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THE GLACIATED RIVER BASINS OF EASTERN ENGLAND

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RÉSUMÉ

La plus grande partie de l'est de l'Angleterre est de faible relief et seuls les cours supérieurs des rivières du nord qui prennent leur source dans les Pennines drainent une région dont l'altitude dépasse 300 m. La zone de précipitations dépassant 1 m par an est également restreinte à cette même bordure nord. La plus grande partie de la région dont les eaux s'écoulent vers la mer du Nord est formée de bas plateaux couverts de till glaciaire, et de larges régions près des sources du Wash et de la Humber sont des alluvions situées à faible altitude. La glaciation a agi comme un grattoir, effaçant la plus grande partie des traces de l'évolution au Quaternaire ancien. Après la disparition de la dernière calotte glaciaire recouvrant chaque bassin hydrographique, seules quelques terrasses fluviales se sont développées, mais on n'a pas établi pour elles un canevas général concernant leur corrélation. Comme la plus grande partie de la moraine de fond est composée de sédiments locaux, il doit y avoir eu une importante érosion glaciaire, surtout dans la plupart des régions basses, qui se sont développées et rejointes, déterminant la convergence des rivières vers la Humber et le Wash. Les escarpements tournés vers le nord ont été fortement érodés. Ils ont reculé de quelque 5 km et ont été abaissés d'au moins 100 m. L'érosion contemporaine des falaises côtières a produit beaucoup plus de sédiments qu'il n'en est amené par les rivières : leur volume dépasse même le total combiné des sédiments et de la charge transportée en solution. Cet équilibre fait ressortir la faible extension des bassins intéressés et leur caractère essentiellement de faible relief.

North of the River Thames, most of England was glaciated during the Quaternary. In these basins terraces are much less well developed than in the Thames valley, while within the area covered by the Last (Devensian) glaciation, the lower parts of the river valleys are cut into a till deposited within the last 25 000 years. It might be thought that the presence of glacial deposits which may be dated stratigraphically would give more control over the history of these basins. In fact it must be admitted that our present knowledge is very insecure, and in many ways the deposits of the youngest glaciation in each basin act as a blanket, effectively obscuring the relationships between form and age that may have been there. In addition we have no consensus of the changes to be attributed to the invading ice, although this will be a particular concern of this contribution. Finally, we are

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only just beginning to measure the rates of current denudation within this area, but some estimates of the discharge of water, sediment, and solute load will be assembled.

The area we are concerned with may be divided into three main regions, and each of these conveniently subdivides into two. In the centre is the Trent-Ouse basin, reaching the North Sea through the Humber, and draining nearly one-fifth of England. Along the coast part of the North York Moors, and the till plains of Holderness and Lindsey drain direct to the sea. North of the Trent-Ouse basin the eastern half of northern England is drained by three sizeable rivers, the Tees, Wear and Tyne, and several smaller ones north of the Tyne. Finally, our third region lies to the south, consisting of the Wash drainage (the rivers Witham, Welland, Nene and Ouse) and the short rivers of the low plateaus of East Anglia.

The total discharge of these rivers totals about 300 m^3 sec^{-1}, or about 10 km^3 water in a year. Almost two-thirds of this comes from the Humber, the Tyne contributes about 50 m^3 sec^{-1} and the entire Wash drainage no more than 30 m^3 sec^{-1}. These modest discharges arise from the highly asymmetrical distribution of precipitation in the British Isles, with high totals almost restricted to the western hills and mountains which drain to the Irish Sea. As figure 1 shows, only the highest parts of the Pennines have annual totals of over 1 000 mm. The total discharge is also limited by the convergence between the north-south trend of the main water-parting of England, and the west of north alignment of the east coast. From the divide on Hadrian's Wall, north of the Tyne, to the coast at Newcastle is only 70 km. It is the same distance westward to the divide from Teesmouth, although by the latitude of York it is 130 km, and reaches 150 km between the Wash and the Potteries.

It should also be appreciated that, like so much of the North Sea basin, most of this area is lowland. The 300 m contour is a significant limit, and apart from a small outlier in the North York Moors, ground above 300 m is restricted to a belt some 250 km and an average of 30 km wide along the western edge of the area draining to the North Sea. The highest summits on the water-parting exceed 600 m along the entire distance, with the highest point at Cross Fell, almost 900 m. Yet this high ground forms less than 10 % of the area draining to the North Sea, and much of it is below 100 m. At the head of the Wash, and again west of the Humber gap through the Chalk, extensive lowlands of alluvial and glacio-lacustrine sediments lie very close to sea-level. Over most of East Anglia the till plateaus on the Chalk lie below 100 m, while in the East Midlands the more dissected till plateaus on the Jurassic rocks generally lie between 100 and 160 m. Other low-lying areas include the more irregular till surfaces of Lindsey, Holderness and the lower Tees basin, which are mostly below 25 m above sea-level.

