FRONTISPIECE

Remains of part of Hallsands village situated on an abandoned abrasion platform cut into mica-schist. According to Worth (1904) the beach level in 1894 was higher than the top of Wilson's Rock shown in the foreground beyond low water mark, and stood about 6 m above its present level. The results of marine erosion are exemplified by the incipient caves and notches cut into the highly fractured mica-schist which was protected from direct wave attack prior to dredging in the inter-tidal zone during the period 1897–1902.

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SOME ASPECTS OF THE QUATERNARY HISTORY OF START BAY, DEVON

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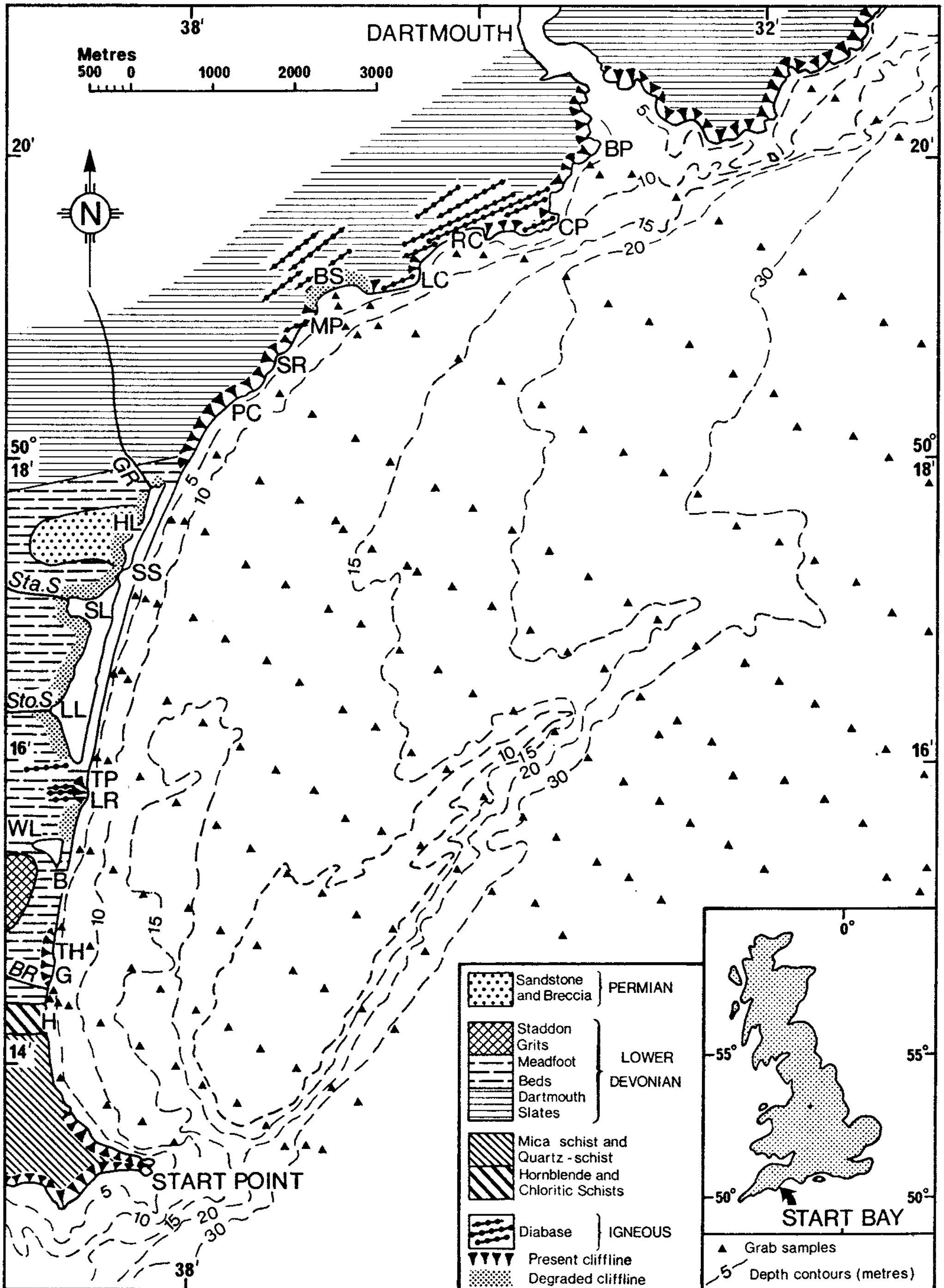
Introduction

The demand for all types of aggregates has increased from about 62 million tonnes in 1948 to about 220 million tonnes in 1970, and production is likely to be around 330 million tonnes in 1980. In the last decade alone the annual yield of marine sand and gravel has trebled to a total of 14 million tonnes. Bearing in mind the strong pressures to protect the environment, particularly in south-east England, from the scars of an expanding extractive industry, it is not altogether surprising that attention has been focused lately on the resources around our coast, despite the fact that so far there has been no systematic survey of offshore sand and gravel deposits.

Apart from the recent work of Crickmore *et al.* (1972), and Dickson and Lee (1973), no previous studies have been made to predict shingle movement by wave action in the nearshore zone, and to examine the effects of gravel extraction offshore on the incidence of coastal erosion. Possibly, the main reason for this lack of research is that there are practically no proven cases of coastal erosion resulting directly from offshore sand and gravel exploitation. Nevertheless, there has been considerable controversy for many years about the extensive damage sustained by Hallsands fishing village, the remains of which can be seen little more than two kilometres north of Start Point in Start Bay, Devon (Fig. 1; Frontispiece). The disaster occurred between 25 and 27 January, 1917, during an unusual but critical combination of spring tides, north-easterly gales and 40-foot waves, but at the time the local inhabitants unequivocally attributed the event to the effects of dredging offshore and to the removal of shingle from the foreshore at Hallsands between 1897 and 1902. Until now this standpoint has never really been substantiated scientifically. Worth (1909) estimated that at least 395×10^3 m^3 of shingle, equivalent to nearly 97 per cent of the present-day beach volume, were removed from the vicinity of Hallsands during the period dredging was in operation, with the result that the beach level was lowered by 6 m by the winter of 1903–4.

However, the question has never been raised previously, either in discussion immediately after the disaster, or in a recent article by Wilson (1970), whether or not Hallsands was actually built on bedrock sufficiently resistant to withstand storm wave attack and marine erosion, and on a sector of the coast that may be particularly vulnerable during such a critical combination of events as just mentioned.

During the past four years, the Institute of Oceanographic Sciences, Taunton (formerly the Unit of Coastal Sedimentation) has directed an inter-disciplinary research programme in Start Bay towards an examination of environmental problems. The work has been undertaken in collaboration with the Department of Physics, University of Bath; the Department of Maritime Civil Engineering, University of Liverpool; the Institute of Oceanographic Sciences, Bidston Laboratory (formerly



ABBREVIATIONS					
GR Gara River	*BR* Bickerton River	LC Leonards Cove	PC Pilchard Cove	LL Lower Ley	B Beesands
Sta.S Start Stream	BP Blackstone Point	BS Blackpool Sands	SS Slapton Sands	TP Torcross Point	TH Tinsey Head
Sto.S Stokenham Stream	CP Combe Point	MP Matthews Point	HL Higher Ley	LR Limpet Rocks	G Greenstraight
	RC Redlap Cove	SR Shiphill Rock	SL Slapton Ley	WL Widdicombe Ley	H Hallsands

Fig. 1.

