Murchison, R. I. 1851 On the distribution of the flint drifts of the south-east of England. *Q. J. Geol. Soc.* **7**, 349–398.

Skempton, A. W. & Northey, R. D. 1952 The sensitivity of clays. *Géotechnique* **3**, 30–53.

Skempton, A. W. & Petley, D. J. 1967 The shear strength along structural discontinuities in stiff clays. *Proc. Geotech. Conf.* (Oslo) **2**, 29–46.

Thurrell, R. G., Worssam, B. C. & Edmonds, E. A. 1968 *Geology of the country around Haslemere.* London: H.M.S.O.

Topley, W. 1875 *The geology of the Weald.* London: H.M.S.O.

Weeks, A. G. 1969 The stability of natural slopes in south-east England as affected by periglacial activity. *Q. J. Eng. Geol.* **2**, 49–61.

West, R. G., Lambert, C. A. & Sparks, B. W. 1964 Interglacial deposits at Ilford, Essex. *Phil. Trans. R. Soc. Lond.* B **247**, 185–212.

Williams, R. B. G. 1975 The British climate during the Last Glaciation; an interpretation based on periglacial phenomena. *Ice Ages: ancient and modern. Geol. J. Spec. Issue No.* 6, pp. 95–120.

Worssam, B. C. 1963 *Geology of the country around Maidstone.* London: H.M.S.O.

Wymer, J. J. 1974 Clactonian and Acheulian industries in Britain – their chronology and significance. *Proc. Geol. Ass.* **85**, 391–421.

Discussion

B. C. Worssam (*Institute of Geological Sciences, 5 Princes Gate, London SW7 1QN*)

Mr B. C. Worssam remarked on the correspondence of the valley-bottom and hill-top solifluction sheets described by Professor Skempton and Dr Weeks from the Weald Clay outcrop in the Sevenoaks area, to the younger and older Head deposits respectively of the Haslemere district (Thurrell, Worssam & Edmonds 1968). The younger Head deposits of the western Weald pass laterally into the Fourth Terrace of the Arun, which must in consequence be of Devensian age, with the Arun's Third, Second and First terraces representing stages in rapid downcutting that continued through the Devensian (Worssam 1973, p. 3, fig. 5).

Valley bulges occur on the Weald Clay outcrop in the Arun basin, in small valleys incised below the level of the Fourth Terrace. They are therefore considered likely to be of Devensian date. An example is provided by a small valley draining westward from Rusper (TQ 205373) on Sheet 302 of the One-inch Geological Map. Other bulges date from earlier in the Pleistocene, for instance that at Newdigate Brickworks (Worssam & Thurrell 1967, p. 266), which is overlain by Higher Terrace (Dines & Edmunds 1933) deposits of the River Mole and hence may well have a general Wolstonian date. Most of the bulges on the Weald Clay are located in valleys incised into high ground formed by outcrops of the Horsham Stone and of the Small-'*Paludina*' limestone horizon. It is suggested that the valley bulging has been facilitated by the relief of the ground surface outcrops and, possibly, by the presence of displacement shears of tectonic origin (Skempton & Petley 1967). These shears are commonly observed in the cores of deep boreholes in Weald Clay (e.g. Worssam & Ivimey-Cook 1971, p. 13).

References

Dines, H. G. & Edmunds, F. H. 1933 The country around Reigate and Dorking. *Mem. Geol. Surv. Gt Br.* 204 pp.

Skempton, A. W. & Petley, D. J. 1967 The strength along structural discontinuities in stiff clays. *Proc. Geotech. Conf.* (Oslo) **2**, 29–46.

Thurrell, R. G., Worssam, B. C. & Edmonds, E. A. 1968 Geology of the country around Haslemere. *Mem. Geol. Surv. Gt Br.* 169 pp.

Worssam, B. C. 1973 A new look at river capture and at the denudation history of the Weald. *Rep. Inst. Geol. Sci.* no. 73/17, 21 pp.

Worssam, B. C. & Thurrell, R. G. 1967 Field meeting to an area north of Horsham, Sussex. *Proc. Geol. Ass.* **77** (for 1966), 263–271.

Worssam, B. C. & Ivimey-Cook, H. C. 1971 The stratigraphy of the Geological Survey borehole at Warlingham, Surrey. *Bull. Geol. Surv. Gt Br.* **36**, 1–111.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

14

FIGURE 12. View from point 533513 looking towards the ridge north of Morleys Farm. Devensian chert gravel is exposed in a stream channel just behind the view point and high-level (Wolstonian) gravel caps the ridge.