PREGLACIAL LANDFORM EVOLUTION

The first two decades after the war saw intensive work by British geomorphologists on the preglacial history of the British landscape. The success of Wooldridge and Linton in establishing the evolution of the unglaciated area of south and southeast England, suggested that a similar approach could be used elsewhere. Although it is now fashionable to despise this period when geomorphological research was almost restricted to denudation chronology, it can surely be justified as a necessary piece of investigation, disappointing since it was in the end unable to sustain any real conclusions, but nevertheless an approach that had to be followed through. It was not at first sight apparent that the careful field mapping (as opposed to the reconaissance exploitation of the contours on large-scale maps) of ground form would throw so little light on the very difficult problem of the age and origin of the higher parts of the landscape. Indeed, as Linton's masterly summary prepared for the 1964 International Geographical Congress showed, the work had certainly narrowed the possibilities down, and there will be many who would still support his main conclusions. Restating these briefly they are: 1. the recognition of an ancient subaerial surface, with monadnocks, probably of Early Oligocene age. This summit surface is now uplifted differentially, and in southern England at least is warped; 2. below are two main stages of partial peneplanation, the lower of which comes down to 250-300 m and generally forms the summit surface of the scarplands of eastern England; 3. locally transgressing the lowest parts of this surface is a marine plain of Calabrian age; 4. although there are some significant exceptions, the surface form of the British Isles shows a striking degree of adjustment to structure.

Applying these concepts to the present area, we note that by chance the detailed mapping of surface forms has not been carried through the Pennines. It does seem that the summit level of the southern Pennines has been uplifted less than in the Alston Block, the northernmost section of the Pennines, where Trotter described a surface rising to 800 m around Cross Fell, a residual of 893 m. Hudson notes a summit surface with similar residuals in the Askrigg Block to the south, giving the altitude as 550-700 m. These differences in summit altitude accord with the structural divisions within the Pennines, and ties in with the recognition of granites beneath the two northern blocks. To accept relatively greater post-early-Oligocene uplift here is not, of course, to agree with Cuchlaine King who has championed Trotter's view that the major bounding faults have noved so recently that the whole surface reflects the degree of late-Tertiary uplift. There is as yet no hard evidence either way, but the argument depends in part on the correlation between the Carboniferous bedding and surface form, and this does not seem to require recent uplift, while the detail of relief at the faults themselves shows none of the very tight association of structure and form found in active areas such as the western United States. Early Tertiary uplift is, of course, certain; it is major Late Tertiary uplift which is in doubt.

In the southern Pennines, as in North Wales, recent work on deposits let down into deep pockets in the Carboniferous limestone has gone far to clothe our vague outline of the Tertiary history of these uplands. Deep pocket deposits have long been known from Derbyshire, but it was thought that their lithology indicated the preservation of part of a former Triassic cover. As such they did little to aid our understanding of the origin of the upland surface below which they lie; indeed they did much to keep alive the recurrent view that the surface was an exhumed sub-Triassic feature. Careful investigations by Walsh and others has shown that these great sinkholes include a great thickness of Tertiary material, with subsided blocks of Namurian shale at their base. The uppermost layers are dated as Upper Miocene-Lower Pliocene, and the clay (lignitic at the top) and sands accumulated in a terrestrial environment on a land surface of relatively low slope. Since the base of the pocket deposits includes broken masses of Namurian shale, it is concluded that the original sedimentation took place on a surface at about 450 m. This is the intermediate surface of the southern Pennines, and the date for the summit surface,

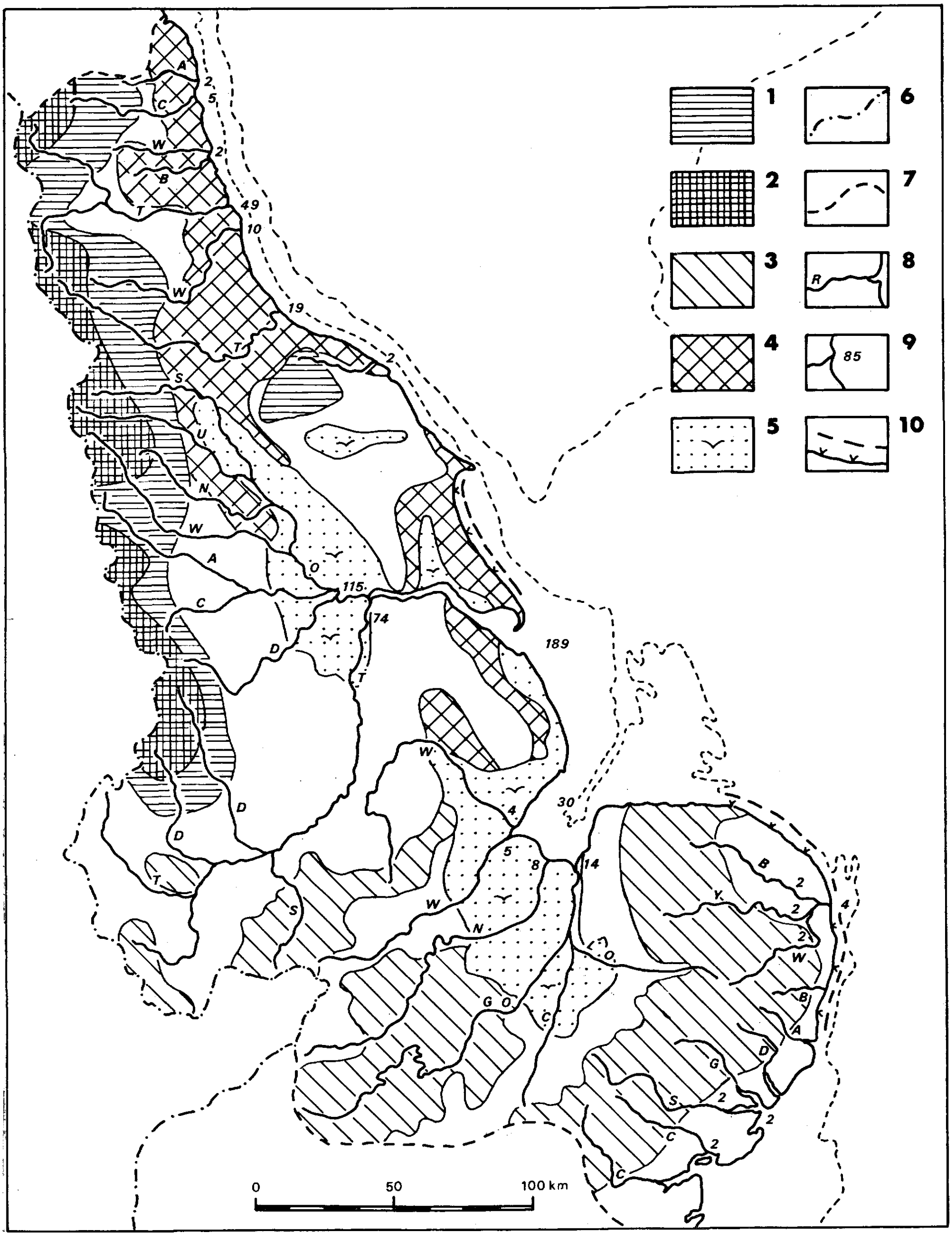

FIG. 1. — *The River Basins of Eastern England North of the Thames. 1, land above 300 m; 2, area with over 1 000 mm precipitation per annum; 3, older drift plateaus (Anglian and Wolstonian tills); 4, newer drift (Devensian tills); 5, main areas of alluvium and associated glacio-lacustrine deposits; 6, main water-parting of England; 7, other water-partings; 8, main rivers with initial letters (see list below); 9, mean discharge of main rivers in* $m^3\ sec^{-1}$*; 10, active cliffs with retreat* ~*1* $m.yr.^{-1}$*, the offshore line indicating the approximate position*

and the Late Pliocene land surface that was in places transgressed by the Calabrian Sea.

Finally it may be helpful to return to the general pattern of landform, and to emphasize some points which may be overlooked almost because they are so obvious. We have already stressed the broad extent of lowland around this part of the North Sea basin, and the way most of the high ground forms a narrow belt along the water parting, from Derbyshire to the Scottish border. As Linton pointed out, the summit surface of the weaker rocks (really everything younger than the Lower Coal Measures) nowhere rises above the pre-Calabrian land surface except for the single exception of the North York Moors. Equally, it is common for the more resistant rocks of the scarplands to rise to the level of that surface, so that the northern edge of the unglaciated Chilterns rises to 246 m, the Jurassic in Northamptonshire to 210 m, and the Chalk of East Yorkshire to 246 m again. We shall show that it is likely that the summits have long been rather lower between the Humber and the southern part of East Anglia, but we cannot be sure of that until we have some estimate of the amount of lowering accomplished by the ice-sheets. The upland-lowland boundary is well marked, and corresponds closely to the 300 m contour. The eastern margin of the Pennines commonly drops off rather abruptly below this level, and this landform boundary can be traced the whole length of the hills. It emphasizes the adjustment to structure (in the full Davisian sense) that we have already noted. Inspection in more detail of particular elements of this boundary emphasize this conclusion—for example in the well-developed cuesta of the Fell sandstone north of the Tyne which rises to 441 m in Rothbury Forest and to 315 m above Chillingham. It remains possible that the margin has been emphasized by some monoclinal warping in the Late Tertiary, but it does not seem a necessary condition.

In general, the preglacial rivers flowed along the same courses as today. Even where thick deposits of till and other glacial sediments were laid down, the tendency was for the new surface to rise and fall with the buried sub-drift surface so that rivers tended to reoccupy the general lines they had followed before glaciation. This occasionally involved reversal in the direction of flow, while there was often local divergence between the buried and the present valley. Nevertheless, there seem to have been some considerable differences in the preglacial pattern, especially in terms of the present Humber drainage. Reconstruction is, of course, difficult and some of the older courses we can recognize may themselves be relatively short-lived routes followed at some stage within the complications of the glacial period. Thus it seems certain that the Trent was very recently diverted from the Lincoln Gap through the Jurassic limestone to its present course along the Lias outcrop to the Humber. It is possible that this represents a return to an earlier route from which it had been diverted by ice to the north, but it is more likely that the Lincoln route itself was a stage of northward adjustment from an earlier route even further

of the shoreline at the end of the Flandrian transgression, i.e. retreat over the last 6 000 yr. The offshore contours are at −20 and −40 m. — Key to rivers, from N-S: *A, Aln; C, Coquet; W, Wansbeck; B, Blyth; T, Tyne; W, Wear; T, Tees; S, Swale; U, Ure; N, Nidd; W, Wharfe; A, Aire; C, Calder; O, Ouse; D, Don; T, Trent; D, Derwent; D, Dove; S, Soar; W, Witham; W, Welland; N, Nene; GO, Great Ouse; C, Cam; LO, Little Ouse; B, Bure; Y, Yare; W, Waveney; B, Blyth; A, Alde; D, Deben; G, Gipping; S, Stour; C, Colne; C, Chelmer.*

south along the line of the Ancaster Gap towards the Wash. The Yorkshire Derwent similarly suggests late diversion to the Humber from a direct route to the sea through the Vale of Pickering, now blocked by moraine. Further north the opposite has happened, with the preglacial Wear Valley leading north to join the Tyne replaced by a more direct route to the sea. Whether the Swale was formerly tributary to the Tees is less certain.

One other Quaternary adjustment involved a major shift of the main water-parting of England. Prior to the Wolstonian glaciation, the Soar headed near Stratford on Avon, and the main water parting ran from the Lickey Hills, southwest of Birmingham, directly across to Edge Hill. As Shotton has shown, the ice advance up the Soar Valley impounded Glacial Lake Harrison at about 125 m. The western margin of this lake lay against the ice in what is now the lower Severn valley. Thick lacustrine silts were exposed when the Severn ice barrier failed, and a new drainage line rapidly cut back into the lake deposits, no doubt aided by the discharge of meltwater into the declining lake. This headward erosion by the Avon shifted the divide some 35 km northeast to east of Coventry leaving the Soar with an appreciably smaller catchment. The mean annual run-off from this area is fairly low (mean discharge of the Avon at Evesham is 13.07 $m^3 sec^{-1}$ from 2 210 km^2), so we may estimate the Trent below Nottingham to have lost 12 % of its former discharge by this change in catchment area.

QUATERNARY GLACIATION

Great Britain was glaciated from a number of centres, mostly those western, upland areas which are today areas of unusually heavy precipitation. At maximum extent the ice from these domes merged to form a continuous ice-sheet, reinforced by Scandinavian ice that crossed the North Sea basin. In the south the ice tended to swing round from a south-eastward direction to southward or even west of south, drawn by the more rapid melting from easier access to Atlantic air, and no doubt also constrained by the presence of the ice to the east. At low points in the main water parting vigorous streams of ice poured across from the western centres, only to become caught up in the predominantly southerly movement. South of the Scottish border ice moved eastward through the Tyne gap, across Stainmore, down Airedale, and into the upper part of the Trent valley. Between these points the higher ground may have been ice-covered, but the depths were not great enough to allow significant discharge. In the Pennines south of the Aire gap, and again in Staffordshire, meltwater channels also crossed the present water parting. Within the Pennine system, the Cross Fell area was possibly an area of ice-dispersal, and the area around the head of Wharfedale was certainly an area with sufficient accumulation to provide an additional local centre of ice movement. To the north the Cheviots too may have been an area of local dispersal.