Map showing the geology of the Start Bay coastline, and the position of grab sampling stations along traverses used for the geophysical survey.

the Institute of Coastal Oceanography and Tides); and the Institute of Geological Sciences, Continental Shelf Units I and II. The study has included continuous seismic profiling, bottom sampling, gravity and vibrocoring, analysis of nearshore wave conditions and changes along the foreshore, especially on Slapton barrier, an investigation of tidal currents, and an interpretation of the geological history of the Bay itself. An attempt has been made to determine the origin and composition of the Skerries Bank and to evaluate its relationship to the water circulation and sediment movement within the Bay and to the incidence of coastal erosion, which in turn is controlled by short- and long-term changes in the offshore sediment budget.

As far as I am aware only the hydrography of Start Bay has been described previously (Robinson, 1961), and a study made of Quaternary sediments in adjacent areas by Clarke (1970). The results and conclusions of this inter-disciplinary research have been reported in the *Journal of the Geological Society* (1975). The purpose of this particular paper is to review very briefly the main points of geological and geomorphological interest that have come to light and to summarize and to put into perspective the main causes of the Hallsands disaster.

Regional Setting

A detailed account of the geology of this part of Devonshire is given by Ussher (1890, 1933), Dineley (1961) and Richter (1967), while Mercer (1966) summarizes the natural history of the Slapton Ley Nature Reserve. In brief, Start Bay is an asymmetrical embayment about 60 km² in area. The coastline is comprised of Lower Devonian rocks, structurally aligned east-west, which can be divided into the Dartmouth Slates, Meadfoot Beds and Staddon Grits (Fig. 1).

The submerged valley of the River Dart is the most significant geomorphological landform on this sector of the Devon coast. The Gara and Bickerton rivers, and Start and Stokenham streams, which drain the immediate hinterland of Start Bay and which transported sediment to the exposed English Channel floor during times of lower sea level, are now cut off from the sea by barrier beaches such as Bee Sands and Hall Sands and flow into either Slapton Ley or smaller coastal lagoons.

Slapton Ley is also a coastal lagoon, commonly known as the Higher Ley and Lower Ley, which occupies the site of a former marine embayment, the limits of which are defined by a degraded cliffline along its landward margin (Fig. 1). It is enclosed from the sea by a shingle barrier, named *Slapton Sands* on the O.S. 1-inch Sheet 188. This barrier, in fact, is part of a sequence of barrier beaches, composed essentially of granules and small pebbles, which extends almost continuously from Hallsands to Pilchard Cove over a distance of about 9 km. Only Tinsey Head and the Limpet Rocks-Torcross headlands interrupt the continuity of this large accumulation of beach gravel.

The generalized submarine contour pattern in figure 1 has been depicted from Admiralty Chart 1634 on a scale of 1 : 25,000. It shows that the seabed in Start Bay constitutes a gently sloping shelf at a depth of 11–15 m, the outer edge of which is demarcated by a slightly curved break of slope trending in a general north-east–south-west direction. It can be seen that the axis of the Skerries Bank follows the line of this shelf. The Bank has been relatively stable for nearly a century according to the surveys that have been made since 1813, but the accuracy of the earliest charts is somewhat suspect because of their small scale and lack of detail. Even so, it is worth noting that during the time the Bank has apparently been stable many other offshore banks in shallow waters around the British coast have migrated steadily shoreward (Robinson, 1961).

GEOPHYSICAL AND GEOLOGICAL EVIDENCE

(a) *Bedrock Morphology and Buried Channels*

By using a combination of geophysical and geological techniques, including continuous seismic profiling, side scanning sonar, diving and vibrocoring, it has been possible to determine the bedrock morphology and to record the nature and structure of an overlying sequence of Quaternary superficial deposits over a large area of Start Bay. One significant geological feature is a pronounced break of slope in the bedrock surface which trends approximately parallel to the modern coastline along the entire length of the Bay at an average depth of 42 m (Fig. 3). This particular depth is of interest because it is comparable to that of a submerged cliff near Plymouth reported by Cooper (1948) and to what Clarke (1970) considered to be an ancient coastline in Tor Bay. Around Start Point and near the Dart River the break of slope in the bedrock surface crops out at the seabed as a continuation of the present-day cliffs. The feature is interpreted as pertaining to an ancient coastline which has probably been exposed to subaerial processes on more than one occasion during periods of lower sea level.

A number of buried channels, varying between 100 m and 450 m in width, dissect the bedrock surface between the present shoreline and the 42 m contour (Figs. 3 and 4). These appear to be former extensions of the modern drainage network. Most of the buried channels gradually shallow shoreward and have been incised into the bedrock little more than 7 m, on average, apart from one channel which is more than 40 m below the approaches to the Dart River.

(b) *Superficial Deposits: Seabed Bottom and Core Samples*

Bedrock is unconformably overlain by a sequence of gently dipping Quaternary superficial deposits. A total of 17 gravity, 53 vibrocore* and 193 seabed bottom samples of these deposits have been collected from the stations shown in figures 1 and 2. On the basis of their texture and composition, the superficial deposits can be divided into three discrete lithological units which have been described previously as *barrier*, *bay* and *bank* deposits by Kelland and Hails (1972).

The barrier deposits consist of shingle or beach gravel and are confined to a relatively narrow zone extending from the backshore of the barrier beaches to, on average, about 200 m beyond low-water mark (Fig. 2; Table 1 for grain-size statistics). Sub-angular flints and well rounded quartz pebbles are the dominant constituents which comprise almost 85 per cent of the total population. Other rock types include rhyolite, felsite, granite and quartz porphyry with locally derived fragments of mica-schist, shale and slate.

On the other hand, the bay deposits are composed mainly of medium- to fine-grained sands with varying proportions of silt, clay, whole and broken shell. They attain a maximum thickness of 28 m about 2 km south-east of Blackpool Sands (Borehole 85) and can be divided into an upper and a lower horizon by an angular unconformity with an inclination to the south-east of about 1 : 150. The upper horizon is grey or greenish-grey in colour, reflecting the presence of glauconite and

* Relatively undisturbed sediment samples obtained with vibratory coring equipment (Plate II).

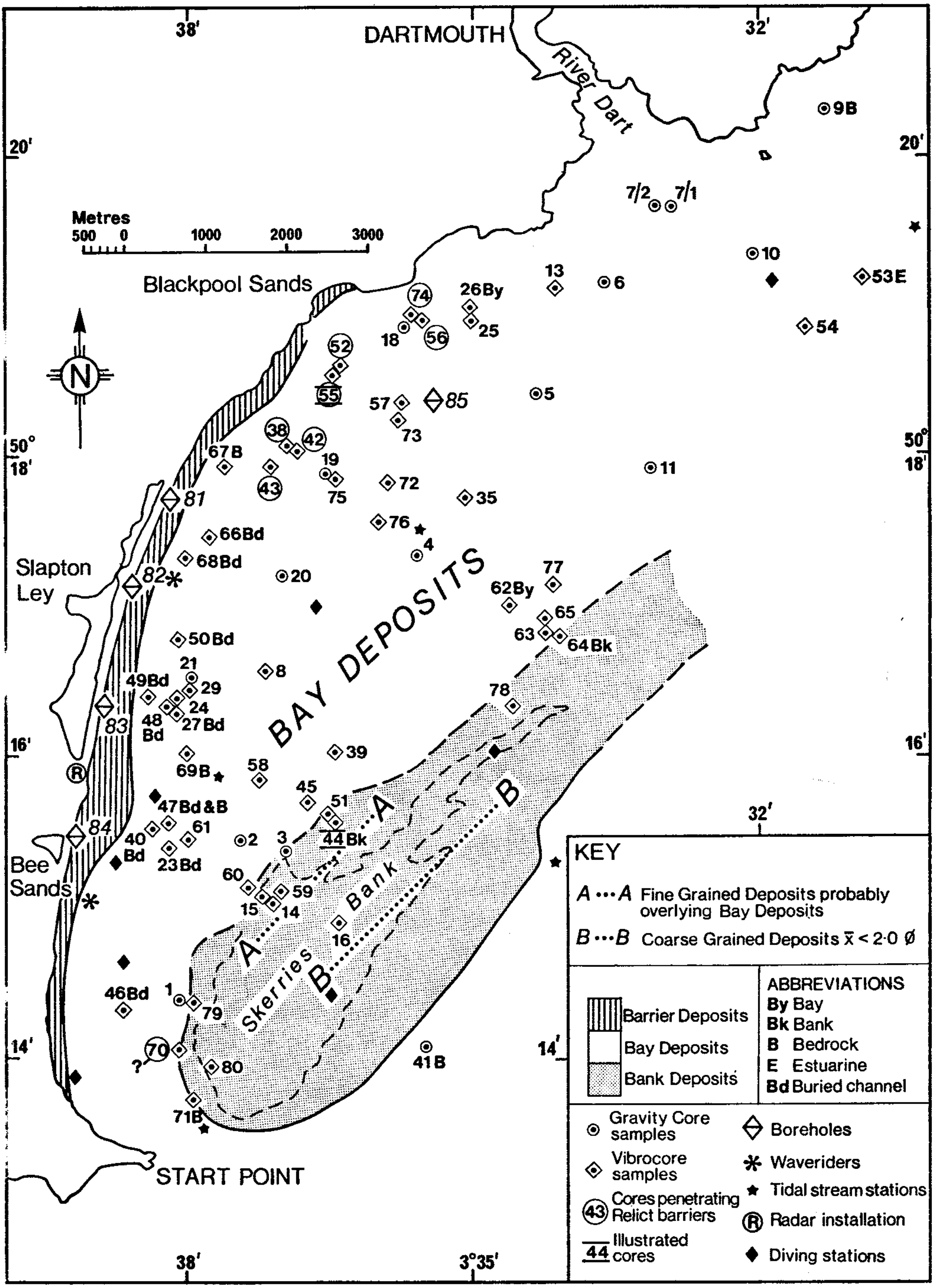


Fig. 2.

Distribution of barrier, bay and bank deposits within Start Bay. Gravity and vibrocore stations are also shown together with tidal stream and diving stations.

Table 1. *Statistical parameters, calculated by using central moment equations, for grab and core samples collected from the three lithological units and buried channels*

GRAB SAMPLES

	Barrier	Bay	Bank
Range of mean grain size (in phi-units)	−3·09ϕ to −2·36ϕ	0·41ϕ to 3·99ϕ	0·70ϕ to 3·50ϕ
Range of standard deviation values	1·73 to 0·65	3·57 to 0·36	2·48 to 0·39
Range of skewness values	−1·39 to 4·21	−2·16 to 4·79	−1·58 to 0·05

CORE SAMPLES

	Buried channels	Bay	Bank
Range of mean grain size (in phi-units)	−2·90ϕ to 0·52ϕ	−0·46ϕ to 4·11ϕ	0·90ϕ to 2·85ϕ
Range of standard deviation values	2·90 to 1·38	3·58 to 0·36	0·91 to 0·47
Range of skewness values	−1·56 to 3·13	−4·37 to 2·53	−0·94 to 0·21

The "phi-units" are measurements of grain diameter, and correspond to the negative logarithm to the base two of the particle size in millimetres. It was introduced by Krumbein (1936) to reduce a logarithmic scale to simple numbers. Thus on this scale sand (2 m–0·2 m) is indicated as 0ϕ–1ϕ.
(Ref. Krumbein, W. C. (1936). Application of logarithmic moments to size frequency in sediments. *Journ. Sed. Petrol.*, **6**, 35–47.)

chlorite, but a few samples have a distinct reddish-brown or brownish-grey tinge, indicating fine-grained material derived from neighbouring Permo-Triassic strata. In contrast, the lower horizon is an intercalated sequence of estuarine sands, silts and clays thinning to a feather edge along a line trending approximately south-west to north-east which continues under the Skerries Bank, and attains a maximum thickness of 18 m off Redlap Cove where it approaches to within 25 m of chart datum. This horizon also outcrops in the deeper water off the entrance to the River Dart.

The bank deposits unconformably overlie the bay deposits and grade laterally into them, within a transitional zone which coincides with the inner margin of the Skerries Bank (Hails, 1975). They are composed of coarse shelly sand and attain a maximum thickness of about 18 m.

Gravel horizons have been traced in an area 1 km wide and up to 6 km long between Redlap Cove and immediately opposite the middle of Slapton Ley (see also Kelland and Hails, 1972; Kelland, 1975). I interpret them as delimiting the positions of relict barriers, at depths of 17 m, 21 m and 30 m respectively, below chart datum (Figs. 2 and 3). Significantly, the gravel horizons are nearly parallel to the modern coastline, but inshore they either pinch out against the shelving bedrock or outcrop at the seabed.

The 70 cores collected from the three lithological units, and also from the buried channels and relict barriers, vary in length up to 4 m. The petrographic characteristics of the bedrock penetrated at six core stations in areas where the unconsolidated deposits are usually less than 1 m thick indicate a close affinity with the Meadfoot Beds, Dartmouth Slates and mica-schists, which outcrop along the adjacent coastline (Figs. 1 and 2; Plate I). Core 41, though, on the Channel side of the Skerries Bank