FIGURE 14. Section of core from a depth of 3.5 m in borehole 317H, showing brecciated Weald Clay. The core diameter is 10 cm.

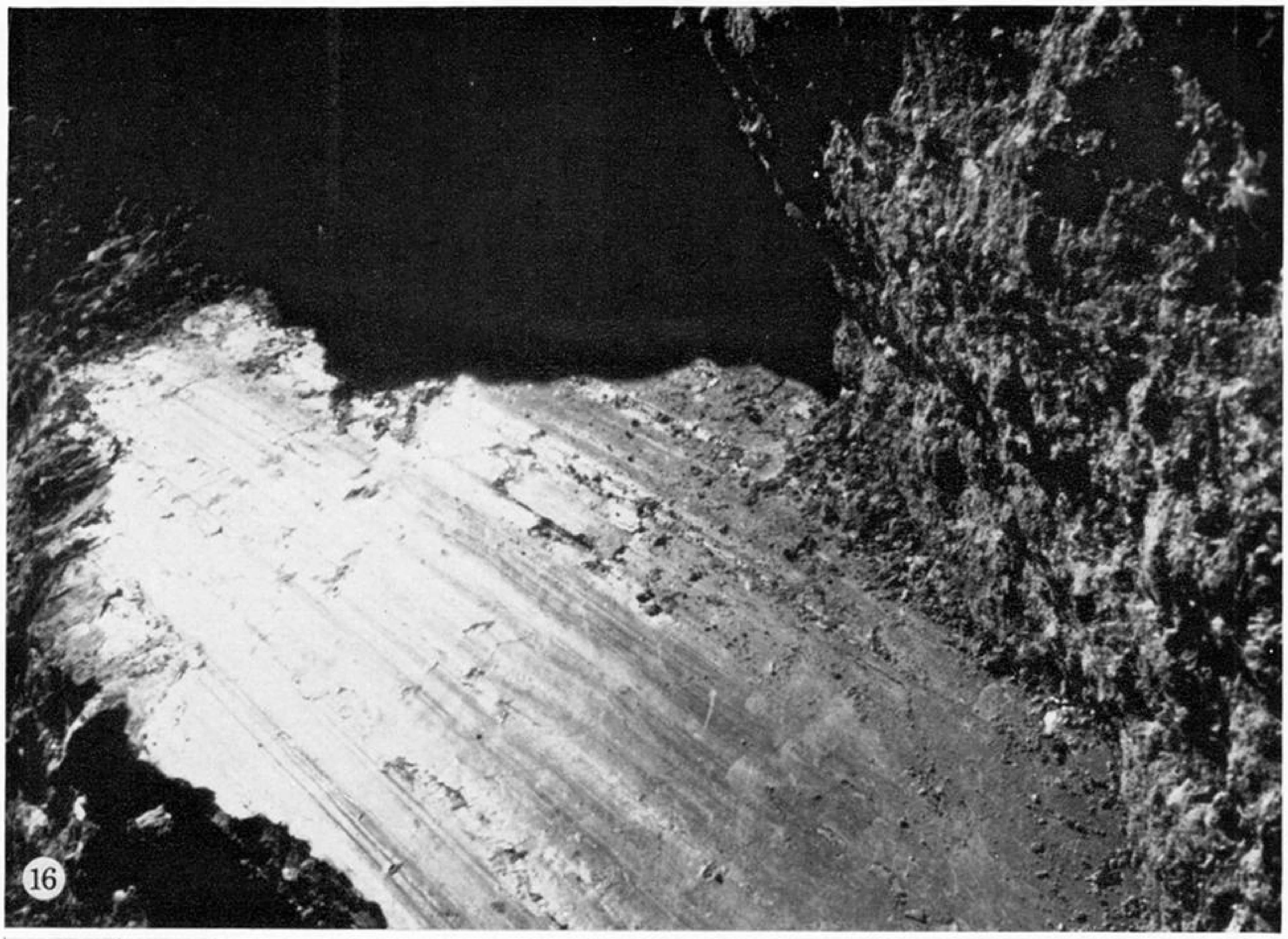


FIGURE 16. Pit F2. Slip surface in gouge clay beneath the upper chert gravel and overlying Late Devensian interstadial fossil soil.

FIGURE 17. Lobe F, looking northwest. The Lower Solifluction Sheet extends beyond the edge of the lobe, in the foreground.

FIGURE 22. Postglacial stream erosion in the valley east of Dale Farm.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES