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

The Quaternary History of the English Channel [and Discussion]

G. A. Kellaway, J. H. Redding, E. R. Shephard-Thorn, J.-P. Destombes, H. H. Lamb, A. J. Smith, L. H. N. Cooper and C. Turner

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The Quaternary history of the English Channel

By G. A. Kellaway,* J. H. Redding,† E. R. Shephard-Thorn* and J.-P. Destombes‡
* *Institute of Geological Sciences*, 5 *Princes Gate, London SW*7 1*QN*
† *c/o Ove Arup and Partners*, 13 *Fitzroy Street, London W.* 1
‡ 8 *rue d'Angleterre, Ambleteuse* 62154, *France*

Several lines of evidence for former glaciation of the English Channel are considered. These include the following major geomorphical features: (1) extensive areas of flat featureless sea bed bounded by cliffs with residual steep-sided rock masses rising about 60–150 m above them, (2) terrace forms bounded by breaks in slope or low cliffs, (3) palaeovalley systems related to the present land drainage, (4) enclosed deeps (fosses); all except (3) may be attributed to a glacial origin. The distribution of erratics on the Channel floor and in the modern and raised beaches of its coasts are attributed to widespread Saalian glaciation. This glaciation was responsible for the deposition of morainic material at Selsey and the damming-up of glacial Lake Solent. The so-called '100 foot raised beach' of west Sussex is now re-interpreted as a fluvioglacial deposit laid down at the northern margin of the English Channel ice.

It is thought that at the height of the Saalian glaciation mean sea-level fell to between 90 and 180 m below o.d. and that for a time the ice was grounded near the western margin of the continental shelf. Possible reconstructions of the limits and main movements of the Weichselian and Saalian ice sheets covering the British Isles and English Channel are included.

1. Introduction

In this account we attempt to show that the English Channel has been subjected to one or more Quaternary glaciations. In dealing with these problems we have tried to bring out the inter-related character of the various lines of evidence and to interpret them as part of the Quaternary history of NW Europe. The non-glacial paradigm which has dominated geomorphology in southern England for over a century has achieved little in explaining the relations of the inland surfaces to the evolution of the coastline and adjacent sea floor. The crude concept of 'periglacial southern Britain' is out-of-date, but by including the Celtic Sea, Bristol Channel and English Channel in the glaciated area we take a step which may require modification of the theories relating to the formation and behaviour of ice sheets formed on continental shelves by heavy precipitation in strongly oceanic regions.

2. Geomorphology of the English Channel

A bibliography of research relating to the geology of the Channel floor has been recently published by Smith, Hamilton, Williams & Hommeril (1972). The youngest sediments that have so far been identified beneath the floor are Plio-Pleistocene sediments in the Western Approaches Syncline (Curry *et al.* 1972). Evidence from the Neogene rocks of Brittany (Milon 1936; Durand 1960) and the Cotentin (Elhai 1963; Larsonneur 1971) and the possible post-Coralline Crag uplift of the eastern part of the Weald and North Downs (Wooldridge & Linton

1955; Smart, Bisson & Worssam 1966; West 1972) relative to the North Sea basin shows that tectonic movements continued into early Quaternary times. Earthquakes centred near the Channel Islands have been described by Mourant (1931).

In its present form the floor of the Channel is a denuded surface with a complex history of tectonic movement, erosion and weathering. The chief distinction between the submarine and inland areas is that marine erosion has recently been more important than subaerial erosion in the coastal regions. Glaciation may have played only a limited part on the mainland of France, but it has almost certainly been the major factor in shaping the adjacent floor and coastline of the Channel. In southern England however glacial and fluvioglacial processes are now seen to be much more important than was formerly suspected. The geomorphology of the three regions of inland France, the Channel floor and inland southern England should, and does, reflect these differences.

Four distinctive groups of features characterize the floor of the Channel. These are:

(*a*) Extensive areas of very low relief, largely featureless save for isolated groups of islands or stacks rising in some cases as much as 120–150 m above the sea floor.

(*b*) Terrace-like gently sloping shelves bounded at their outer edges by well-marked breaks in the slope or submerged cliffs.

(*c*) Palaeovalley systems, either open or infilled.

(*d*) Enclosed deeps or fosses, which may also be open or infilled.

(*a*) *Areas of low relief*

Between the Straits of Dover and the continental margin the floor of the English Channel and its Western Approaches form a broad shelf which declines towards the west with an average gradient of 1:6000. This low relief is combined locally with a smooth flat bedrock surface which is of a singularly monotonous character. It might in fact be likened to flat glaciated terrain, and, if exposed by a fall in sea level, would show something of the same relief, with isolated circular, crescentic and elongated lakes situated in rock basins linked by anastomosing or meandering rivers. This aspect of the submarine relief is often taken for granted in works dealing with the geology of the floor of the Channel, but it is a very important element in the geomorphology.

(*b*) *Submarine shelves and submerged cliffs*

In the Straits of Dover and the eastern part of the Channel a positive break in slope appears at the 37 m isobath. Prestwich (1892) was among the first to recognize the existence of this feature which separates a gently inclined terrace on the shoreward side, with an average height of 27 m, from an area of somewhat deeper water. In some places, as for example the western side of the deep water channel that runs north–south through the Straits of Dover and, again, on an east–west line south of Beachy Head, the steepness of the feature warrants the use of the term cliff. Other submerged cliff-lines can be identified off Portland Bill and also near the coasts of Devon and Cornwall.

Although the submerged cliff-lines indicated in figure 1 are bounded shorewards by a positive break in slope at a depth of 35–40 m below O.D., the terrace level narrows in a westerly direction and the negative break which occurs at about 55 m in the eastern part of the Channel lies at greater depths in the west, corresponding with the gradient of the Channel floor.

On the southern side of the Channel a series of breaks in slope associated with submerged cliffs also separate a shoreward terrace from the deeper water near the centre of the Channel

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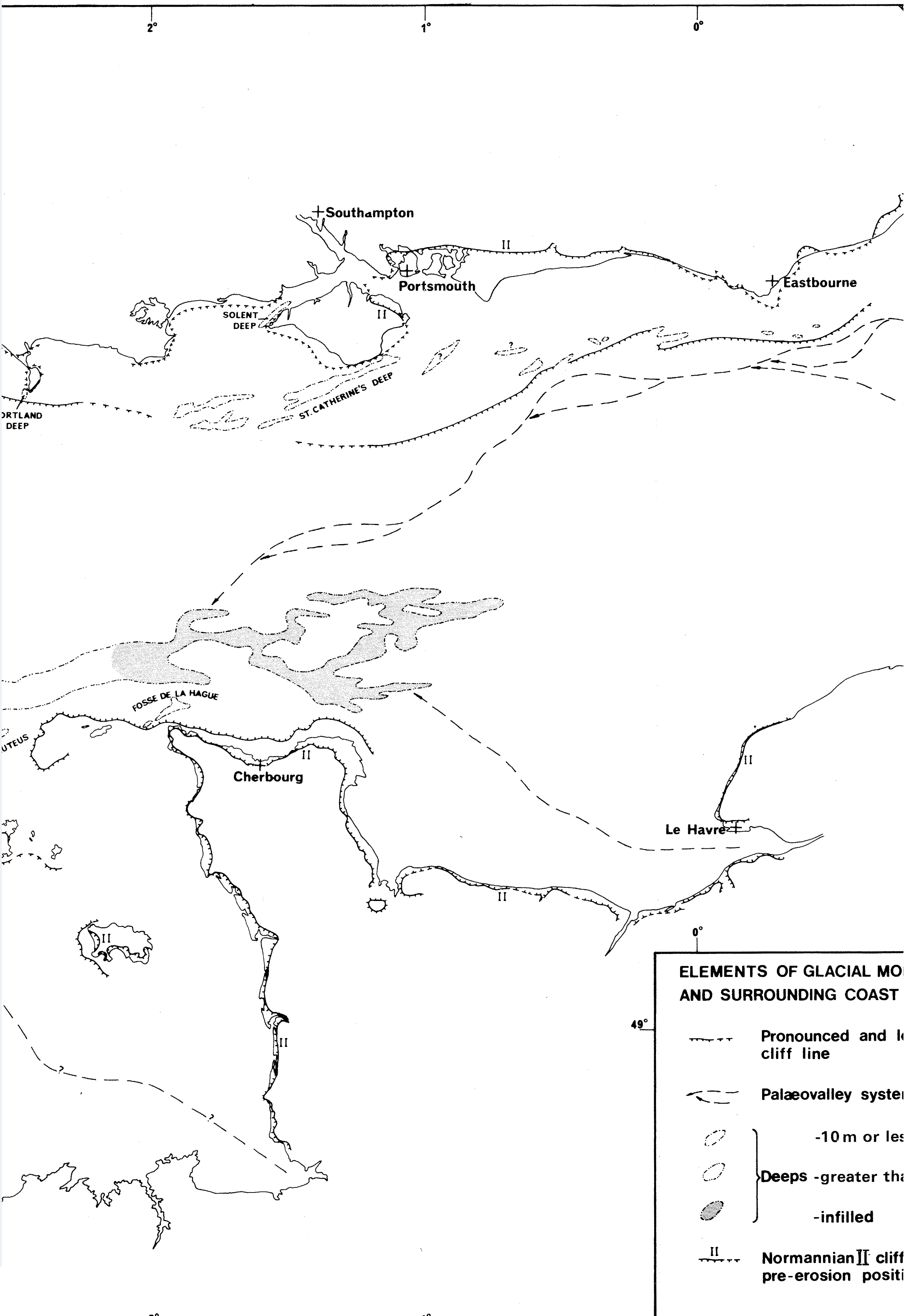
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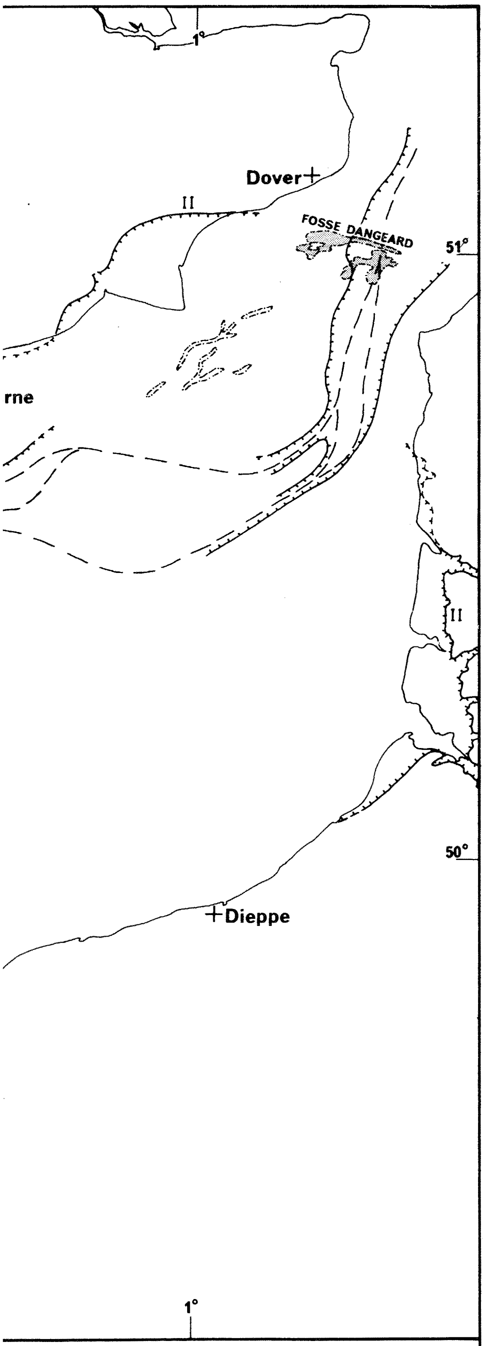

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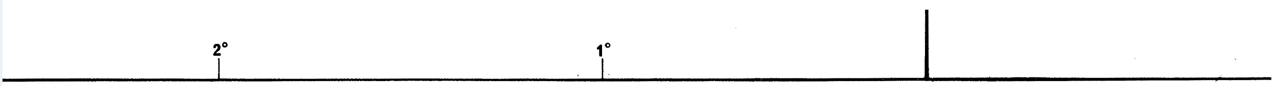

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FIGURE 1

(*Facing p.* 190)

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(figure 1). There are, however, areas on both the French and English sides of the Channel where the cliff-line appears to have been breached or eroded. Thus in Lyme Bay and off the coasts of Calvados and the Isle of Wight, and again south of Dungeness, there is no definite break of slope between the shoreward terrace and the central part of the Channel. It is thought that this feature may have considerable significance.

There appears to be no simple relation between the position of the submerged cliff and the bedrock geology. Locally, off the coasts of Devon and Cornwall the cliff-line appears to be associated with the contact between the Permo-Triassic strata forming the lower surface and the Palaeozoic and metamorphic rocks on the shoreward side (Curry *et al.* 1972; Dingwall 1971). North of the Cotentin Peninsula off the Channel Islands and north coast of Brittany the cliff-line corresponds fairly well with the boundary between the Palaeozoic, metamorphic and igneous rocks on the shoreward side and the softer Mesozoic and Tertiary strata which form the sea bed in the deeper central area of the Channel floor (Boillot 1964; Larsonneur 1971). Further west along the Brittany coast the cliff-line lies progressively further away from the contact of the Tertiary and older rocks and is incised in the older harder basement formation.

South of Beachy Head an almost continuous cliff-line can be followed westwards almost to Lyme Bay. This cuts across Wealden, Upper Cretaceous and Tertiary strata and appears to bear no relation to the recorded structure. In the Straits of Dover the relief is even more discordant and appears to cut across Jurassic and Cretaceous rocks with little or no evidence of structural control.

(*c*) *Submerged palaeovalleys*

Palaeovalleys may be continuous with the valleys of present day rivers or may exist in the form of linear or sinuous depressions on the floor of the Channel, in some cases related to the presence of fosses or closed depressions into which they may lead. Of these, the palaeovalley of the Seine, has been studied in the greatest detail (Robert 1969; Larsonneur 1971). It would appear that the position of the valley indicated by submarine contouring is approximately the same as that of the buried palaeovalley, though the latter is more deeply incised than would appear from soundings. The bedrock profile of the Seine palaeovalley appears to be graded for at least part of its course to a base level related to a series of deeps (fosses) that form the proximal end of a system of tributaries leading to the Hurd Deep (Fosse Centrale). Another palaeovalley system that has been identified by bathymetric methods is the one we have called the Eastern Channel valley (figure 1). It can be traced through the deeper part of the Straits of Dover, to join up with the infilled deeps north of the Cotentin.

(*d*) *Deeps or fosses*

Of the four morphological elements discussed in this paper the deeps (or fosses) have attracted the most attention and caused the most controversy. They consist of hollows, circular, crescentic or elongated, either open or partially or completely infilled with sediments and are too deep to have been excavated by normal fluviatile processes. In figure 1 the known larger deeps are indicated with names where available, for example, St Catherine's Deep (figure 2) south of the Isle of Wight. Also included are some of the smaller and shallower deeps which have been identified off the south coast of England. Some of these are marked with a query (?). These may have resulted from localized scouring of infilled sediments associated with palaeovalleys that are, as yet undescribed. Also grouped with the deeps (fosses) rather than palaeovalleys are the infilled channels forming the eastern extensions to the Hurd Deep. These depressions are greatly overdeepened in parts, and though they are connected with the palaeovalleys of the Seine and Eastern Channel the confluence shows a pronounced nick-point or step rather than a graded thalweg (see Larsonneur 1972).

3. Evidence for glaciation

(a) *Submarine features of glacial origin and inland and coastal analogues*

While some of the depressions in the English Channel lie in situations where current action is strong at the present day, others occupy positions where it is minimal, or bears no relation to the form and orientation of the fosses. In the case of Fosse Dangeard now described by Destombes, Shephard-Thorn & Redding (1975) the presence of an infilling dated (in its upper part at least) as Brørup shows clearly that this depression has no connexion with current or melt-water action in Weichselian or post-Weichselian times.

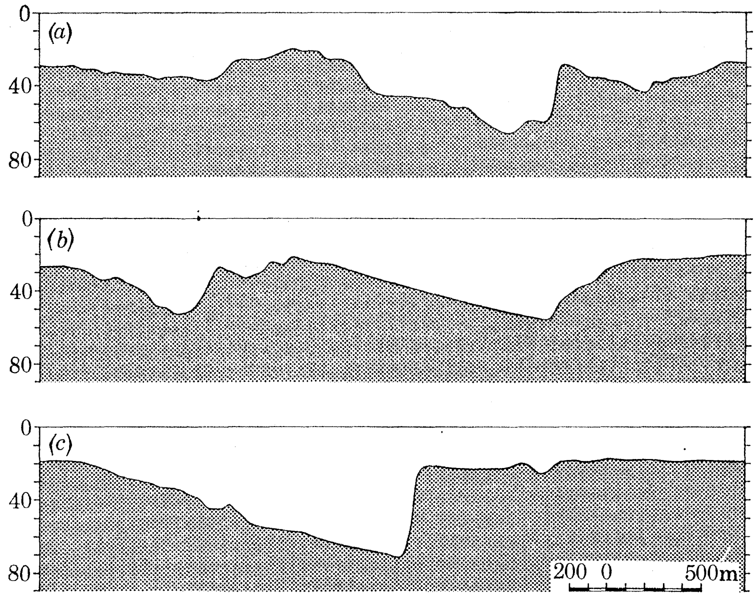

Figure 2. Bathymetric profiles across St Catherine's Deep.

The closed depressions on the floor of the English Channel bear a close resemblance to similar features associated with subglacial drainage patterns recognized in inland areas of the British Isles (Francis, Forsyth, Read & Armstrong 1970; Howell 1973), on the floor of the Bristol Channel (Banner, Brooks & Williams 1971; Al-Saadi & Brooks 1973) and the southern North Sea (Donovan 1973).

Among the deep closed depressions the Fosse Central or Hurd Deep is the most important. This depression and its associated system of channels, about 150 km in length, has been excavated in rock to depths of as much as 150 m below the floor of the Channel, i.e. 240 m below present sea level. Its linear form, orientation and geological structure strongly suggests that it has been eroded along a belt of tectonically fractured and fissured rocks of Mesozoic age. Various explanations, including karstic processes and tidal scour during periods of low sea level, have been advanced in an attempt to account for its formation. The fosse appears to have a complex history of channelling and infilling, and Hamilton & Smith (1972) suggest that it probably contains lenticular sediments of Pleistocene age. It consists of a number of channels, some blocked, others partly open. However, the main channel may never have been completely filled with sediment and the function of existing tidal currents may be to reduce rather than to encourage silting up (Boillot 1963). The width of the Hurd Deep at the general level of the sea floor is from 1.5 to 5 km, but the structure of the sides as shown on the Sparker records suggest that collapse has occurred during the later stages of its formation. It is possible that the inclined beds seen on the walls of the fosse (Hamilton & Smith 1972, fig. 7) are cambered or foundered strata.

A deep closed depression on the floor of Plymouth Sound was attributed by Inglis (1877) to glacial action. Later studies by R. H. Worth (1885, 1898) and Codrington (1898) reinforced this view. Ussher (1907) accepted the possibility that these hollows were at some time occupied by small lakes. However, he was not convinced of the glacial origin of the stiff clay with granite boulders ('boulder clay') adhering locally to the bedrock and did not believe that rivers with a sinuous course such as the Lynher, or the Tamar between Gunnislake and Calshot, could be of glacial origin. Yet the bedrock profile of the Tamar above Saltash is said to be almost flat for 3.2 km, while below Saltash it drops to the Hamoaze and Plymouth Sound where depths of 52–55 m have been recorded. This caused Worth (1898) to remark that the bedrock relief of Plymouth Sound does not differ significantly from that of many Welsh valleys and estuaries which are known to have been glaciated.

If Inglis (1877) was correct in his assessment, then there can be little doubt that at some stage ice flowed off Dartmoor and entered the Sound, since, as he says, the deeps 'occur in just those places where the erosive power of ice would have been greatest, and as the valleys open out (so) the basin shallows'. Moreover, the presence of a residual deposit of till-like material carrying large boulders of granite (a material not normally found in the younger deposits) suggests erosion by ice rather than subglacial melt water erosion in a tunnel-valley. It is not impossible however that at a later stage the greater part of the till and glacial debris was removed by water tunnelling in or beneath the ice. In Weichselian times it is likely that solifluction may also have taken place, thus converting most of the remaining glacial deposits to Head.

The erratics in the high level beach on the Hoe are up to 100 kg in mass (Worth & Champernowne 1884), and were introduced from Drake's Island and Causand Bay in the south-western part of the Sound before cutting of the existing deep channel. In this case they could have been introduced by an ice sheet which invaded the coastal area of South Devon before the formation of the higher raised beach. Then a second glaciation (during which ice carrying granite boulders from Dartmoor flowed southwards into Plymouth Sound) took place before the final melting of the ice sheets and the formation of the Eemian raised beaches.

The river Teign drains the Bovey basin in which deposits resembling till have been observed and where the superficial folding of the Oligocene clays may indicate ice loading and ice pressed structures. Durrance (1971) has described the flat-bottomed trench (suggestive of fluvioglacial erosion) which marks the buried channel of the river near Newton Abbot, and has established that the rock floor at the mouth of the river lies at a depth of −22.9 m O.D. The palaeovalley of the Exe as described by Clarke (1970) passes down the west side of Lyme Bay about 4 km offshore, but shows no subsidiary channels on its western side. This must mean, as Durrance pointed out, that between Teignmouth and the palaeovalley of the Exe the buried channel of the Teign has a negative (i.e. reversed) gradient. This is consonant with glacial action, either through direct abrasion of valley by ice or by the formation of an up-and-over channel in a subglacial tunnel valley.

Not all the south coast rivers can be expected to show closed rock basins or enclosed deeps. The Fal has a deep narrow channel (Carrick Roads) but this appears to be open at the seaward end. Possibly the rivers draining areas where ice was able to accumulate have glacially over-deepened valleys, while those rising in lower ground do not. We have also to bear in mind that some of the sills and broad bars left after deglaciation may have been breached or degraded in Weichselian times by strong fluviatile erosion during periods of low sea level. In such cases the palaeovalleys are probably graded to a level of about −55 m, i.e. at the foot of the cliff bounding the coastal shelf.

Only the Seine, the largest and most important river flowing into the English Channel, has a palaeovalley which can be traced continuously from inland across the modern coast line over the Channel floor to the deep fosse (Hurd Deep) in the central part of the Channel. Here the palaeovalley stops, and the Seine, if it continued as a river, probably became a flow of upwelling water entering one or more englacial channels. In this sense the Hurd Deep may be regarded as part of a huge up-and-down channel, larger but comparable to others well known inland in the British Isles. The rising part of the system, in this case the southwest end of the Hurd Deep, depends on the presence of an ice tunnel containing the water under hydrostatic pressure, until it can once more flow downhill. However, in this case it is likely that the whole system, both the ascending and descending streams were for a time enclosed in ice. Subsequently the sides may have collapsed but this must have happened after the sea reached the lip of the Fosse. The principal palaeovalley which at some stage received water from this part of the Channel floor and conducted it to the margin of the shelf may start about 90 km north of Brest and runs in a west-southwest direction towards the continental margin (Andreieff, Bouysse, Horn & Monchiardini 1972).

We now turn to a brief consideration of the flat undissected surfaces of the Channel floor. These are significant both in the interpretation of the history of the Channel itself and also because of the existence of possible analogues in the almost featureless plateaux which are so well developed in South Wales, notably in Pembrokeshire and Gower. In SW England the examples of the so-called 400-foot platform of West Cornwall and the 200-foot platform of Torquay (Lloyd 1933) may also be mentioned.