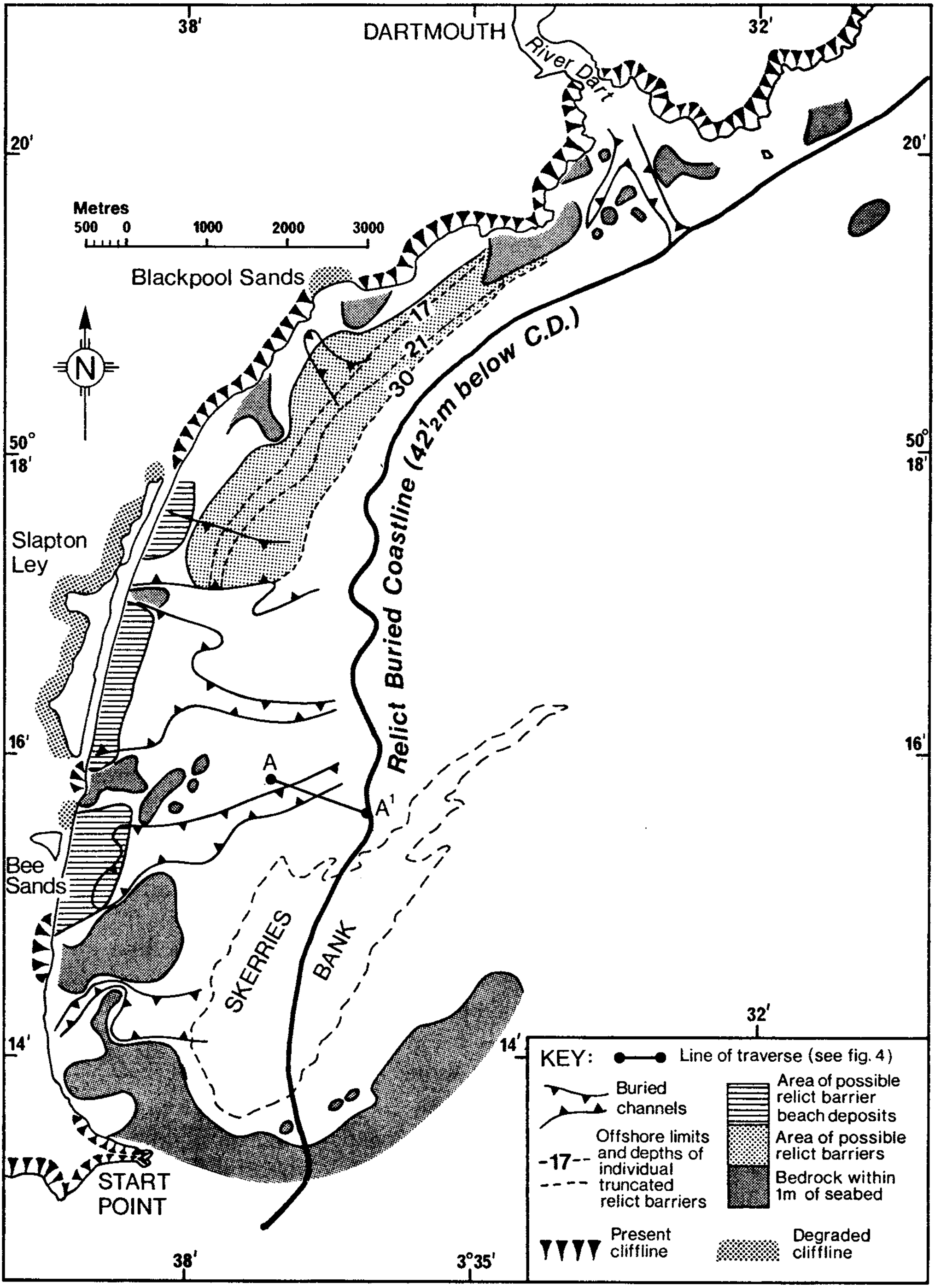


FIG. 3.

Map to show relict buried coastline, buried channels, location of relict barriers, and bedrock within 1 m of the seabed (based on Kelland, 1975).

penetrated slightly weathered Permo-Triassic strata and similar bedrock material has also been recorded at a depth of 32 m near Blackpool Sands (Table 2).

Table 2. *Summary of the log of Core 85 sunk to a depth of 34·5 m from the M.V. Whitethorn approximately 2 km south-east of Blackpool Sands, Start Bay*

0–10 m	Fine-grained, brownish-grey sand with shell fragments and complete shell. Brownish-grey clay at 4 m, 6–10 m. Shell fragments and comminuted shell at 3 m, 8–10 m.
10 m	Sand with very small sub-angular to angular rock fragments in the granule to pebble size grade. This depth is considered to mark the boundary (unconformity) between the upper and lower horizons of the bay deposits, as detected on the geophysical records.
11–28 m	Grey, greenish-grey fine-grained sand, with brown mottled patches and clay pellets. Occasional shell fragments at 11 m and 12 m. Greenish-grey laminated fine sand, silt and clay at 17 m and 25 m.
29 m	Gravel with silty, fine-grained sand. Mainly angular pebbles.
30 m	Angular to sub-angular cobbles with small pebbles, mostly of vein quartz; also mica-schist and sandstone fragments.
30·5–32 m	Partially oxidized grey material, possibly weathered bedrock.
32–34·5 m	Bedrock—Permo-Triassic reddish-brown sandstone and breccia, the latter containing pebbles of sub-angular to sub-rounded vein quartz and medium-grained sandstone.

The buried channel deposits recorded in ten cores consist of gravel set in a variegated matrix of fine- to coarse-grained sand. Relict barrier deposits occur in eight cores (Fig. 2) and, like the buried channel deposits, consist essentially of beach gravel analogues in composition, shape and size to the barrier beach gravel along the modern shoreline. In most of the cores the relict barrier deposits vary in thickness between approximately 1 and 2 m, but they are in fact considerably thicker, as shown on the geophysical records, and the measurements given here reflect the maximum penetration of the vibrocorer. Usually they are overlain by bay deposits little more than 2 m thick (Plate I). In core 70 possible relict barrier deposits overlie a sequence of slightly laminated sands and clays which, in turn, overlie a 1·2 m thick blue clay, and a freshwater peat containing pieces of wood, a sample of which from the uppermost 10 cm. has been dated 8108 $\pm$ 60 years B.P. ($\delta^{13}C$ ‰ $= -27\cdot9\%$).

Because of difficulties encountered in vibrocoring the bank deposits, only short cores averaging 2 to 3 m in length have been obtained so far. Most of the cores, like the bottom samples, contain coarse-grained sand and broken shell although there are a few areas in the Bay where the bank deposits are actually composed of medium- and, sometimes, fine-grained sand.

Discussion

Certain evidence has come to light, both in the geophysical and geological records, to suggest that the "Quaternary palaeogeography" of Start Bay has not differed markedly from the modern environment, particularly with regard to barrier growth and migration during the past 9,000 years or so. The existence of relict barrier shorelines on continental shelves is an extremely interesting problem that still commands the attention of marine geologists, stratigraphers and geomorphologists studying the Quaternary, and questions about their evolution and ultimate submergence still remain unanswered. The existence of submerged depositional strandlines in various parts of the world does not adequately explain how they have survived wave action during marine transgressions.