It has always been accepted that the ice streams crossing the Pennines have modified the routes they followed. The form of Stainmore suggests modification by the ice-stream, and the trail of erratics of Shap granite has emphasized the reality of the flow. Outside our present region, Linton has shown that radial troughs were imposed on the Lake District, while Gresswell has produced convincing evidence for ice scour as the Irish Sea ice-sheet moved out of the Irish Sea and into the Cheshire Plain. Some subglacial features are due to subglacial meltwater, such as the buried tunnel valleys of East Anglia, but these frequently lie within much larger troughs which can only have been the work of ice itself. The chalky tills of eastern England alone are estimated as about 200 km^3, with an average of about 30 % chalk. It is unlikely, given the directions of ice flows across eastern England, that much of this can have been excavated from beneath the North Sea, so we must envisage considerable modification of the land area during glacial times. Nor is denudation restricted to the Chalk—the large proportions of blue, unweathered clay in the Chalky till of East Anglia, with derived fossils such as *Gryphaea incurva* suggest considerable erosion of the Lower Cretaceous and Jurassic clays.

In one or two areas it seems possible to set limits to the extent and style of glacial erosion of the lowland landscape. In Durham, Beaumont has shown how the till rapidly acquires a proportion of Magnesian limestone fragments once the escarpment is crossed, stabilising after a few kilometres to something like 50 % local material. The pattern of incorporation suggests particularly intense denudation at the scarp and relatively little after 4-5 km down the dip-slope. Along the southern boundary of Cambridgeshire, the chalk scarp is a low feature with a gentle slope, contrasting with the steep and high escarpment in the Chiltern Hills beyond the limit of glaciation. Rather secure evidence suggests that the scarp has been set back about 5 km, and lowered by 50-60 m at its crest. Perhaps equally interesting is a drift-free zone fully 10 km wide in front of the scarp which seems to have been the main area of erosion. We may note a very similar scarp-front hollow in the Vale of Belvoir. Here again the drift cover over a wide area is negligible, and we believe that there has been extensive lowering and extension of the Vale by glacial erosion.

Widespread glacial erosion has not so far been established outside these particular localities, but it seems very likely that both the Vale of York and the Wash-Fens embayment have been considerably modified by ice. We envisage both deepening and the integration of a formerly more segmented vale form. In the case of the Wash it is very likely that the breach in the Chalk is an ice streamway of the style Gresswell proposed for the Dee and adjacent troughs. Thus the Vale of York is approached from the north by a major ice stream that as we have already shown eroded the scarp of the Magnesian limestone in Durham. That ice stream was reinforced southwards by tributary streams, each of which caused major modifications to the Pennines valleys down which it flowed. One we have seen carried Shap erratics across Stainmore and was vigorously supplied from the Vale of Eden ice flow. Others to the south carried lesser flows of ice from west of the Pennines (although some did get across as into upper Wensleydale) but were reinforced from the accumulation area centred on Dodd Fell. This ice did not lose its power as it approached the Vales of York. In the area immediately west of Harrogate strongly streamlined forms cut across the local structure and show the erosional power of this margin of the Vale of York ice-stream. No doubt the erosion and integration of the vale at the head of the Humber did as much to ensure the size of the Humber catchment as the minor derangements that triggered the diversion of the Trent and the Derwent.

If ice had a major role to play as an erosional agent, conversely the deposition of till and gravel have greatly modified the land. Here we need to differentiate between the older and more subtly dissected plateaus of East Anglia and the East Midlands, and the tills of the Last (Devensian) glaciation further north. In Lindsey, Holderness, the northern part of the Vale of York, Durham and Northumberland, the tills have been dissected by the major rivers, but the smallest channels still find themselves flowing round the features left by the decaying ice. This is true whether they are the irregular morainic mounds of Alford in Lincolnshire, or the drumlins north of York. The relationships on these young and irregular glacial drifts remind us of the relationship between river discharge and power of erosion, for it is all too easy to fail to relate the profound incision and land-surface organization achieved along the main valleys to the glacial relics along the interfluves. In addition land elevation and distance to base-level has played its part, for dissection is necessarily slow within the Vale of York or the lower Tees valley, and can proceed rapidly where the little burns of the Northumberland coast have cut steep-sided gorges into the elevated till plain.