Flat surfaces which have been strongly glaciated by thick continental ice sheets are now emerging from beneath the sea in the Hudson Bay and the Baltic as isostatic uplift (following the Weichselian glaciation) exceeds the extent of glacio-eustatic rise in sea level. Many such areas show remarkable groups of marine beaches and strandlines (Flint 1971, fig. 13-12). In such terrain there may be no sharp erosional breaks dividing the emerging surface into altimetric units. This may be partly due to lack of time for erosional strandlines to be formed. Yet in Norway where isostatic uplift and marine erosion are in progress and the rocks are also very hard, we find the Norwegian strandflat, one of the most remarkable platform-like surfaces in NW Europe.

Several theories have been put forward to explain the origin of the strandflat (Nansen 1922; H. Holtedahl 1955, 1959). The scale and incidence of the erosion suggests that near sea-level glaciation and low-altitude ice sheets and ice shelves are likely to be the agents primarily involved. The apron-like ice masses occupying the piedmonts of British Columbia and SE

Alaska have produced somewhat similar effects locally on the lowlands at the foot of the North American cordillera. However, the coastal zone of the Antarctic ice sheet (Taylor 1922; Nichols 1968) and its huge floating ice shelves (Thiel 1961) probably approximate most closely to the required conditions (Dahl 1947; O. Holtedahl 1961).

The strandflat appears to have formed under conditions where the snowline lay at or near sea level so that the coastal glaciers and ice shelves were able to develop even where a large supply of inland ice was not available. Owing to the form of the ice, erosion must have been concentrated at the sole of the ice mass where projecting rocks in the floor were abraded, and at the margins where lateral erosion at the ice contact took place. Where isolated rock masses were too high and too massive to be over-ridden and abraded by the base of the ice they have been oversteepened by lateral erosion at the lower part of the ice contact slope. In this way the pyramidal and pinnacle-like rocks of the Traena Group were produced (O. Holtedahl 1961, fig. 182). Ice-eroded shelves, of which the strandflat is a special case, are characterized by

(1) Infrequent occurrence of deep ice-scoured basins and U-shaped valleys.

(2) A superficially 'flattened' appearance due to severe abrasion of the upper surfaces of small protruding rock masses.

(3) The presence of steep (or vertical) rock walls or cliffs at the marginal contact slopes.

(4) The presence of big pyramidal, or stack-like masses of rock with strongly oversteepened sides rising abruptly, and often in splendid isolation, from the floor of the flat surrounding shelf.

The general applicability of these conditions to many parts of the western continental shelf and coastal areas of the British Isles hardly needs emphasis. They may be found on the Rockall Bank, off parts of western Scotland, in the Bristol Channel, off the south coast of Cornwall and in the Normand–Breton Gulf. Some of the islands in the Bristol Channel are notable for their almost vertical sides (e.g. Lundy Island rising to 142 m O.D., and Steep Holm rising to 72 m above O.D.). Both of these are composed of hard rocks (granite and Carboniferous Limestone respectively). In the Severn estuary and Somerset levels (now silted up) there are a large number of very steep-sided isolated hills, e.g. Brean Down, Worle Hill, and Nyland Hill which show almost identical features. Glastonbury Tor (rising to 158 m O.D.) and Brent Knoll (137 m O.D.) are composed of much softer Mesozoic rocks. In these examples the effect of glacial oversteepening and withdrawal of ice support has been to produce a ring of Pleistocene landslips. Indeed, the clay slips of Brent Knoll, most of which are strongly degraded, have incorporated fragments of Chalk which are thought to have been introduced by ice surrounding the hill (Kellaway 1971).

Landslips which may have been due to glacial oversteepening and dissection by melt water are widespread both on the coast and inland in Great Britain. In many coastal examples such as Axmouth, the Isle of Wight and Eastbourne, the situation of the slips suggests a locus of very strong glacial or fluvioglacial erosion.

If, however, the erosion of the flat surfaces of the continental shelf and the steep mainland and island cliffs are to be attributed to the formation of low-level ice sheets and glaciers on a large scale, it also follows that on the outer margins of the continental shelf subglacial tunnel valleys cannot have formed beyond the contact of the ice mass with the bedrock. Beyond this limit the melt water would have been free to form a number of distributaries which would only maintain their separate identity by virtue of turbidity and temperature. It may be for this reason that no single palaeovalley in the English Channel can be traced individually across and down the edge of the continental slope. It is possible that a palaeovalley carrying water from the Seine and the Hurd Deep may exist on the floor of the Channel north of Brittany, but it may be represented on the continental slope by a group of deep ravines carrying the sediment loaded melt waters of the Seine and other streams issuing from beneath the ice.

At the time of the optimum of the English Channel glaciation the ice sheet may have been grounded at or near the edge of the continental slope, possibly with a floating ice shelf extending beyond this limit. Sea level is likely to have been above −180 m O.D. but probably lower than −90 m O.D. which is the generally accepted Weichselian figure.

(*b*) *Erratics and moraines*

The most impressive shingle ridge on the south coast of England is the Chesil Beach in Dorset, a tombolo 26 km in length situated west of the limestone promontory of Portland Bill.

The source of the abundant non-local material in the Chesil Beach has long been a matter of discussion (Arkell 1947, 1949). Bunter pebbles, igneous and metamorphic rocks from Devon and Cornwall and far-travelled erratics from northern England and Scotland are present, and as Strahan (1898) and Arkell (1947) have indicated, the non-local material can hardly be travelling round the coast line of Britain and crossing Lyme Bay in a continuous stream at the present day. This led Strahan to suggest that derivation from local Tertiary rocks is taking place, but, as Arkell pointed out, huge quantities of Bunter pebbles and Permo-Triassic porphyry pebbles could not be obtained from this source. Why then should these rocks, mingled with Chalk flints, Greensand chert and erratics from the north of England and Scotland, be found in such quantity in the Chesil Beach? Some of these pebbles could have been obtained from Permo-Triassic rocks in Devon or on the sea floor in the western part of Lyme Bay. It is curious, however, that there are very few pebbles in the Chesil Beach from the rocks of Start Point or Torquay, the schists, hard Devonian grits, igneous rocks, quartzites and marmorized limestones of this area, if present, are feebly represented.

Arkell concluded that the existing beach began its life at the beginning of the Neolithic submergence as a bay-mouth bar stretching from an extended Portland Bill westward across what is now West Bay (Lyme Bay) to join some lost headland of Cretaceous and Triassic rocks seaward of Beer Head and Dowlands Cliff. However, the capacity of the sea to move this material may have been somewhat overestimated according to the observations of Neate (1967). It is more likely, however, that a vast amount of morainic drift, derived partly from English Channel ice and partly from material brought down the Teign, Otter, Axe and other valleys by ice or melt water was concentrated in marginal channels before being re-sorted by the advancing sea, first in Eemian and later in Weichselian and Holocene times. The presence of Scottish and North of England rocks in this area suggest that these might have travelled from the Bristol Channel by way of the Axe or the Exe. The relationship between the palaeovalleys of the Teign and the Exe (p. 193) prompts the suggestion that the Permo-Triassic porphyry pebbles were conveyed into Lyme Bay while ice was moving down the Teign valley and that additional downcutting of the palaeovalley of the Exe took place subsequently, thus cutting off the supply of material from the southwest.

Scattered Bunter pebbles, similar in size to those found in the Chesil Beach, are found occasionally in the Plateau Gravels east of Dorchester and occur inland in the Weymouth area at altitudes of up to 70 m above O.D. (Arkell 1947). They are also found in the lag concentrates on the sea floor of the English Channel. The presence of submarine erratics, including large boulders, was known to Prestwich (1892), and other early geologists, but the first systematic investigation of their distribution on the Channel floor was carried out by Dangeard (1929) on board the *Pourqoui Pas?*

In general it may be said that there are three principal suites of foreign stones in the raised and low level beaches on the northern shores of the English Channel. One of these, derived principally from Brittany, the Channel Islands and the Cotentin peninsula, has some rocks in common with the erratics in the Normannian raised beaches of Calvados. On the English shore these erratics are generally confined to the coast between the Isle of Wight and Beachy Head and are usually associated with greywether sandstone (sarsen) and Upper Jurassic, Cretaceous and Tertiary rocks. West of the Isle of Wight, on the coast of the Isle of Purbeck and in Lyme Bay (Arkell 1947) the erratics are generally of western or northwestern origin. On the south coast of Cornwall is the Giants Rock of Porthleven (Flett 1946) a boulder weighing about 50 tonnes derived from NW Scotland or some adjacent area of the sea floor. The most easterly known occurrence of boulders of Scottish rocks on the south coast of England is at Yarmouth, I.O.W. Here there are two small boulders of gneiss (one identified as Lewisian), one found by Professor J. A. Douglas at Yarmouth, I.O.W. on the beach, the other is built into an eighteenth-century garden wall about 400 m inland. Unfortunately neither of these is known to have been embedded in a Pleistocene deposit.

Nearly all the boulders found within or below the base of the Brighton raised beach in Hampshire and Sussex consist of rocks from Dorset, Hampshire and West Sussex associated with rocks from NW Brittany, the Channel Islands and the Cotentin peninsula. It is possible that some Pembrokeshire rocks may be present and there are a number of examples of rocks of unknown origin. Boulders up to 10 tonnes were formerly abundant at Selsey Bill but these are rarely visible at the present time owing to the effects of marine erosion and encroachment of the shingle. Much information on the erratics of the Selsey moraine (p. 198) and the raised beach deposits of East Hampshire and West Sussex will be found in the Memoirs of the Geological Survey covering One-inch New Series Sheets 315 (Southampton), 316 (Fareham & Havant), 317 (Chichester), 330 and 331 (Lymington & Portsmouth), 332 (Bognor). The boulders include one of the few glacially striated erratics known on the south coast of England, namely a boulder of Bognor Rock (a local Tertiary sandstone) weighing about 2 tonnes (Reid 1892). This clearly indicates that ice of sufficient thickness to smooth and striate this rock formerly existed in the Bognor area, though Reid attributed this to the action of floating ice.

East of Selsey, at Pagham Harbour, erratic blocks were formerly seen in large numbers; Prestwich (1892) recorded a boulder of granite 8.4 m in circumference. The boundary stone of Rustington (West Sussex) is one such erratic (probably a rock of French origin) which is covered by marine growth and has therefore been brought inland from the seashore. The small boulders found in the basal Eemian deposits at Selsey (West & Sparks 1960, pp. 98–99) were derived from the pre-existing glacial deposits, which were mostly cleared from the surface of the Bracklesham Beds before the Eemian beach gravel was laid down. Farther east in the Worthing–Lancing–Seaford area the boulders found in raised beach deposits are of similar provenance but become progressively smaller in size. Near the mouth of the Adur at Lancing excavations in the Brighton Raised Beach deposits showed numerous boulders (up to about 1 ft (30 cm) in diameter) of granite, diorite and metamorphic rocks in the basal layers. At Brighton erratics are less abundant however, and at Seaford Head where Breton and Channel Islands rocks are frequently washed ashore, foreign pebbles are seldom more than 10–15 cm in diameter. These have been investigated by B. Auvray of the University of Rennes, who has identified a number of Breton rocks among the collection made at Seaford Head. They include rocks matching the granite of Ploumanach on the coast of Tregor (NW Brittany).

Floating ice (glâce flottant) has been widely canvassed in the past as a means of erratic dispersal in the English Channel but there is no evidence of grooving of the sea floor by floating ice comparable with that found in much deeper water off NW Scotland (Belderson, Kenyon & Wilson 1973). Nor, in view of the shallow nature of the Channel would such grooving be expected to occur, especially in Weichselian times. Boillot (1964) has shown that some of the pebbles on the sea floor have been split *in situ* by frost action, presumably at a time when the bed of the Channel was exposed by lowering of sea level during the last (Weichselian) cold period. This particular part of the sea floor can have experienced little disturbance since being frozen at that time.