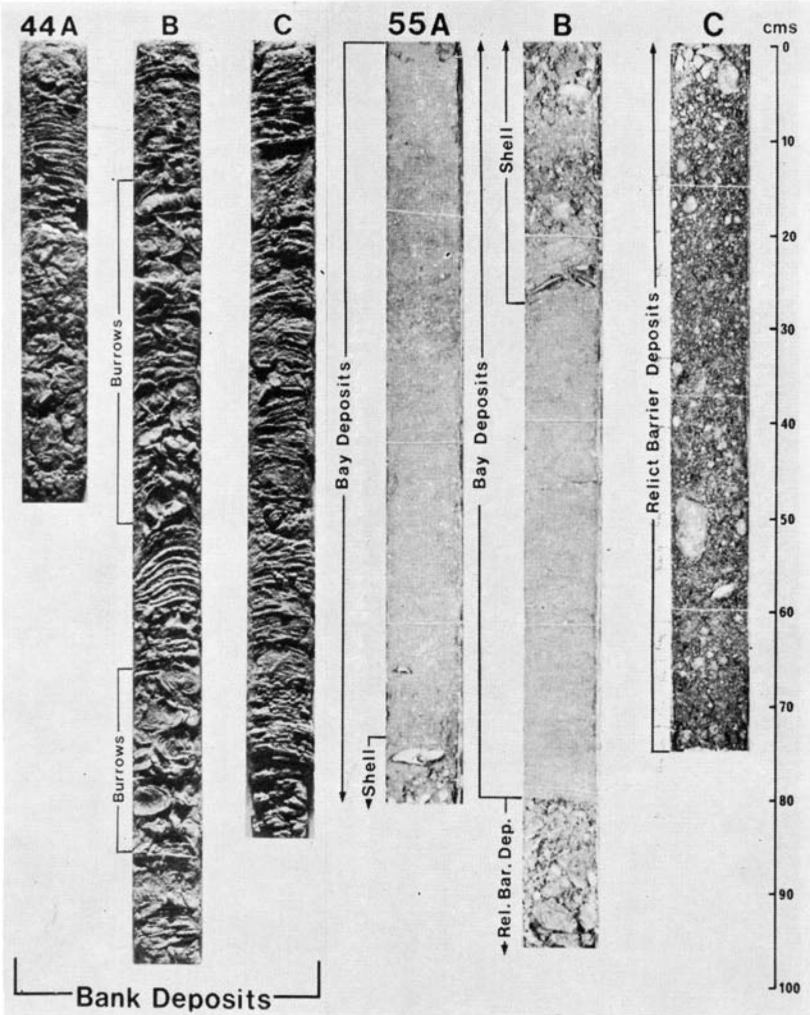


Plate I.

Sections of vibrocores obtained from stations 44 and 55. Number 44 shows an impregnated core of laminated bank deposits, and number 55 bay and relict barrier deposits. The bank deposits show evidence of burrowing by animals.

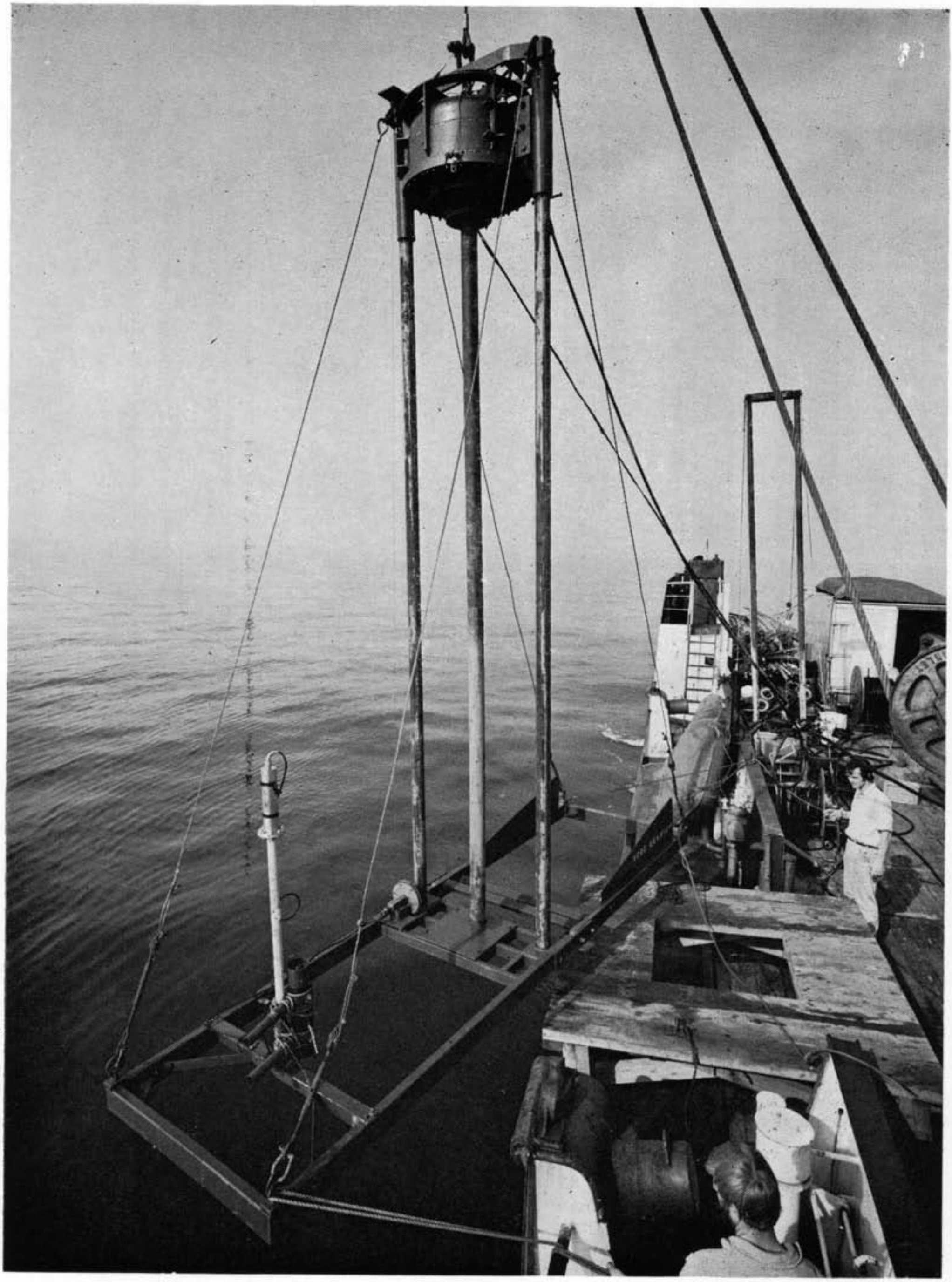


PLATE II.

Vibrocorer used by the Institute of Oceanographic Sciences (Taunton) to obtain cores from Start Bay. Photograph by permission of The Netherlands Rijkswaterstaat and the Royal Society of London.

Previously, I claimed that Hutton's doctrine of uniformitarianism, "the present is the key to the past", is particularly pertinent to the study of barrier coasts because of the difficulties in understanding littoral constructional features (Hails and Hoyt, 1969). Erosion, beach building, and the reworking of sediments are important foreshore and nearshore processes that modify coastal accumulations prior to their incorporation in the geological sequence. It is therefore necessary to understand the changes produced near the modern shoreline in order to interpret the origin of preserved sediments.

In this respect it is worth examining briefly the morphological characteristics of of the barrier beaches in Start Bay, especially "Slapton Sands". Firstly, there is little variation in the width of the Slapton barrier along most of its length, although it narrows from 110 m at its northern end to about 83 m at Torcross. Secondly, it stands 5·5 m above high tide level at Torcross and nearly 8 m above this datum near Pilchard Cove. Thirdly, virtually no material appears to be moved alongshore because there is no field evidence to show that erosion at one end of this barrier is balanced by deposition at the other. It seems most likely that it has been built seaward as material has been moved alongshore by waves.

Certainly, barrier growth in the immediate and distant past cannot be associated with the elongation of spits because remnant lateral recurves or hooks, turned landward by current deflection or by wave refraction, and also indicative of intermittent growth, are entirely absent from the Ley side of the Slapton barrier. There are small areas of shingle, known as "washovers", along its inner margin, but these have been deposited in the Ley by the action of "overwash" when storm waves have broken over low parts of the barrier.