While in theory we ought to be able to appreciate the older drift plateaus of the East Midlands and East Anglia as more advanced stages of the process of adaptation to a fluvial regime, it must be admitted that the jump in stage is too great to achieve this. For most of this century the contrast between the constructional features of the Newer drift and the smooth surface of the Older drift has been appreciated, yet we still cannot be sure whether the contrast is due to age or was an original feature. On balance there seem reasons to believe that most of the older till plateau was always fairly smooth. Its dissection has proceeded much further in the East Midlands than in East Anglia, where lower altitude, the combined results of subsidence along with the North Sea basin, glacial erosion of the highest parts of the former Chalk escarpment, and the overall eastward slope of the summit surface, has reduced the vigour of the rivers and left the main interfluves almost unscathed.

We finish this section by returning to the problem of the altitude of the preglacial summit surface of East Yorkshire and Lincolnshire. If glacial erosion has, on the whole, been confined to the vales where the ice was deeper, particularly where it was channelled between hills as in the northern part of the Vale of York, then the cuesta summits still lie close to their preglacial level. The exceptions are where scarps lying across the direction of ice movement have been overridden and lowered—by 50-60 m in the case of the Cambridgeshire chalk. These glacially-lowered scarps are free of drift, as are almost the entire cuestas on the Jurassic limestone and Chalk either side of the Humber. Thus if free of drift is synonymous with glacial erosion, then these cuestas may have been lowered 50-60 m, and in preglacial times summit levels may have been more nearly accordant with the rest of the English scarplands. However, the absence of drift from these cuestas might instead be a result of the generally parallel relationship between their alignment and the direction of ice flow, most readily concentrating movement, and thus erosion, in the intervening vales. I find this explanation the most convincing, and coupled with plateau forms which do not suggest glacial erosion, conclude that the lower summit heights of the area between the Market Weighton axis and the southern limit of glaciation are a preglacial feature. They are related to the long-established line of the river Trent, but surely reflect a long-established tendency for the North Sea downwarp to extend into this part of eastern England.

RIVER TERRACES

In contrast to the extensive flights of terraces found beyond the glacial limit, the glaciated river basins have a relatively restricted flight of terraces. The best developed flight is along the Trent, and these will be discussed in most detail. Some of the Wash rivers have two or three distinct terraces, but many rivers have little more than a single terrace above the present foodplain. In the case of the northern basins this is the result of the short period of time since deglaciation, while in the case of East Anglia, recurrent sinking of the land seems to have prevented normal terrace development as suggested by Steers many years ago. Instead these valleys have relatively thick alluvial sequences in the lower parts of the valleys. The knowledge of these is restricted to the upper layers, and the history of these was worked out by Jennings and Lambert in the course of establishing the origin of the Norfolk Broads.

On the continent it has been fashionable to account for river terraces predominantly in terms of changing regime with climatic change, and in particular to view the terrace as an aggradation feature related to cold conditions. In the lower parts of the valleys the possibility of interglacial sea-level rise causing aggradation has of course also been appreciated, and this has been the most common explanation of terraces in the British literature. The improved understanding of river behaviour that has come from such American workers as Leopold, Wolman and Schumm suggests that neither of these views has much to commend it. Rivers do not need to aggrade to form a terrace, since in the course of flowing to the sea at all they form a floodplain composed predominantly of point-bar deposits and in thickness equivalent to the depth of the channel at bankfull discharge. If such a floodplain is dissected a terrace will result. Clearly climatic change or sea-level change may bring about incision into a floodplain, and in particular a fall of sea-level or the reduction in sediment load with improving climate and revegetation of the valley sides are both likely to bring about floodplain incision and terrace formation. Those few terraces formed by aggradation *sensu stricto* (as opposed to cut and fill) are readily recognized since they are appreciably thicker than normal terraces.