Although the composition of some of the small boulders on the floor of the channel is known, it is difficult to obtain information on the larger ones. These have in some cases been located by fishermen, but being too big to collect in a trawl have not been available for study.

The concentration of big boulders in the Selsey area of West Sussex was explained by Reid (1892) as due to floating ice. After the great storm of 1891 he found on the foreshore at Selsey a number of erratics partly embedded in what he believed to be undisturbed Bracklesham clay (Eocene), and also a number of vacant holes from which the boulders had disappeared. Reid explained that the boulders stranded on the Bracklesham clay had been dropped from floating ice which, rising and falling with the spring tides (some of the holes were too high to be reached by ice flows at normal high tides), pressed the boulders down into the underlying clay. The empty holes were accounted for by suggesting that some of the boulders became frozen into the base of the ice which then floated off, presumably on the spring tide.

We find this theory to be unacceptable. We have assumed that none of the boulders were removed by the local inhabitants before Reid studied the foreshore. He does not mention the possibility that the remaining boulders were originally embedded in glacially disturbed Bracklesham Beds, and we have, for the purposes of this discussion, accepted his interpretation that they had been forced into undisturbed clay. Yet this still leaves unanswered the problem of the open holes in soft clay. Such cavities would not long survive the conditions which he envisaged and would quickly be degraded or infilled with sediment.

It therefore appears to us that there are two possibilities. Firstly that the boulders, which may have included Chalk and soft Tertiary material as well as hard igneous rocks, were destroyed or were removed in Eemian times from a matrix of disturbed Bracklesham clay, the voids being then filled with loose sand and shingle. This was subsequently washed away by the sea. Alternatively, there is the explanation that some of the boulders may have been washed away or broken up by the very heavy seas in the great storm of 1891, immediately preceding Reid's visit. From observation of the Sussex coast made over the last 30 years this is an event which may have occurred more than once, and which could account for the presence of occasional boulders which have been found both on the existing coast and sea floor (and in the Eemian raised beach deposits) in the vicinity of the ancient Selsey moraine.

The boulders of the Bognor–Portsmouth area cannot have been introduced by floating ice in Eemian or post-Eemian times, and the position of the inland boulders is such that they could only have arrived in floating ice at some very much earlier period.

(c) *Valley bulges and tunnel valleys*

Valley bulges occur in all the southern counties of England from Kent to Devonshire. If, as has been suggested, some of them are of glacial origin (Kellaway 1971), then their distribution could be used to demonstrate the former existence of a Cenozoic ice sheet or ice sheets, even in the absence of erratics or of any of the familiar characteristics such as ice moulded surfaces, moraines or till deposits.

Some of the valley bulges in south of England valleys are situated near the sea, a few reach the coast, and one, the valley bulge of the Char (Dorset), can be traced to low-tide mark where the belt of contorted Lower Lias continues for an unknown distance out to sea. No evidence of valley bulging has yet been recorded from the coastal regions of northern France. If the existence (or absence) of valley bulges in the Mesozoic and Tertiary terrain of Normandy and Picardy could be established, this might indicate the extent to which these coastal areas were invaded by ice. However, valley bulges are not easily detected and it may be that further investigations will reveal their presence in northern France.

In Arctic regions depressions up to 600 m in diameter are also left by the destruction of pingos or ice mounds. These are mainly restricted to silty or sandy Drift deposits and are generally shallow. Small cavities, less than 100 m in diameter, might also result from superficial erosion of the contents of large pipes or sinkholes, but it is unlikely that cavities as large as the major fosses would result from karstic processes in view of the absence of any comparable forms inland.

(d) *Reappraisal of the Slindon '100 ft' raised beach*

The feature that has become accepted as the 100 ft raised beach of the South Coast, comprises deposits of sand, locally overlain by or passing laterally into gravels, resting on an irregular surface of Chalk and Eocene strata at altitudes of 21–42 m O.D. between Portsdown Hill, Hampshire and Arundel, Sussex (Calkin 1935). The 'beach' deposits are overlain by Coombe Rock (Head) of later age. Marine fossils have been collected from the sands at Waterbeach, near Chichester (Reid 1903, p. 40; Fowler 1932), though they are generally unfossiliferous (Hodgson 1967). They were regarded by Zeuner (1959) as deposits laid down at a Tyrrhenian sea level 32 m above O.D. and broadly equated with river terraces at similar levels (e.g. the Boyn Hill Terrace of the Thames) as products of the penultimate interglacial. Elsewhere in Britain marine shells have been found in Quaternary sands and gravels at much greater altitudes, but most of these occurrences are demonstrably of glacial origin, or represent formations laid down before the Anglian glaciation of East Anglia.

Looking at a map illustrating the occurrence of 'raised beaches' at the 30 m Slindon level one is struck by the severely limited extent of these deposits to coastal Hampshire and Sussex. No other fully authenticated marine deposits at this level are known from the shores and islands of the English Channel. This contrasts sharply with the widespread occurrence of raised beaches at a level 5–8 m above present sea level in the same area, that are attributed to the high sea level of the Eemian interglacial. We consider it very curious that the supposed major interglacial stand of sea level at the Slindon level should have left such limited evidence of its presence.

The rivers of Hampshire and West Sussex show none of the geomorphological adjustment to the Slindon 'beach' level that one might expect. Nor, indeed, are there terrace levels in the headwaters of these rivers, whose reconstructed thalwegs would grade to the implied sea level (Thurrell, Worssam & Edmonds 1968).

The presence of a fossil cliff marking the northern limit of the Slindon deposits is ill-substantiated, although some authors have drawn small-scale sections indicating a feature comparable to the magnificent Brighton raised beach displayed at Black Rock. The supposed beach platform on which the deposits rest is, so far as we know, from examination of emphemeral exposures over the years, highly irregular, and in the existing Slindon gravel workings appears to slope towards the north rather than to the south. Finally the very large altitudinal range through which the deposits have been recorded in Hampshire and West Sussex is difficult to reconcile with an interglacial period of high sea level, making due allowance for minor climatic oscillations.

Marine fossils were collected from exposures at Waterbeach by Reid (1903) and have been preserved in the Geological Survey collections. Reid's detailed account of the deposits at Waterbeach describes the sand as containing 'splinters of flint' and 'occasional small shells', but this is hardly borne out by re-examination of the specimens. With the possible exception of a form recorded as *Trophon*, not preserved in the Survey collection, the largest specimen recorded by Reid is a thin, abraded fragment of a valve of *Macoma* 6–7 mm in length. Fragments of *Balanus* range only up to 5 mm and those of *Mytilus edulis* spat up to 3 mm. In addition there are a number of polished, rolled and rounded shell fragments (including pectinids) and bryozoa that average 2–3 mm in size. The foraminifera show a unimodal size range, and are polished as though by aeolian action. The whole assemblage of abraded fragments and the sands in which they occur, could have been transported by winds of no great strength from beach or outwash sands. The Slindon sands are typically barren over their known extent (Fowler 1932; Hodgson 1967) and show no traces of bioturbation such as might reflect the activities of marine organisms in a 'lug sand' or nearshore environment.

An examination of a sample of the Slindon sand made by Mr M. J. Hughes of the Institute of Geological Sciences revealed no Quaternary foraminifera, though a derived Cretaceous form was found.

The blocks of bored chalk recorded from Waterbeach (Reid 1903) are of special interest. A large piece preserved by the Geological Survey (past of a mass weighing 100 kg) proves to be a part of a foreshore reef that has been broken off. The fractured edge is only slightly abraded and could not have undergone much weathering or wave or beach erosion, yet it is associated in finely laminated sands with huge battered flints and 'cannonshot' pebbles which are obviously the product of high-energy environments. It seems to us that these large blocks of bored chalk could only have attained their position in the sands by being dropped from ice floating in a fluvioglacial channel or pro-glacial lake, having first been broken from their parent reefs by glacial action or frost-wedging and picked up by the ice. Far-travelled erratics of granite, basalt, quartzite and other non-local rocks are common near Chichester but are less abundant farther east.

Exposures recently examined in the present workings at Slindon [SU 972072] show small-scale faulting and distorted laminations in the sands indicative of compaction after dewatering, a characteristic of rapidly laid down fluvial and fluvioglacial sediments and unusual in a marine environment.

In the southern part of the Slindon workings, recent excavations have also revealed the presence, beneath the Coombe Rock and Slindon sand and gravel of a bed of stiff grey clay resting on Chalk and infilling solution pipes. The clay contains large subangular to rounded fragments of rotten chalk, large flint nodules with protuberances cleanly broken off, with shattered flints and razor-sharp flint shards. The Slindon gravels and sands above, fill channels

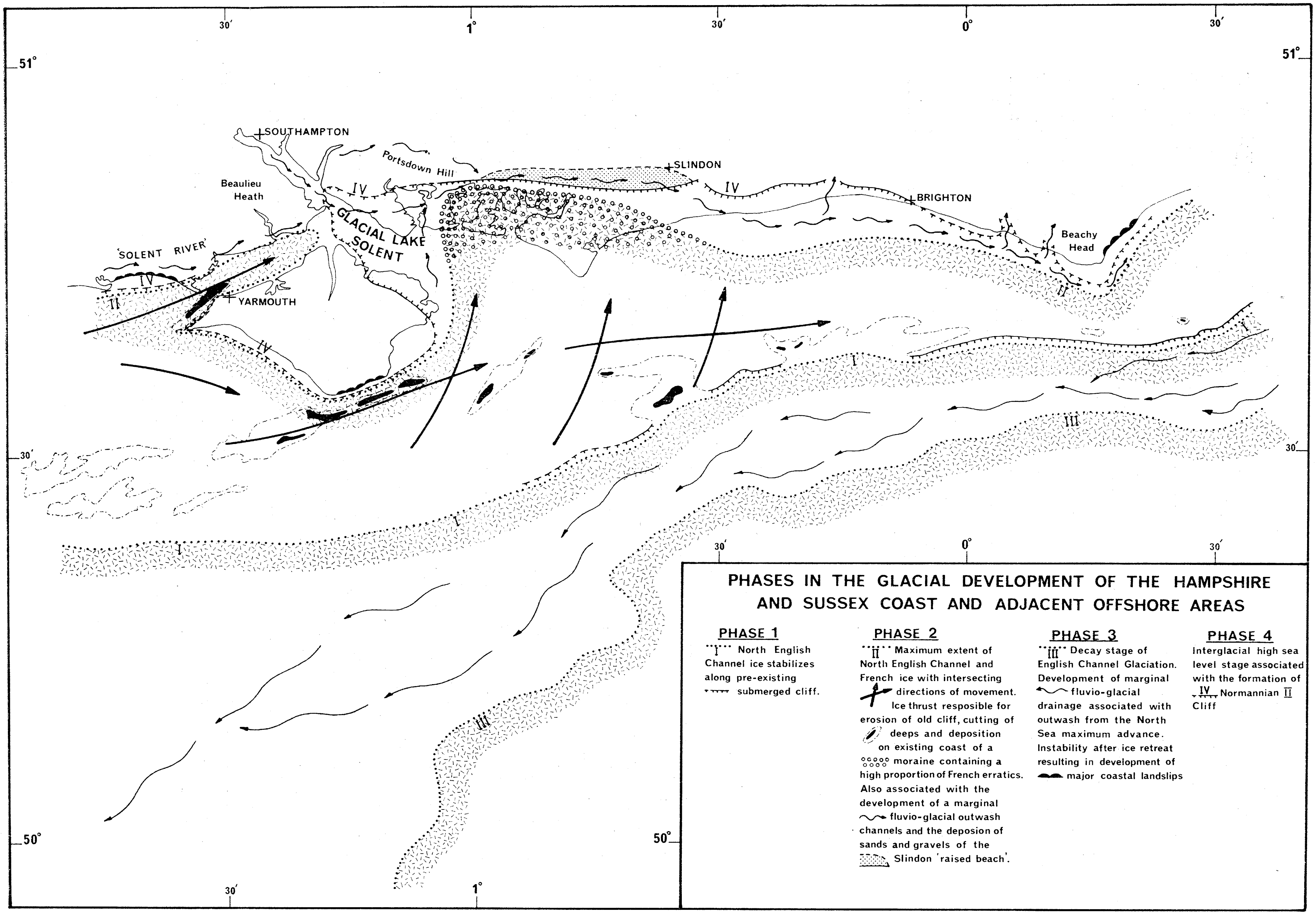

FIGURE 3. Phases in the glacial development of the Hampshire and Sussex coast and adjacent offshore areas.

cut in the underlying boulder clay and show evidence of collapse into the solution pipes. At one site it appears that subsidence occurred during the sedimentation of the sands, in other pipes it took place both during and after deposition, deforming the sedimentary layers of the sand. The clay is currently undergoing detailed petrological and microfaunal study. It bears little superficial resemblance to the local Tertiary clays of the Woolwich and Reading Beds, which are typically colour mottled. We think it may well be a glacial deposit of some kind; possibly a flow till deposited at a former ice front, prior to the laying down of the sands and gravels which now rest upon it.