If this evidence, then, is a reliable indication of the mode of barrier growth during the later stages of the Flandrian (Holocene) rise in sea level, it seems reasonable to suggest that the offshore relict barriers extending from Redlap Cove to approximately the middle of Slapton Ley were built on a gently sloping seafloor parallel to the coast, and that their growth accompanied the shoreward migration of material. The important question that arises is why these relict barriers should be confined to this part of the Bay. One reasonable explanation is that, when sea level was a few metres below its present level, nearshore wave conditions and wave energy dissipation at the shoreline were somewhat different from those existing in the Bay today.

Evidence that shallow lagoons formerly existed, enclosed in part from the sea by barrier islands, has been obtained from a detailed microfaunal study of the bay, bank and buried channel deposits (Lees, 1975). Typical foraminiferid assemblages representing brackish water, salt marsh, coastal (saline) lagoon and shallow sea environments are listed in Table 3. These assemblages show that at about 8,000 years or so ago, as determined from the C-14 dating of the peat recovered in Core 70,

Table 3. *Dominant foraminiferid species in assemblages from former environments in Start Bay*

Salt Marsh	Brackish Water	Coastal (Saline) Lagoon	Shelf Sea
Elphidium articulatum	*Ammonia beccarii*	*Ammonia beccarii*	*Ammonia beccarii*
Trochammina inflata	*Elphidium articulatum*	*Elphidium* sp.	*Cibicides lobatulus*
	Elphidium excavatum	*Planorbulina mediterranensis*	*Quinqueloculina seminulum*
	Protelphidium anglicum	*Quinqueloculina seminulum*	*Textularia sagittula* group

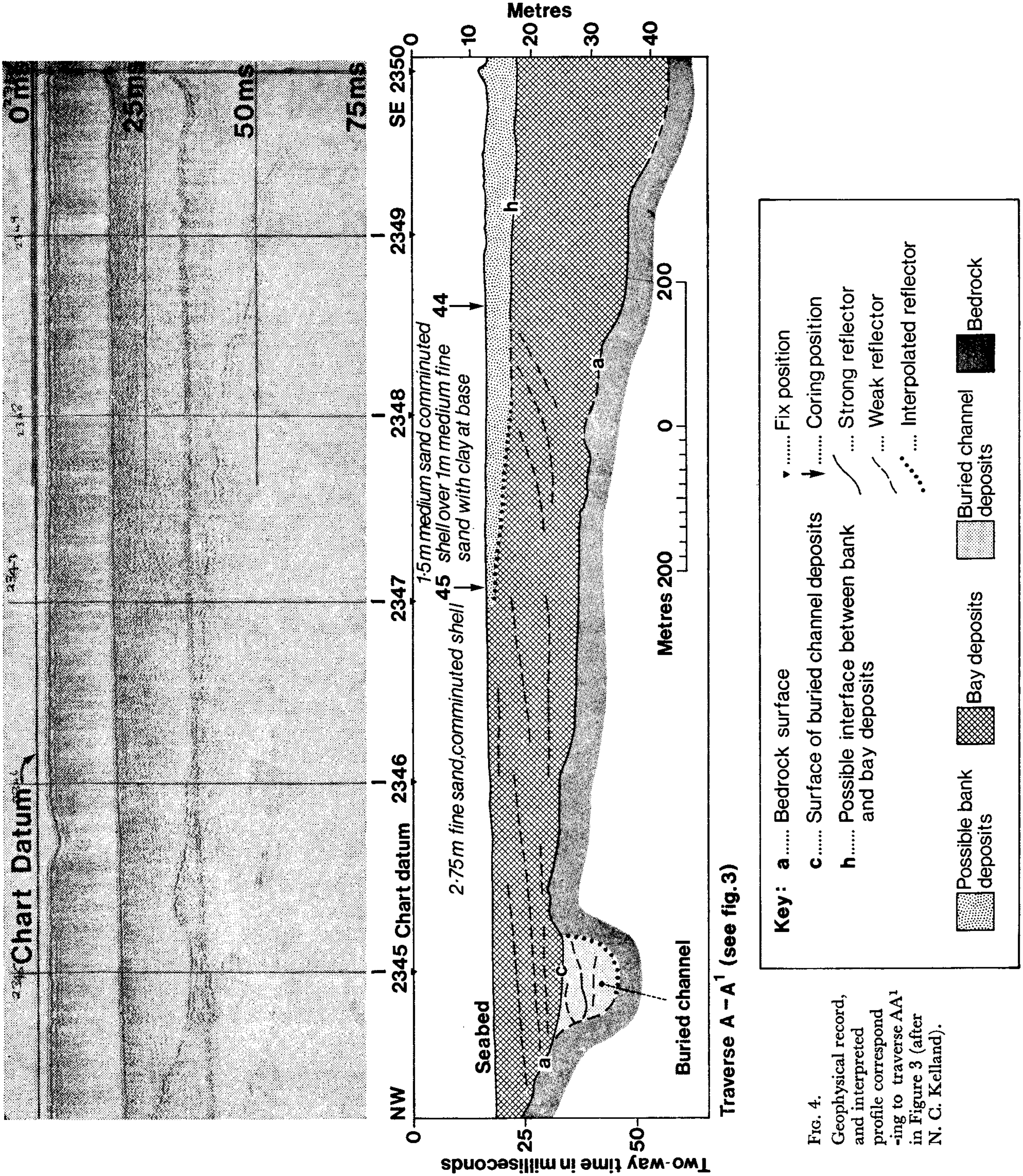


FIG. 4. Geophysical record, and interpreted profile correspond-ing to traverse AA¹ in Figure 3 (after N. C. Kelland).

a barrier-lagoon coastline existed along the inner margin of the present-day Skerries Bank, as shown in figure 5. The north-easterly extension of this former coastline is rather difficult to trace because so far an insufficient number of cores have been collected in this particular area. Also, as shown in figure 5, a shallow sea extended over the area now occupied by the Skerries Bank into the present English Channel. The foraminiferid evidence shows that the barrier-lagoon complex migrated shoreward and transgressed former river channels slightly incised into the seafloor. Areas of salt marsh occurred behind barriers which in turn were separated by estuaries.

Thus, it seems likely that ephemeral barriers retreated towards the modern coast as the sea rose to its present level. However, some barriers may have been completely destroyed by wave action, leaving no trace of their former existence, whilst others may have been only partially removed, as appears to be the case off Redlap Cove (see also Fig. 3). In the latter instance, estuarine-lagoon sediments can be transgressed by the barrier deposits that originally protected them from wave action.

There is virtually no difference in the composition and texture of the gravel deposits within the Bay and therefore they can be best described as being *polycyclic*, having undergone erosion, transportation and deposition on many occasions (Hails, 1975).

