THE STABILITY OF COASTAL CLIFFS ALONG A SECTION OF THE CEREDIGION COASTLINE

by

David G Jones B.Sc.

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Certification of Research

This is to certify that except where specific reference is made, the work described in this thesis is the result of the investigation of the candidate.

Candidate David G. Jones.........................
Director of Studies A T Williams..................

Declaration

This is to certify that neither this thesis, nor any part of it has been presented or is currently submitted in candidature for any degree at any other University or Polytechnic.

David G. Jones.
....
David G. Jones
(Candidate)

Cyflwynedig

Er cof am fy nhad
'cyn i'r Erydwr mawr
gnewian y glannau
o filfedd i filfedd'

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ABSTRACT

D.G. Jones - The Stability of Coastal Cliffs along a section of the Ceredigion Coastline

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Investigation of cliff recession along 20km of the West Wales coastline has recognised erosion processes and mechanisms. Cartographic evidence has established considerable spatial variability in long-term retreat rates between the solid rock sections and those of tills and glacial clays. Mean contemporary recession rates of 13cm yr^{-1} have been measured in the glacial embayments where storm wave action is considered the primary direct agent initiating cliff erosion. Morphological evidence suggests that different mechanisms have produced recession in other areas.

Cardigan Bay is a medium-to-high energy storm-wave dominated environment receiving on average twelve storms per year. A wave-hindcast procedure provided measures of storm intensity (maximum value of 4.8×10^5 Joules/m crest width), those from the north-westerly quadrant contributing 82% of all destructive waves. Climatic and tidal influences were assesed in terms of tidal coverage of different cliff heights along the coastline.

Theoretical wave refraction modelling has predicted a series of longshore residual littoral sediment cells. The position of such cell boundaries in terms of 'high' and'low' beaches has been assessed by extensive field surveys. Longshore variation in beach levels was considered to be constant over the study period while changes in 'sweep' zones were seasonal though single storm events did result in a significant lowering of beach level by up to 1.5m.

Field and laboratory determination of basic physical properties of the tills did not differentiate between them although inherent variations of grading were found within each till unit. Comparative values of uniaxial compressive strength were obtained to represent the geotechnical properties of the various cliff materials.

Temporal and spatial variation in erosion rates were considered to be a function of environmental, beach and cliff factors. The significance of each factor was tested statistically using stepwise multiple regression. Beach volumes were most significant in explaining spatial variation whereas no consistent relationship was evident for strength of materials.

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CHAPTER 1.

INTRODUCTION

1.1 Importance of research

In June 1980, the Secretary of State for Wales authorised the Environmental Engineering Division of the Welsh Office to carry out a survey of the coastline of Wales in order to obtain basic information for a review of coastal policy and an assessment as to the effectiveness of the Coast Protection Act 1949. This Act made each maritime district council in Great Britain a coast protection authority with legislative powers to protect land against erosion or encroachment by the sea.

Part of the Terms of Reference for this survey was to identify areas of erosion and accretion and to gather information on history and rates etc., where available, and on property at risk.

In recent years the Welsh Office has been sponsoring a limited amount of research into cliff stability and erosion along unprotected coasts and this investigation into the problems of recession along a particular section of the Cardigan Bay coastline is part of that policy.

1.2 The problem of coastal erosion

Erosion is a problem that affects all unprotected coastline except in those areas where the cliffs are of very hard rock, the greatest rates being recorded from areas where active cliff lines are formed in unconsolidated material.

Corrective measures are varied and require different approaches and attitudes. Engineering solutions in terms of protective structures against toe erosion or large-scale slope stabilisation are often neither economically feasible nor environmentally desirable.

In the great majority of cases, the problem is accepted by coastal authorities as intractable and when nothing more than a minimal amount of open land is being lost annually, councils are generally content with the policy that the cost of coast protection works must be justified by the value of what is being protected - that is, the application of normal cost/benefit criteria.

The areas of greatest concern along the Ceredigion coast are the boulder clay/till flats and cliffs between Llanrhystud and Aberaeron and particularly at New Quay (Plates 1.1 and 1.2). Although the area is predominantly rural in character, a number of properties,including holiday caravans, are threatened and one house has already had to be demolished due to wave-induced landslippage.

Current evidence for retreat is the presence of rapidly receding field boundaries and fences and the disappearance of coastal footpaths and trackways within living memory.

1.3 Historical background to study area.

The former County of Cardiganshire (now Ceredigion) is well-known for its seafaring traditions, both deep-water ships and coasting vessels. The inaccesibility of inland parts of the county led to a flourishing coastal trade. Both New Quay and Aberaeron were active ports in the eighteenth and nineteenth centuries but today are primarily holiday resorts.