Thus, in conclusion, we consider that the Slindon deposits are of fluvioglacial origin, fed by a glacial lake (Lake Solent), dammed up by English Channel ice which deposited the Selsey moraine. The lake had two overflow channels. One proceeded by way of the northern slopes of Portsdown Hill at Southwick, the other, later channel probably passed the eastern end of Portsdown Hill near Havant (figure 3). Our reading of the evidence may require amendment in the light of further work (we have had insufficient time to complete our researches) but it may remove many of the perplexing correlation problems posed by the acceptance of a widespread 32 m 'Tyrrhenian' sea level in NW Europe.

4. Quaternary history

(*a*) *General outline*

In order to fit the evidence for the glaciation of the English Channel into the Quaternary time scale we have attempted reconstructions of the Weichselian and Saalian ice sheets for NW Europe (figure 4). Table 1 lists the principal events of these glaciations as far as we can determine them.

The reconstruction (figure 4) of the Weichselian glaciation agrees with most existing ones as far as inland areas of the British Isles are concerned, but suggests a considerable reduction of the ice-covered area in the North Sea. Eastern Aberdeenshire ('moraineless Buchan') is shown as free of ice and it is suggested that the Scandinavian ice sheet may have terminated at or near the Skagerak. This part of the reconstruction is based on recent evidence from the southern North Sea (Oele 1969 and personal communication) which suggests that in Weichselian times the Rhine did not flow through the Straits of Dover but took a northerly course (Oele 1969). In the Shetlands it is possible that the small radially flowing glaciers were Weichselian and that the older striations indicating movement from Scandinavia towards the Atlantic (Peach & Horne 1879) may be late Saalian.

Our overall impression of the Weichselian glaciation is that it was relatively small, that it affected neither the Bristol Channel nor the English Channel (apart from small local snow and ice fields on adjoining high ground) and that the principal centres of glaciation were in the mountains of NW Ireland, NW Scotland and Scandinavia. Most of the continental shelf was unaffected and even northern islands such as the Shetlands supported only relatively small ice masses.

Our reconstruction of the final phase of the Saalian glaciation (figure 4) differs from most previous versions (cf. Woldstedt 1967, fig. 1) in that it includes a southerly lobate extension of the North Sea ice reaching to and beyond the Straits of Dover (see Destombes *et al.* 1975). We have encountered some difficulty in constructing this outline owing to the uncertainty

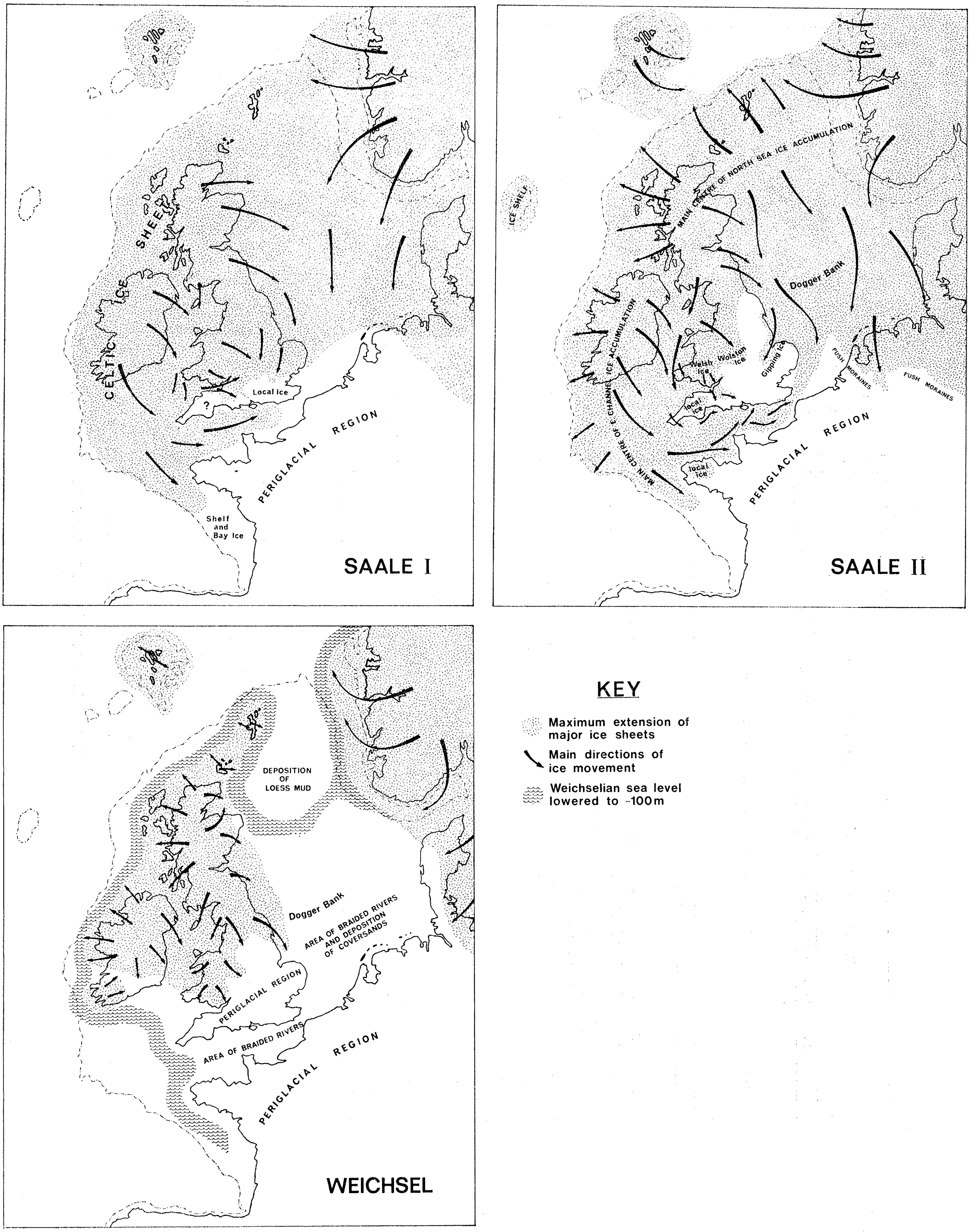

FIGURE 4. Reconstructions of the Weichselian and Saalian glaciations.

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Principal events so far identified in the English Channel	Sea level	Tentative correlation between Southern Britain and the Continent	1000 yrs BP	Stages
DEVELOPMENT OF MODERN-DAY ASPECTS OF THE CHANNEL (SANDBANKS, SAND WAVES, ETC.)		FLANDRIAN/HOLOCENE	13,	1
Major part of Channel floor exposed – incisement of river to base of submerged cliff – braided rivers on floor of Channel	−120 m	LATE and MIDDLE DEVENSIAN/WEICHSELIAN G.	32, 64, 75,	2, 3, 4
Final infilling of FOSSE DANGEARD (Brørup) BRIGHTON/NORMANNIAN II Raised beach deposits. Boulder erratics derived from pre-existing glacial deposits inter-glacial deposits of Stone, Selsey, etc.	+8 m	EARLY DEVENSIAN/WEICHSELIAN G. IPSWICHIAN/EEMIAN I.G.	128,	5
Isostatic adjustment completed in period of rising sea level – final melting of all ice in southern England (Coombe Rock formation) Local ice cap on Dartmoor. Glaciation of Tamar and Teign valleys. Draining of Lake Solent Melting of English Channel Ice – Slindon Fluvioglacial deposits – Lake Solent 43–45 m levels Selsey Moraine associated with MAXIMUM EXTENT OF LAST ENGLISH CHANNEL GLACIER (Initial excavation of FOSSE DANGEARD) Bristol Channel Ice filling Salisbury – Romsey Gap	−180 m	WOLSTONIAN/SAALE II (WARTHE) G.	195,	6
Possible remnants of higher (Normannian I) raised beaches uplifted by isostatic rebound in Western Channel Portland and Plymouth Raised Beaches	±0 m	HOXNIAN/ HOLSTEINIAN (in part) I.G./I.S. Complex	251,	7
Lake Solent 76 m level High level plateau gravels of western New Forest PENULTIMATE ENGLISH CHANNEL GLACIATION Bristol Channel Ice invades Stour, Frome, Avon and Wylye valleys	−150 m	ANGLIAN/SAALE I (DRENTHE) G.	297,	8
		HOLSTEINIAN I.G.	347,	9
Glaciation of western Salisbury Plain. Northern Drift (Berrocian) Glaciation of the Cotswolds		BEESTONIAN/ELSTERIAN G.	367,	10
		PASTONIAN/ CROMER III I.G. Cromer Complex		11

Oxygen isotope curve of Shackleton & Opdyke (1973)

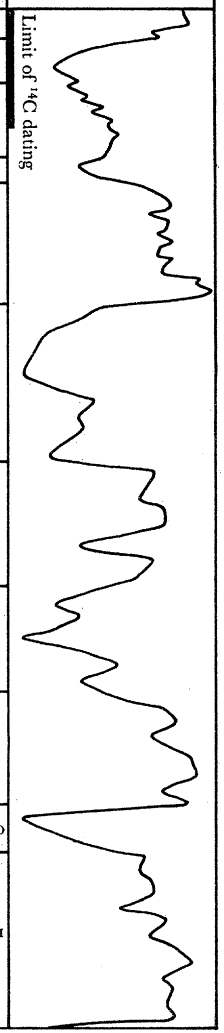

TABLE 1. LATE QUATERNARY CORRELATIONS

attaching to the relationship between the East Anglian deposits and the coastal deposits of the English Channel. It is therefore possible that some adjustments will be required.

The most important feature of this map is the wide extent of the ice sheet covering the continental shelf and extending over the greater part of the British Isles, with the possible exclusion of parts of southern England. Here, however, there were almost certainly ice fields of quite substantial size and it is possible that some of the so-called 'Head' deposits may be soliflucted and decalcified tills. Local ice may also have been present on the high ground of western Brittany.

We estimate that the upper surface of the ice may have achieved levels of 1800–2500 m above present sea level in western Scandinavia, 1500 m off NW Scotland and 900 m over SW Ireland. The ice was able to surround or bury the high plateau of Central Wales, to over-ride the Wrekin (400 m) in the west Midlands of England and to pass over without deflexion, the 275 m high mass of Charnwood Forest in the East Midlands. It carried unbroken *Turretella* shells from the floor of the Irish Sea to Upton-on-Severn, near Gloucester, and the great mass of ice which passed over the Pembrokeshire uplands and being deflected by Exmoor turned eastwards up the Bristol Channel filled the Somerset lowlands, burying all but the highest parts of the Mendips and filling the gaps leading southwards to the Hampshire Basin and the English Channel coast.