My petrographic studies show that most of the quartz pebbles have been derived locally from the quartz-schist near Start Point. Other constituents, especially the

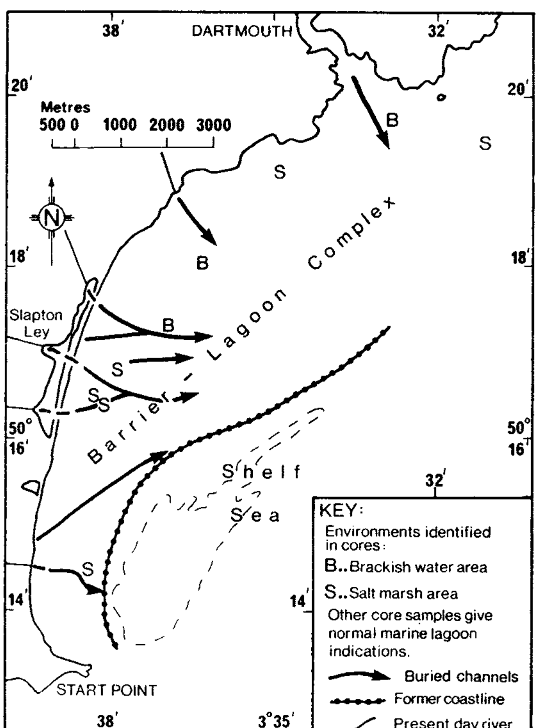


Fig. 5.
Reconstruction of former environments in Start Bay, as determined by foraminiferid evidence (based on Lees, 1975).

granite and felsite, have been transported from the Dart River catchment, and, according to Worth (1890), subsequently eroded from the Triassic breccias and conglomerates of south Devon. Most of the volcanic pebbles have a fairly local origin as well. However, it is apparent from the composition of the bedrock shown in Figure 1 and from the evidence of the submarine geology that there is no local or neighbouring source to explain the relatively high content of flints (flint and quartz constitute between 90 and 96 per cent of the gravel) in the modern barrier, relict barrier and buried channel deposits.

The nearest land area and coastal source from which the flints could have been derived are respectively the Haldon Hills 40 km to the north and the Chalk cliffs at Beer, 58 km to the north-east. The most probable source is the floor of the English Channel, 40 km to the east well beyond the limits of the Start Bay shelf. Thus, it might be inferred from the existing evidence that the barrier deposits have been transported shoreward in response to minor oscillations of sea level during the Flandrian transgression and possible earlier eustatic changes of sea level.

The provenances of most of the heavy minerals in the bay deposits are the Dart River catchment, and the neighbouring Devonian sedimentary rocks, but again it is almost impossible to say how many times some of these have been reworked from older unconsolidated shelf sediments which, in turn, originated essentially from the sources just mentioned (Hails, 1975).

The area covered by the estuarine lower bay deposits is still not accurately known. However, it seems reasonable to argue that these are *relict*, having been deposited in equilibrium with pre-existing environments prior to partial burial beneath the upper bay deposits. The fact that the latter only form a thin veneer, less than 1 m thick in the nearshore zone, probably reflects the winnowing of fine-grained sediments by tidal currents and waves, and perhaps to a lesser degree points to land-derived material from the Dart catchment being trapped in the lower reaches of the river. Certainly, at present, there is no conclusive evidence to indicate that sediment is reaching the coast either from offshore or by movement alongshore, and therefore it is proposed that Start Bay is a *closed system*.

Some insight into the relative stability of the Skerries Bank has come from the work of Acton and Dyer (1975). They conclude that peak tidal currents over this bank are not very high, being lower than those in the adjacent seaward area, and that residual currents are negligible along its crest. Although this may explain the relative long-term stability of the Skerries, little is known about the reasons why the shape of the crest changes so frequently. The origin of the Bank is still not known despite the work described in this paper, and it seems that only stratigraphical and palaeontological information from deep cores will resolve this intriguing problem. However, it has been established that a barrier would have been established slightly seaward of the modern-day "Slapton Sands" if the Bank had occupied approximately the same position in the recent past as it does today (Hails, 1975; Holmes, 1975). On the other hand, without a bank, a barrier beach would have been built at the base of the degraded cliffs which flank the inner margin of Slapton Ley.

Data have been used from a computer program, which takes into account refraction, diffraction, reflection, absorption, shoaling effect and wave breaking, in order to analyse nearshore wave conditions and to deduce wave energy dissipation at the shoreline. The possible effects of the Skerries Bank on wave refraction have been considered too. The pattern of wave rays (curves that are everywhere perpendicular to the wave crests on a refraction diagram) over the Bank and inside Start Bay for periods between 7 and 14 seconds is shown in figure 6. The influence of the Bank

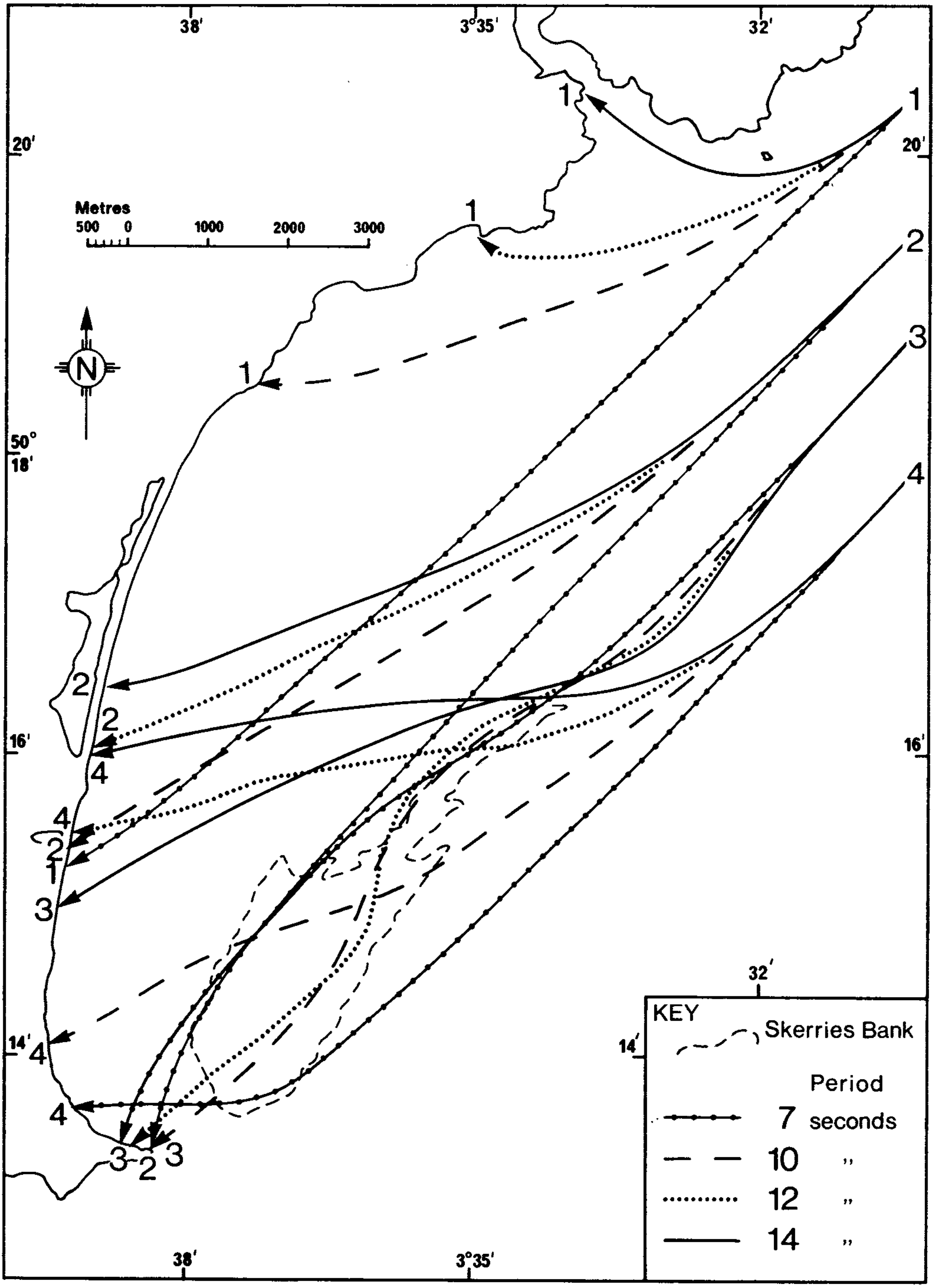


FIG. 6.