The Trent sequence is full and may useful serve as a basis with which to compare other sequences. They have been examined from a number of points of view, morphological, archaeological, petrological and faunal content, and there is now considerable agreement on the conclusions. As with other Midland rivers, the highest surviving terraces immediately postdate the retreat of the Wolstonian ice-sheet from the area. The height of these terraces above the present floodplain varies a good deal from one valley to another since it is a measure of the amount of incision since that stage. In the middle Avon valley the highest terrace (Avon No. 5) is about 45 m above the floodplain, but in the Trent, the highest part of the Hilton terrace in the Burton-Derby area is about 27 m above the floodplain. The separation changes little downstream, and the Eagle gravels southwest of Lincoln reach 34 m with the nearby Trent floodplain at about 6 m. This terrace is sometimes described as fluvioglacial, a somewhat imprecise term. There are lumps of chalky till within the gravels, and the bedding has been described as "torrent bedding," so it may be that discharge and load were rather higher than when some of the later terraces were formed. A Lower Hilton terrace at 12-18 m above alluvium records a further stage in valley initiation, and below that is the Beeston terrace, 9 m above alluvium and containing *Hippopotamus,* usually an indication of Last Interglacial (Ipswichian) age. The upper part of this terrace is closely associated with discharge from the Irish Sea ice-sheet, which poured meltwater into the Trent through the Churnet and other spillways. Thus the geomorphological relationships and the faunal evidence suggest that both the last stage of the Ipswichian terraces (to which the Hilton terraces must also belong) and the maximum advance of the

Devensian ice are not readily separated within the Trent valley, at least on altitudinal grounds. No doubt there was some reworking without much change of level.

Following the Devensian advance, two further stages are recognized. Downcutting throughout the whole length of the Trent valley has left the Beeston terrace separated from the floodplain level, while below Nottingham, a clear knickpoint leaves a further terrace, the Floodplain terrace, about 3 m above the floodplain at Newark. These seem to be of Lateglacial age and mark the adoption of the course to the Humber. It is worth noting that the limited rejuvenation into them has worked about 165 km up the Trent, or 40 km above the present tidal limit at Cromwell Lock. On this basis we are not likely to find postglacial terraces far up the other rivers south of the Newer Drift limit, and we would thus expect terraces on the rivers draining to the Wash to have lower terraces of Ipswichian age (corresponding to the Hilton and Beeston terraces) and perhaps to have higher terraces of Wolstonian or even Hoxnian age, particularly if current views are correct and East Anglia was not covered by Wolstonian ice.

No other river draining to the North Sea north of the Thames has a terrace as high as the Upper Hilton. Indeed, apart from a local feature on the Wear clearly related to the decay of the Devensian ice-sheet, only the Great Ouse has a terrace as high above the floodplain as the Lower Hilton. Presumably this reflects the vigour of the sizeable discharge of the Trent, and perhaps the preferential development of an early drainage line with the melting of the Wolstonian ice, concentrating discharge and sediment along the Trent valley. On several rivers the highest terrace lies about 10-13 m above the present floodplain, this is true of the Nene, Welland, Aire, Wharfe and Tees. It is noticeable that where rivers have a terrace above 10 m, then three terraces are recognized above the present floodplain, usually an intermediate one at 6-7 m, and the lowest 3 m above the floodplain. Whether the sequence of three can be correlated with the Trent sequence is not known. Finds of *Hippopotamus* have been made at two sites outside the Trent basin, the 12 m terrace of the Aire in Leeds, and the terrace of the Cam in Cambridge. Many of the rivers entering the North Sea also have buried channels. Reported depths for these are generally confined to borings in connection with docks or bridges, and necessarily reflect the maximum depths attained within the present coastline. It is not known how far depths continue to fall out to sea. The constraint is of course less likely to be the sea level attained during the Last glaciation (or earlier) than the extent of incision into the relatively gentle floor of the North Sea. In this respect the more northerly rivers had a decided advantage since deeper water lies much nearer the present coast. Indeed in the south the offshore submarine slope is as low as, or even lower than the gradient of the lowest part of the present rivers; in the north even though the rivers are much steeper, offshore slopes generally exceed the gradient of the present river channels. The contrast is likely to have led to some differences in behaviour with fluctuating Pleistocene sea-levels.

CONTEMPORARY EROSION

For perhaps 30 million years the rivers have discharged water, sediment and dissolved substances into the North Sea from this part of England. There have been small changes in the contributing area, but these will have been overshadowed by changes in the relative levels of land and sea, and the catastrophic changes of the glacial period. For a longer period south of the Humber, and for perhaps 25 000 years to the north, the present channels have discharged water, sediment and solute loan, while for 6,000 years or so the sea has stood near its present level and attacked the existing coast. We have very few measurements of discharge of sediment or solutes, and even these must be used with the usual caveats about disturbance due to man. Nevertheless, it seems useful to conclude this rather historical account by trying to tabulate contemporary erosion.