The precise limits of the phases of the Saalian glaciations in Devon and Cornwall are as yet unknown. The main flow of ice during the final phase lay offshore of the North Devon and Cornish coast. No Irish rocks have yet been positively identified from SW England; nearly all the erratics are of Welsh, Lake District or Scottish origin. It is apparent that the great flow of ice moving southward from the Irish Sea met resistance to a westerly spread probably from ice generated over SW Ireland and the northwestern part of the Celtic Sea. Beyond the Scilly Isles part of the ice moved in the low ground in the English Channel where it eventually impinged on the lower slopes of the Armorican land mass. Here the flow was largely diverted by this huge land barrier, part moving eastwards and north eastwards into the English Channel, the remainder, though still restrained to some extent by ice on the western shelf, passing southwards into the Bay of Biscay, where it may have contributed to an ice shelf fringed by bay ice, the whole accumulation resembling the Filchner or Ross ice shelves in Antarctica.

(*b*) *Hoxnian and Eemian sea levels*

The present coastline of the English Channel differs only in detail from the pre-Weichselian (Normannian) one. Locally, as at Sangatte (Dubois 1924) and Brighton (White 1924), the old Pleistocene cliff can be seen in section in the modern one; elsewhere, as at the northern end of the Cotentin peninsula (Elhai 1963) and between Start Point and Prawle Point in south Devon (Ussher 1904), the ancient and modern cliffs are separated by a coastal plain or shelf of varying width. This may retain Normannian beach deposits overlain by Head, and locally, by Flandrian sediments. In other areas the raised beach deposits were removed by solifluction in Weichselian times, leaving the old wave cut platforms and fossil cliffs buried by Head. The presence of re-entrants in the Pleistocene cliff line shows that the embayments marking many of the existing estuaries are of considerable antiquity. On the whole it is remarkable how small is the effect produced on the coast line by marine erosion and solifluction over the past 120000 years (figure 1).

Two sets of raised beaches described as Normannian I and Normannian II (Dangeard &

Graindor 1956) have been recognized in the English Channel. Normannian I, the so-called Main Monastirian beach (Zeuner 1959), is said to correspond with a sea level of up to 20–22 m above high sea level, i.e. 18–20 m above O.D. Normannian II is represented by the Brighton raised beach of the Sussex coastal plain and Isle of Wight (Prestwich 1892; White 1924; Smith 1936; Hodgson 1964, 1967). This was formed when mean sea level stood at a maximum altitude of about 8 m above O.D. An Ipswichian flora and fauna has been found beneath the Brighton raised beach deposits at Selsey, Sussex (West & Sparks 1960). The comparable raised beach at Sangatte near Calais can now be dated as pre-Brørup (A. Lefebre, personal communication), and is presumably of Eemian age, between 80000 and 120000 years old.

Comparing this information with the oxygen isotope curve for the Atlantic and Caribbean (Shackleton & Opdyke 1973) it would appear that the Normannian II beaches should fall in stage 5 while any Normannian I strand lines should correspond with an interstadial in stage 6 or, alternatively, be linked with the interglacial of stage 7 (? Hoxnian). The very close parallelism between Recent and Eemian coastlines (figure 1) in the English Channel suggests that neither isostatic recovery nor recent tectonic movements (apart from those associated with subsidence in the North Sea Basin) have had a major effect on the Normannian II (8 m) strand line in the southern part of Britain though the sea levels cannot be determined with sufficient accuracy to identify minor changes of level. The Eemian shorelines of the English Channel can, however, be related with some confidence to those of the Netherlands (Jong 1967, fig. 7, p. 312), making due allowance for post-Eemian downwarping in the North Sea basin.

Normannian I beaches marking an 18 m (Main Monastirian) sea level are said to be well developed on the north coast of France and in the Channel Islands (Dubois 1924; Zeuner 1959). We have expressed elsewhere (p. 202) our disbelief in the existence of the 100-foot (or Tyrrhenian) 'raised beach' in Sussex. We also doubt the validity of many other high level 'raised beaches' of the French and English coasts, notably the 37 m so-called raised beach of Jersey (Dunlop 1893; Naish 1919; Zeuner 1959). It is possible that some of the gravelly and bouldery deposits of the Cotentin, e.g. L'anse du Brick (Elhai 1963, pp. 412–414) may be explicable as glacial or fluvioglacial material. The altitude of the so-called higher Normannian beaches in the northeast of the Cotentin ranges from 10 to about 25 m but Elhai (1963) has already indicated that some of these may be remanié Triassic pebbles in solifluction deposits.

Among the features said to be associated with the raised beach platforms of the Channel Islands are 'undercuts' and potholes (marmites) which are assumed to be of marine origin. Many of these, including the Pinnacle (Jersey), could equally well be due to glacial or fluvioglacial action.

On the northern coast of the English Channel, the only deposits which might be classified as Normannian I are those found west of the Isle of Wight. The first, and in some ways most important of these, is the raised beach of Portland (Arkell 1957). This has some of the characteristics of a marine strand line though its fauna also has anomalous features (Zeuner 1959). It is said to relate to a mean sea-level corresponding to a position about 12 m above O.D. In view of our lack of knowledge about Quaternary tidal ranges however (Green 1943), and the sloping surface of the Portland Limestone bedrock on which the deposits rest, it is possible that the inferred difference (4.5 m) between the sea level at Brighton (8 m above O.D.) and that of Portland may be more apparent than real. Of these deposits, the one at Portland contains a higher proportion of erratics and a fauna (Baden-Powell 1930) which may be cooler than that of the Brighton raised beach.

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West of Portland two comparable high level beaches are found, one in Torbay, the other in Plymouth Sound. The Torbay beach is seen at Hope's Nose, Torquay (Lloyd 1933). It may mark a mean sea-level about the same as Portland and carries a fauna which is said to be similar.

With the possible exception of a fragmentary beach at Hallsands near Start Point, the other raised beach platforms found on the coast between Torquay and Plymouth lie mostly at levels similar to those found in the Brighton raised beach deposits of the West Sussex coastal plain. Most of the beach deposits have been destroyed however and the platforms are normally covered by Head.

Two beaches are said to be present at Plymouth (Worth 1885; Masson-Phillip in Zeuner 1959), one representing a sea level of about 8 m above O.D. and the other about 18 m above O.D. This implies that the Portland–Hopes Nose beach may have risen isostatically, and now stands about 11 m above the Brighton level at Plymouth and about 4.5–6 m in the area between Portland and Torquay. It would therefore be logical to attempt to correlate these beaches with the so-called raised beach at Penlee, near Mousehole, in west Cornwall (Reid & Flett 1907). The base of the Penlee 'beach' is said to lie at about 20 m O.D., indicating a higher sea level than that of Plymouth Hoe. On the other hand, there are no reports of bored or barnacle-covered surfaces. The pebbles resting on the waterworn rocks are mostly of local origin and could be fluvioglacial gravels filling part of a melt-water channel. The presence of so many large erratics in the high level beach of Plymouth Hoe is also disturbing, though in this area some marine shells were found (Worth 1885). The Torquay and Portland beach deposits have yielded a considerable marine fauna, but the mixture of cold-temperate and warmer forms is worrying, as the Portland beach in particular is rich in erratic material, has a poorly developed cliff, and appears to have been deposited in a high-energy environment in which no far-travelled shells are likely to have survived. In the absence of evidence to the contrary we have treated the Plymouth, Torquay and Portland occurrences as marine deposits, but in view of their isostatic interest the deposits undoubtedly require re-examination to confirm or refute their assumed marine origin.

If the Plymouth–Torquay–Portland raised beaches are truly marine, then it is likely that isostatic recovery was in progress in the western part of the English Channel in pre-Eemian times. On the assumption that the Hoxnian deposits of East Anglia were in process of formation over a period of 10000 years, strand lines of this period in the English Channel could have a wide altimetric range. Since basement subsidence was occurring simultaneously in the Netherlands, correlation of the Dutch–East Anglian and English Channel successions is likely to be very difficult.

As a corollary it follows that the common practice of correlating terrace-deposits in the Hampshire Basin and Thames Valley on archaeological and altimetric evidence, while relating them to 'Hoxnian' sea levels is likely to be productive of nothing but confusion.

One low-altitude bored marine surface was seen by Reid (1892) beneath the so-called 'mud-deposit' of Selsey in West Sussex. The contemporary sea-level is unknown but the bored surface of Eocene rocks may possibly post-date the introduction of the Selsey erratics, and is almost certainly older than the Ipswichian channel-filling described by West & Sparks (1960), who were unable to find any evidence of a warm shell-bearing marine deposit beneath the Brighton raised beach. Our own observations at Selsey confirm those of West & Sparks, and we suggest that the most likely explanation is that, like the derived erratics, which have been incorporated in the Ipswichian deposits, the 'warm shells' have been derived from Saalian morainic material which was undergoing erosion in early Eemian times.

Owing to its bearing on the glaciation of the Somerset lowlands from which ice and melt-water probably reached the English Channel, the relevant evidence for the Bristol Channel must also be considered. In the Bristol Channel no Normannian I beaches have been positively identified. At least two strand lines, one at about 21 m O.D. the other at about 30.5 m are visible on the northern face of the Brean Down promontory at Weston-super-Mare. These show no evidence of marine origin and are probably fluvioglacial. Marine strand lines are found at Spring Cove and Woodspring near Weston-super-Mare and these may be roughly comparable with the Eemian beaches of Gower (George 1932; Bowen 1973). There is, however, some doubt as to whether the cutting of the ill-defined shelves on which the marine deposits rest was contemporaneous with the beach formation.

(*c*) *Fluvial and fluvioglacial terraces of the South Downs and Hampshire Basin*

None of the river terraces of Kent or Sussex are aggraded to the so-called Goodwood–Slindon or '100-foot raised beach'. Of the Sussex rivers the Arun is the most important. This has its 4th terrace graded to a Brighton (Normannian II) strand line (Thurrell *et al.* 1968) and may be Ipswichian. We are less sure of the fragmentary deposits of the 6th terrace which may be graded to a 'Hoxnian' or to a Saalian interstadial sea level, but could equally well have been formed in a lowlying area ponded by pre-Eemian ice blocking the southern exit of the valley below Arundel. The smaller rivers of East Sussex, notably the Cuckmere, Ouse and Adur, have no regular river terraces in the seaward portion of their valleys. There are, however, flat-lying or gently sloping spreads of gravel standing at levels of about 21–30.5 m above O.D. and covered by Head. These may represent lake levels produced by ice ponded lakes at the seaward end of the broad valleys in which these small rivers are notable misfits.

In the Hampshire Basin the Plateau gravels of the New Forest and Solent area fall roughly into two groups, the higher gravels extending to about 128 m above O.D. have all the appearance of ancient fluvioglacial deposits. They are highly dissected and cambered and this marks them off from the lower gravels, notably those forming the well marked plateaux at Beaulieu and Lymington in the southern part of the New Forest. The origin of the Plateau Gravels of the Hampshire Basin, thought to have been laid down by the 'Solent River' and its tributaries, has been the subject of much discussion (Darwin-Fox 1862; Codrington 1870; Reid 1892; White 1915, 1917; Bury 1926; Green 1946, 1947; Green & Calkin 1950; Arkell 1947, 1951; Everard 1954).