Map to show refraction of wave rays (orthogonals) with north-easterly swell over the Skerries Bank.

on wave refraction is clearly seen when north-easterly swell enters the Bay with the result that wave rays (orthogonals) are focused immediately opposite the villages of Beesands and Hallsands. Therefore, it is fairly conclusive now that both these settlements are situated on a sector of the coast which is particularly vulnerable to wave attack from the east, particularly the north-east. It follows, then, that dredging over the five-year period, 1897–1902, aggravated a delicate situation with regard to coastal erosion. There is little doubt, since no material was entering Start Bay to replenish that removed by man, that the Hallsands disaster can be attributed to the legacy of dredging shingle (beach gravel) from the inter-tidal zone, combined with a critical combination of 40-foot storm waves, north-easterly gales and spring tides.

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Summary

An inter-disciplinary study has been directed towards environmental problems in Start Bay, such as the effects of short- and long-term changes in the offshore sediment budget on the incidence of coastal erosion and the relationship between the Skerries Bank and water circulation and sediment movement within the Bay. The bedrock morphology and the nature and structure of overlying Quaternary superficial deposits have been determined by such techniques as continuous seismic profiling, side scanning sonar and vibrocoring. The major geological features identified include a buried cliffline at a depth of 42 m, buried channels and relict barriers. Three lithological units, known as *barrier*, *bay* and *bank* deposits, have been recognized in the superficial material overlying bedrock.

The main conclusions of the study, supported by C-14 dates and foraminiferid evidence, are that:

(a) A barrier-estuarine-lagoon complex has migrated steadily shoreward during the past 8,000 years B.P.

(b) Start Bay is a *closed system* under present-day conditions since there is no conclusive evidence that sediment is reaching the coast, either from offshore or from adjacent areas.

(c) The relative stability of the Skerries Bank may be explained by the values of the residual currents which approach zero along its crest.

(d) The influence of the Skerries Bank on wave refraction and energy dissipation along the shoreline is such that Beesands and Hallsands are situated on sectors of the coast that are particularly vulnerable when storm waves are accompanied by north-easterly winds.

(e) Long period swell, in the order of 14 seconds, can reach Start Bay.

(f) The 1917 Hallsands disaster can be attributed to the legacy of dredging beach gravel from the inter-tidal zone between 1897 and 1902, combined with a critical combination of 40-foot storm waves, gales and spring tides.

APPENDIX I

Field and Laboratory Techniques

(a) geophysical survey, seabed bottom sampling and vibrocoring

Bottom samples were collected with either a Shipek or a modified van Veen grab sampler at stations located approximately 500 m apart along traverses normal to the shoreline and used for the geophysical survey.

Positional control in Start Bay was provided by a Decca Navigator Mark XII receiver operating on the south-west British chain. The variable errors were not compensated for, thus introducing an apparent shift of 40 m west-south-west from the true positions. However, this shift has not introduced significant errors in either the grab sampling or vibrocoring positions because the same grid has been used for both geophysical survey work and sediment sampling. The vibrocorer used for obtaining undisturbed samples consists of a submersible coring rig with power unit which, in operation, is linked to the surface by a power cable from a shipboard generator and lifting cable. A T-shaped frame maintains the core barrel in an upright position during coring.

(b) Analytical procedures

(i) *Core Preparation*

Plastic liner tubes containing vibrocores were cut into 1 m lengths in the field and transported in a vertical position to the laboratory in order to minimize disturbance.

In the laboratory, they were opened by making longitudinal cuts through the plastic liner with a butane heated knife. These cuts are, in fact, made along lines which are drawn according to the orientation required. The sediment itself is then cut either with a cheese wire or a palette knife, the latter being used for shelly material or pebbles. The two halves of the core are treated differently according to the information required from sedimentological analysis. Usually, one half is used for standard grain size and mineralogical analyses whilst the other half is used for descriptive and photographic purposes, including impregnation where lithology allows. After photographic records have been taken the cores containing sand are allowed to dry before being impregnated with Nitrol Profile lacquer to a depth of about 1 cm. Once the lacquer has hardened the impregnated material is removed and the remaining material, if required, is used for sampling purposes. The impregnated section is brushed lightly to remove any adhering unimpregnated material. Any structure is now visible, including changes in the "relief" in the form of laminations. Of course, cores containing clay cannot be impregnanted in this way and any structures in these are therefore usually examined by X-ray radiography. It has been found that gravel horizons in cores rarely show any structure, but these are impregnated as well in order to maintain continuity with the sand sections.

(ii) *Grain Size Analysis*

A 25-gram split of each bottom sample and each lithological unit, including any horizon showing an apparent lithological change within a unit, identified in the cores was sieved through a set of British Standard Metric Sieves (BSMS) at the 0·25 phi interval for fifteen minutes. The retent of each sieve was weighed to four decimal places although the results listed in the text have been rounded to two decimal places. Although the silt and clay fraction contained in many of the Start Bay samples is reasonably small, it was considered necessary to obtain weights at the 1·0 phi interval by the Andreason Pipette method rather than lumping it as a "residue-pan" fraction. Therefore, none of the sample data, from which moment measures were computed, was open-ended. The phi interval of the fine "tail" fraction remained constant in each calculation and did not affect the comparison of lumping the rest of the data.

Statistical measures were calculated by using central moment equations. All calculations were made by using a DEC PDP—11/20 computer and a program written and described by Seward-Thompson and Hails (1973). Briefly, this program uses all available data, obtained from standard sedimentological analyses, regardless of the phi interval, and computes statistical parameters by direct integration of a piece-wise linear approximation to the cumulative curve. This has the advantage that the distribution curve is known and hence the limitations of the parameters obtained can be assessed. This approximation appears to introduce no greater degree of inaccuracy than is already present in standard sampling and analytical procedures (Hails *et al.*, 1973).

(iii) *Heavy Mineral Analysis*

The calcium carbonate was removed from a 50-gram split of each bottom and core sample before it was sieved at the 1 phi interval (+2, +3 and +4 phi). The light and heavy mineral fractions were then separated from these three size intervals in tetrabomoethane (S.G. 2·95) using the conventional laboratory method. The heavy residue was separated into strong, moderate, weak and non-magnetic fractions by an isodynamic separator, before being mounted in Canada balsam on a petrographic slide for microscopic examination and grain counts.

The percentage number of each mineral in an individual sample was determined with a mechanical stage and by counting 300 grains.