We are concerned here with all material discharged into the sea, whether as suspended load, as bedload, as dissolved load, or direct from coastal cliffs. Thus the balance differs considerably from that for mud along put forward for the whole North Sea basin by McCave. First of all, the rivers we are concerned with discharge an estimated 300 $m^3 sec^{-1}$ water each year. There are published figures for the Tyne, where Hall estimated the discharge as 130 000 Mg (tonnes) by suspension, 20 000 bedload, and 80 000 in solution. He noted that these figures gave a mean rate of erosion of 70 mm $10^3 yr^{-1}$ and that this looked reasonable when compared with the rate derived from the upland catchment of the Catcleugh reservoir, with a rate of 127 mm $10^3 yr^{-1}$. Expressed by volume, this gives a combined solid discharge of 115 000 m^3, and solute discharge of 62 500 m^3. While the solid discharge is likely to be higher for the relatively steep Tyne than for some of the rivers further south, we may be sure that the solute figure is far from representative, indeed it may be a low estimate for the Tyne itself. We have a figure of 70 $m^3 km^2 yr^{-1}$ from Pitty for the Carboniferous limestone outcrop of the Peak District, and a figure of 43 $m^3 km^2 yr^{-1}$ for $CaCO_3$ for the Yare (Edwards, 1972). Figures for larger basins do not seem to be available, but if the mean rate for the Trent is only half that for the Carboniferous limestone outcrop, solute discharge alone is likely to be of the order of 300 000 m^3.

Applying these figures to the liquid discharge of the rivers we are describing here we get the following range of values:

liquid discharge, 300 $m^3 sec^{-1}$, or 10 $km^3 yr^{-1}$;
solid discharge (largely in suspension), 400 000-700 000 $m^3 yr^{-1}$;
solute discharge, 500 000 m^3-1 200 000 $m^3 yr^{-1}$;

and the most probable figures seem to be $5 \times 10^5 m^3 yr^{-1}$ as solid discharge, and $9 \times 10^5 m^3 yr^{-1}$ in solution. This total of $14 \times 10^5 m^3$ a year from the rivers is appreciably less than the present sediment loss from coastal erosion. Good estimates are available from Cambers of the long-term rate of retreat for the till cliffs of Holderness and Norfolk. In both areas rates are around 1 myr^{-1}, indeed the average is above that for Holderness. Annual losses are calculated at $7.5 \times 10^5 m^3$ for Norfolk, and $10^6 m^3$ for Holderness. Estimates for the long cliff-line to the north are far more approximate, but it seems unlikely that the annual figure can be less than $5 \times 10^5 m^3$, and it could be twice that, for although many of the cliffs show till over rock, till comes down to the beach in places, while elsewhere the "rock" is relatively weak shale. Thus a reasonable estimate for the coastal erosion seems to be $25 \times 10^5 m^3 yr^{-1}$, or almost twice the combined total of solid and dissolved discharge from the rivers. This figure no doubt reflects the history of sea-level over the last 10 000 years, and in particular the continuing slight rise of sea-level at the present time. The figures also draw attention to the drastic change in sediment balance that may be brought about if present attempts to stop cliff erosion are successful. Indeed, since all but a bare 10 % or so of the river sediment is mud, while the cliffs run as high as 60 % sand and gravel, something like 96 % of the contemporary supply of beach sediment must come from cliff erosion. Finally they draw attention to the relative balance of marine and subaerial erosion in a situation such as that of eastern England where the rivers are short and the coastline long. We should perhaps end by reminding ourselves that no drop of rain reaching the North Sea by an English river north of the Thames has to travel more than about 150 km, while a sixth of the discharge comes down the Tyne which is not more than 90 km from source to mouth.

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DISCUSSION

F. AHNERT. — *Would you please comment some more on your statement regarding the different height, in different river systems, of river terraces having the same age. As they relate to the same base level, they must have different gradients. Is this an expression of different grain sizes and/or different discharges?*

K. H. CLAYTON. — Yes. Gradients vary with differing discharge, while in particular the rate of incision at a given distance from the sea is related to discharge as well as to height above base-level. I am sure it is wrong either to correlate river terraces on different rivers by height above the present floodplain, or to imagine that height of a terrace above a floodplain is in any direct way related to past base-level.

B. D'OLIER. — *Why is it that glacial erosion is less when high ground such as the Lincolnshire Wolds lies parallel to the ice-flow, than when high ground lies tranverse to the flow direction?*

K. M. CLAYTON. — As the ice can move freely each side of the uplands, the speed of flow over the higher ground is reduced, and so there is little or no erosion.