In general, the interpretation of the extensive terrace deposits of the 'Solent River' and New Forest fails to deal with the vast scale on which gravel deposition has occurred repeatedly at comparatively high levels in the New Forest and the adjacent areas of the Hampshire Basin. The horizontal segments of the various fluvioglacial terraces in the Solent and Southampton Water show no measurable gradients, and where inclined terraces join these segments they do so with little evidence of grading (Green 1946; Everard 1954). In view of the lack of evidence for a '100-foot' raised beach in West Sussex, it appears to us that the problem of accounting for the high standing water level required to form the 46 m terrace of the southern New Forest is insuperable, since this would require a general pre-Eemian strand line of 46 m above O.D. Without glaciation the possibility of isostatic change would not arise, therefore evidence for marine erosion at this level should be expected to occur at intervals along the coasts of the

British Isles and north France. No such evidence exists, though there is a patch of pebbles and boulders in a clayey matrix at 36 m on South Hill, Jersey. This deposit, which may be of glacial or fluvioglacial origin, contains no marine fossils. As Elhai (1963) has pointed out, the 'beach', if marine, is unique on this part of the coast.

Even if such a marine level could be established, this would still leave the problem of even higher terraces in the southern plateau of the New Forest. Some of these extend to about 69 m O.D., and their formation in a 'Solent River' would have required the presence of an enormous mass of land (since destroyed) linking the Isle of Purbeck and the Isle of Wight, with a contemporary sea level higher than the platform incised in the Devonian rocks at Babbacombe, Torquay (Lloyd 1933). We do not believe that there is any evidence for this.

The Selsey moraine, of which only the basal lag deposit remains, provides evidence for the presence of an ice dam in the right place and at the right time, and explains the terrace level and the relation of the inclined and horizontal terraces. It also accounts for the presence of the spillways adjoining Portsdown Hill, and for the fluvioglacial deposits concentrated at Slindon and Chichester in a kame terrace and lacustrine area along the margin of the inferred ice front.

The terrace gravels of the Salisbury Avon include some terraces which are probably contemporaneous with the 'Palaeolithic terrace' of the southern New Forest (p. 196). These Avon terraces continue to rise northwards from the coast to about 60 m above O.D. near Fordingbridge, where the gravels contain Purbeck material derived from the Vale of Wardour. Reid (1902) pointed out that similar but smaller fragments of this material occur in the high-level gravels at about 128 m above O.D. near Bramshaw. This indicates that between the formation of the high-level cambered plateau gravels and the 'Palaeolithic terrace' the Purbeck rocks of the Vale of Wardour underwent considerable erosion.

Yet for this to happen and for gravels to be deposited on such a scale in the Hampshire Basin it would have been necessary for the source of the Nadder in the Vale of Wardour to be very many times larger than at present. On the other hand, the catchment of the Nadder could not be extended much farther to the west without encroaching on the basin of the Stour, which must itself have been much larger. The low ground at the head of the Stour and west of the Vale of Wardour may be an ice-eroded basin (Kellaway 1972) similar to glacial Lake Trowbridge in Wiltshire (Harmer 1907). Therefore ice moving through the gap leading to Romsey could, for a time, have blocked the east–west valley between Salisbury and Romsey, diverting a stream of meltwater down the Avon valley. At the southern exit of the Solent the English Channel ice lying offshore may have dammed the exit, thus creating glacial Lake Solent (figure 3).

Everard (1954) has described submerged terraces in Southampton Water which he believed to be related to those onshore. Since these terraces have inclined surfaces they may be due to successive gravel faces built out into the glacially dammed lake in response to falling outlet levels. The time of final disappearance of the ice blocking the mouth of the Solent may not have differed greatly from that suggested by Green (1946) as the date when the sea broke into the Solent valley. The water appears to have breached the ice and morainic drift forming the barrier between the Isle of Wight and Portsdown Hill, on the side nearest the Isle of Wight. The fact that the Eemian beach deposits of West Sussex contain fairly numerous derived erratic pebbles while those of Bembridge do not (White 1921) suggests that erosion was at a maximum on the southern side. Here the meltwater could have poured across the eastern end of the Isle of Wight, cutting a channel and washing away most of the morainic material. As a consequence the Eemian cliff line, which approximates to the position of one wall of the main spillway, cuts across the eastern end of the island in a direction which is almost at right angles to the general surface relief of the Isle of Wight.

This again reinforces our conclusion that the coastline of southern England and the floor of the English Channel have been determined mainly by the effect of tectonic, glacial and fluvioglacial processes, marine erosion has played only a subordinate part.

(*d*) *Summary of Quaternary history including glaciation*

The glacial history of the English Channel can be traced back to Pliocene times when pebble and boulder beds were laid down in the Cotentin Peninsula during a late stage in the deposition of the Sables Rouges (see summary by Elhai 1963, pp. 166–70). These deposits are considered to be of periglacial origin, but they may mark the onset of the cold conditions presaging a Waltonian glaciation of East Anglia.* The northern erratics found in the base of the Red Crag of East Anglia (Spencer 1971) are not the oldest nor yet the most southerly known Scandinavian erratics of post-Cretaceous age in Great Britain. Prestwich (1871) found a 250 kg boulder of Norwegian prophyry and an icthyosaur bone from the Jurassic (Oxford Clay) at the base of the Coralline Crag in Suffolk. We know of no evidence for erratics in the Pliocene rocks of Brittany and Normandy, however, and it appears unlikely that the Pliocene glaciation of Scandinavia recorded in Suffolk affected the English Channel.

The most southerly known Scandinavian erratics in Britain are those found in a cavity (probably a collapsed pipe) in the Chalk of Purley (Godwin-Austen 1858; Hawkes 1951) south of London. These may be related to the Coralline Crag (also found in pipes in Chalk on the North Downs) but are most likely to be of Waltonian age, emplaced near the margin of the ice during or shortly after the beginning of the movements which led to the elevation of the Weald relative to the North Sea Basin. By this time erosion of the Neogene sediments in the English Channel and in the flanking areas of Brittany, Normandy and southern England is likely to have been well advanced.

A complex series of climatic changes is represented in East Anglia by the later Crag deposits and the Chillesford Beds. The greywether sandstone erratics of southern England are silcretes of a type not yet identified in the local Tertiary rocks, probably formed under warm continental conditions on the drained surface of a cover of Neogene or early Quaternary sands characterized by the occurrence of small rose pink and white quartz pebbles. Greywether sandstone boulders (sometimes described as 'sarsens', though this term includes other siliceous boulders of various ages), first appear in the Clay-with-flints. The latter is a deposit of Pleistocene age and is widely distributed in southern England, where it includes ironstones and other insoluble rocks of non-local origin. It is embraced in the deposits known in France as 'Argile à silex', though the English and French terms are not always synonymous (Pepper 1973). We consider the Clay-with-flints to be decalcified, piped and degraded tills (Sherlock & Noble 1912) which were formed initially by the underdraining of glacial ice carrying a high proportion of chalky debris. The Clay-with-flints is therefore developed preferentially on Chalk and limestone areas and passes laterally into gravelly deposits where the presence of Tertiary or other clays prevented underdrainage of the ice.

The Clay-with-flints of the Chilterns yields characteristic red quartzite erratics which are of non-local origin and also very large greywether sandstone erratics up to 6 m or more in

* See note added in proof p. 213.

length. In the North Downs of Kent and Surrey it contains relict material of Eocene, Oligocene, Pliocene and early Quaternary (Red Crag) age (Dines & Edmunds 1929). Since it is younger than the Red Crag (Waltonian) of East Anglia, the Clay-with-flints may represent one or more of the cold phases of the Cromer Forest Bed Series or, alternatively, a glaciation post-dating the Arctic Freshwater Bed.

The Anglo-Norman plateau glaciations thus recorded by the Clay-with-flints took place at a time when the relief of southern England and northern France was less diversified than at the present time, though broad depressions coinciding with the Thames estuary and with the English Channel were in existence. At an early stage the Northern Drift Glaciation (Berrocian of Arkell 1943) took place. This brought northern ice across the Cotswolds and the Midlands into what is now the Goring gap in the Thames valley above Reading (Hawkins 1923). In the west, the Northern Drift ice certainly reached the latitude of Malmesbury. Little or nothing is known of the history of the contemporaneous Celtic Ice sheet in SW England and the English Channel, but it may have been responsible for the development of the main elements of the high level relief on the uplands of Cornwall and Devon. Much of the drainage pattern of southern England dates either from this period or from the Anglian Glaciation which succeeded it, but at the present time it is difficult to differentiate between these developments. Some of the far-travelled erratics of northern origin in Somerset, Dorset, Devon and Cornwall may have been carried at least part of the way towards their destination in the older glaciation.

When we turn to the younger pre-Weichselian glaciations, their influence on the evolution of the English Channel and of the coast line of Britain and France is readily apparent. Most of the older glacial deposits had been destroyed or badly weathered before the onset of the Anglian glaciation in East Anglia but the presence of greywether sandstone boulders in the ancient moraine at Selsey in Sussex and of striated greywethers in Kent (Chandler & Leach 1936) suggests that areas of Clay-with-flints were undergoing destruction.

Beyond the limit of the Weichselian (Devensian) ice, the most westerly of the glacial deposits to be found in the British Isles are those of the Scilly Isles (Barrow 1906; Mitchell & Orme 1967). Thus the southern limit of the pre-Eemian ice in the Celtic Sea lay at least 190 km south of the Weichselian ice front in St Georges Channel. Similarly in the east of England the Anglian ice from the North Sea and Scandinavia attained a comparable southerly position in the Thames valley relative to the later (Weichselian) ice margin in Lincolnshire. Only in central and south-central England do the Weichselian and pre-Weichselian ice fronts lie closer together, at Wolverhampton and the Vale of Moreton respectively.

The apparent difference may be partly due to incomplete information and correlation problems. Even when allowance is made for these items, it would appear that the nourishment of the ice sheets is likely to be a major factor in this situation. Moreover, ice originating in the NW part of the continental shelf appears to have spread more rapidly and farther south than ice on the east, and it is in this way that the trans-Pennine ice flows in the north of England and the huge glacier-like flows of the Irish Sea, Bristol Channel and English Channel came into being.

Two phases of glaciation, if not two glaciations, are represented on the Scilly Isles (Mitchell & Orme 1967), where outwash deposits may indicate the last glacial phase while the erratics in the older raised beach may denote the former presence of a more extensive cover. The outwash deposits may correlate therefore with the Fremington till (Edmonds 1972) or perhaps with the glacial deposits of Somerset or the Boulder Bed of Trebetherick Point near

Padstow (Dewey 1913; Arkell 1943; Clarke 1969), but whatever their age, they suggest that if the glacial material was deposited by grounded ice (and the evidence favours this) then there was about 130 m of ice surrounding the north side of the archipelago at this time. If this represents only the final phase of glaciation the total thickness must originally have been much greater, but even at the indicated thickness, the melt water from this source should have been sufficient to produce features indicative of englacial and subglacial drainage. In the entrance to the Bristol Channel therefore, where the ice would have been thicker, it should be possible to find closed depressions or fosses similar to those of the Cheshire Basin (Howell 1973) or Swansea Bay (Al-Saadi & Brooks 1973). Closed depressions, some situated on palaeovalleys, are undoubtedly present in the Bristol Channel (Banner *et al.* 1971), where there are also large marginal ice-drainage features, e.g. the up-and-down channel at the Valley of the Rocks at Lynton, indicating that ice marginal and englacial features may have developed simultaneously.

In north Somerset the Court Hill channel at Clevedon (Hawkins & Kellaway 1971) and other glacial deposits near Bristol may be Wolstonian or Anglian, but identification of the effects of the various glaciations in the interior of Somerset, Wiltshire and the adjoining counties is a task for the future. It does, however, have a considerable bearing on the English Channel glaciations because of the development of gaps at Chard, at the heads of the Dorset Frome and Stour rivers, the Vale of Wardour, and at Warminster and Upavon, through which ice and melt water may have moved towards the Channel coast. Therefore in assessing maps showing the glaciation of the British Isles and its surrounding shelf (figure 4) it must be recognized that any such reconstructions are little more than rough approximations at the present time.

A number of problems affect the use of erratics in determining directions of ice movement. Thus the presence of Scottish and NW England erratics in the beaches of Dorset – an area where relatively few rocks from SW Devon and Cornwall occur – suggests that at the height of one or more of the pre-Eemian glaciations, ice may have moved through the Chard gap leading from the Somerset lowlands to the Channel coast. On the other hand, some Scottish rocks were carried down the north coast of Devon and Cornwall and thence round Lands End or through the St Erth gap leading to Mounts Bay, to travel in an easterly direction along the Channel coast.

All the glaciations of the Bristol Channel and English Channel are pre-Eemian. Since, however, the Slindon 'raised beach' can no longer be correlated with the Hoxnian, a Saalian date for the later stages of fluvioglacial Lake Solent (figure 3) and the fluvioglacial lake or channel deposits of Goodwood and Slindon cannot be excluded. This would not be unreasonable in terms of the evidence from inland areas. Glacio-lacustrine complexes such as Lake Harrison (Shotton 1953) and other glacial lakes in the Midlands of England are matched by evidence of glacial strand lines and fluvioglacial deposits in Somerset and Sussex. That this lacustrine episode might accompany or follow the appearance of the Hoxnian flora with its wealth of *Abies* (adapted to heavy snowfall) and *Azolla* (the water fern) would not be surprising. The Slindon 'raised beach' can no longer be correlated with a Tyrrhenian sea level, but it may not be widely separated in time from the Wolstonian of the Midlands. If the Wolstonian glaciation can be equated with the Chalky Boulder Clay of the Midlands, the claim by Martin (1920) that there was a glaciation of the South Downs 'at the close of the Acheulian period, which give rise north of the Thames to the Chalky Boulder Clay' can now be regarded as substantially correct.

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Note added in proof, December 1974. Evidence for an early Quaternary glaciation of the Cotentin (Normandy) has recently been reported (Pareyn, Claude 'La Quaternaire ancien de Saint Sauveur de Pierrepoint (Manche)', Colloque, Caen, 9 September 1974. Sub-Commission on shore lines of northwestern Europe, INQUA).

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Discussion

PROFESSOR H. H. LAMB (*Climatic Research Unit, University of East Anglia, Norwich*)

This first account of much new work on surveying and interpreting the sea-floor topography and coastal, and near-coastal, deposits of the English Channel makes a persuasive case for believing that the area was glaciated during the Saale glaciation. The reconstruction of sea surface temperatures and their distribution over the North Atlantic Ocean at the climax of the last (Weichselian/Wisconsin) glaciation about 17000 years ago from species analysis and oxygen isotope work on the foraminifera, etc., in the ocean-bed deposits, carried out in the last few years under the Climap programme by Dr A. McIntyre of the Lamont Geological Observatory of Columbia University, New York and others using strict quantitative methods, indicates that the departure from present conditions was peculiarly great in the area of the Atlantic from the Bay of Biscay and our southwestern approaches westwards as far as about 30° W. Between latitudes 45 and 50° N in that area the surface temperatures prevailing were apparently more than 10° C below present values both in summer and winter.

This anomaly seems too great to be fully accounted for by the diversion of the Gulf Stream–North Atlantic Drift Current to an east–west course in lower latitudes; it surely demands a substantial supply of seasonal ice-melt water at no very great distance. (By contrast, the departures from present conditions indicated both between Norway and Iceland and over the Newfoundland Banks were only −4 to −6° C.)

There may therefore be some reason for believing in glaciation in the English Channel area also in the last glaciation.

DR A. J. SMITH (*Department of Geology, University College London, Gower Street, London, WC1E 6BT, England*)

Dr A. J. Smith commented that Dr Kellaway's postulated ice movement from the west may have some support from the fact that sediment infilling of the Hurd Deep was thickest towards the western end of that feature. Further, he (Dr Smith) had spoken in his paper of vertical movements of the outer parts of the shelf and it could well have been the case that the regional gradient was not towards the ocean but towards the continent in Pleistocene times.

DR L. H. N. COOPER (2 *Queens Gate Villas, Lipson, Plymouth, PL4 7PN*)

I will take up Sir Kingsley's question in the light-hearted manner in which he asked it. A very short review was then made of a desk study made in Plymouth in 1964 and never published because it appeared to be unacceptable to a number of geological colleagues to whom it was shown. Since it fits remarkably with this paper the material has been updated and will be published elsewhere.

Dr Kellaway welcomed Dr Cooper's remarks concerning the oceanographical implications and expressed the hope that Dr Cooper would publish his work. Recent studies by Shackleton & Opdyke (1973) and Weertman (1974) also suggest that a new approach is needed to the problem of the pre-Weichselian glaciations of the Continental Shelf of NW Europe. Existing concepts are based almost entirely on a modified form of Alpine glaciation with the formation first of piedmont ice sheets and eventually of a continental ice sheet. This may be true of the relatively small Weichselian ice sheets but it does not explain the rapid build up and decay of the huge Saalian ice sheets on the NW European Continental Shelf.

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Dr C. Turner (*Botany School, Downing St., Cambridge*)

The suggestion that the 'hundred-foot raised beach' deposits at Slindon and elsewhere were, in fact, formed under glacial channel conditions is an interesting one, but hardly reconcilable with the presence of Palaeolithic industries undoubtedly associated with these deposits. Assemblages of flint tools have been recovered from two separate sites associated with the supposed beach, at Slindon and at Lavant. These are not scattered finds, but from the quantity of material recovered there but not at other exposures, they must represent truly local occupation. Artefacts recovered from excavations at Slindon within the last year are mostly fresh and unbraded and show little sign of having been moved by ice or torrential water. It is virtually impossible to imagine such human occupation of the sites taking place under either the geomorphic or climatic conditions proposed by Dr Kellaway.

(Further comments, on a 'Saalian' age for the proposed glaciation of the English Channel are included in the discussion on the paper by Destombes *et al.*, p. 243.)

Dr Kellaway said that he and his colleagues were conscious of the perplexing problems relating to Hoxnian and Ipswichian correlation. As far as possible they had based their reconstruction of the English Channel glaciations on field evidence. Dr Turner's suggestion about a possible pre-Cromerian glaciation might well prove to have an application to Britain, and they were grateful to him for drawing their attention to this.

The remarkable degree of uniformity shown by the Brighton–Sangatte raised beach complex (Normannian II) is mentioned in the paper. The marine (Eemian deposits) rest on Ipswichian channel fillings in Sussex and Normandy. In Southern Ireland an equally prominent and persistent group of strand lines appears at comparable altitudes. Yet no Ipswichian deposits have yet been found in Ireland. The evidence could be taken to indicate that the Irish beaches are Hoxnian (i.e. pre-Ipswichian), but these circumstances might also be attributed to the survival of an oceanic flora in Ireland when the Ipswichian flora had become established in the drier area of the Netherlands and eastern England. If the Hoxnian flora could be regarded as an oceanic facies associated both with the Holsteinian interglacial and with some unglaciated areas during the Saalian glaciations, the palaeobotanical evidence might be reconcilable.

With regard to the 'hundred foot raised beach' at Slindon the only Palaeolithic working floor known to the authors is one said to occur on the upper surface of the Slindon sand and beneath the Coombe Rock (Head). This is probably a middle or late St Acheul site and sets a rough upper limit for the age of the Slindon sand and gravel. Battered and eroded artefacts occur in the basal layers of the overlying Coombe Rock. The authors have not found any St Acheul implements or working floors within or beneath the Slindon sand and gravel.

At the time of the main occupation of West Sussex by late Acheulian man there is a break or interruption in the geological record due to subsequent erosion, or to burial of the contemporaneous deposits by the Main Coombe Rock. We have not, as yet, been able to bridge this gap. Nor can we dispose of the possibility that a Normannian I sea level existed from some time in West Sussex.

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

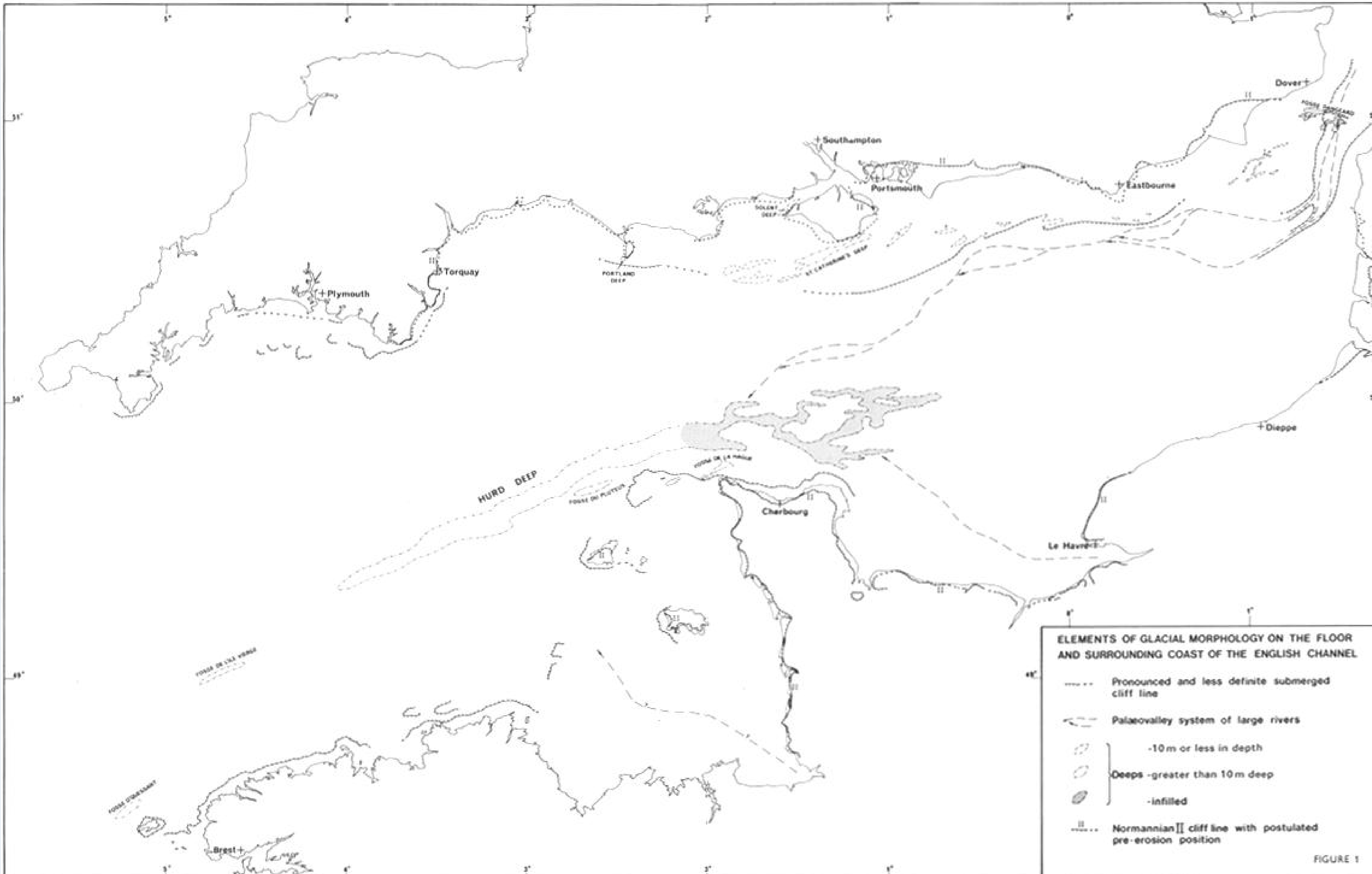
Dover
Southampton
Portsmouth
Eastbourne
Torquay
Plymouth
HURD DEEP
Cherbourg
Le Havre
Dieppe
Brest
ELEMENTS OF GLACIAL MORPHOLOGY ON THE FLOOR AND SURROUNDING COAST OF THE ENGLISH CHANNEL
Pronounced and less definite submerged cliff line
Palaeovalley system of large rivers
Deeps -10 m or less in depth
-greater than 10 m deep
-infilled
Normannian II cliff line with postulated pre-erosion position

FIGURE 1