At New Quay an abrupt turn in the coastline provides a sheltered harbour. The Harbour Company was formed in 1833 and the town quickly established a reputation for ship building but this has all gone and lobster fishing has taken over.

Up to about 1800 the town of Aberaeron was much less important than the smaller, picturesque Aberarth, a mile to the north. Aberarth is marked on Carey's (1599) map, but not Aberaeron. Then the jetties that give shelter to the harbour were built and Aberaeron grew. Coal, lime, timber and slates brought into the harbour, together with exports of corn and miscellaneous farm produce, were a useful addition to the local economy (Fletcher, 1969).

Further north,towards Aberystwyth,settlements are few. The village of Llanon is well-spread out over the wide space between the main A487 trunk road and foreshore. Nearby,Llansantffraid is not without interest; the church is set in a circular churchyard indicating an

PLATE 1.1 View northwards of glacial embayment between Aberaeron and Llanrhystud

PLATE 1.2 General view of boulder clay slopes at New Quay

ancient site while on the south side of the river Peris there are scattered groups of former fishermen's cottages (Robinson and Millward, 1983). Llanrhystud is situated some 1km inland from the coast, the foreshore itself being taken up by several large caravan parks. Ceredigion today is not of particular economic importance, tourism and farming being its main attributes.

1.3.1 Spelling of local place names.

Explanation is given here on the spelling of place names in the text. Nomenclature used in maps and various literature is a mixture of different anglicised spellings evolved through historical usage. There are, for instance, several alternative spellings (both in English and Welsh) to be found for most of the place names within the study area.

Many place names in Wales have recently reverted to the original Welsh spelling and, for convenience, this up-to-date nomenclature has been adopted in this account. Most names are unaffected but, for instance, Cardigan becomes CEREDIGION, Llanrhystyd - LLANRHYSTUD, Llan-non - LLANON, Aberayron - ABERAERON, Little Quay - CEI BACH, while NEW QUAY and CARDIGAN BAY itself, to avoid confusion, have retained their more familiar English names.

1.4 Previous research in the area.

Geological research in the Ceredigion area was begun circa 1842 and perhaps the most perceptive interpretation of the detailed structure of the area remains that of Ramsay, whose sections were published in 1845. Jones (1909, 1912) established the stratigraphical succession from graptolites, contradicting the earlier exposition given by Keeping (1881). Other important written works published to date were those of Jones and Pugh (1915, 1935) and that of Wood and Smith (1958) who recognised the local lithologies, collectively known as the Aberystwyth Grits, as being turbidite in origin. From the geological standpoint the Geological Survey memoir by Jones (1922) is the one full and authoritative work although in the third edition of the Regional Geology handbook of South Wales (George, 1975),northern Cardiganshire is given considerable attention.

The glacial history of the area has been well documented by various workers, notably Williams (1927), Charlesworth (1929), Bowen (1973a, 1973b), and Watson (1970, 1977). The latter concluded that a high proportion of surface forms and deposits may be adequately explained in terms of periglacial origin. From offshore drilling and coring, Garrard (1977) has identified the nature and maximum extent of glacial sediments off the coast while microfauna and microflora from submarine boreholes have enabled Haynes et al.(1977) to reconstruct the late Glacial and Holocene environments within the south and central Cardigan Bay area.

There is a paucity of information on coastal processes within the Cardigan Bay area, particularly in the way they influence erosion rates. In recent years numerous studies have focussed on beach and nearshore processes. Jarvis (1970), in a study of the Dovey estuary, found that tidal activity was the controlling parameter in an estuarine environment whilst the work of Orford (1978) at Llanrhystud is of particular importance in terms of beach gravel sedimentation.

Of relevance to aspects of this study is a detailed two-year investigation by Williams et al.(1981) into beach morphological changes at Ynyslas Spit, near Borth. Although the area was shown to be essentially stable, wave orthogonals produced by a wave refraction model for south-westerly storms indicated a concentration of energy at the distal end of the spit which was confirmed by the considerable erosion recorded along beach profiles in this area.

Also at Ynyslas, Gulbrandsen (1985) analysed the effects of varied tide levels on the ability of a standard wave refraction technique (Dobson, 1967) to predict shoreline energy distribution. This study showed that erosion correlated well with predicted shoreline energy distributions if short period waves are refracted on the rising and high tides, and that longer waves correlated well with areas of less erosion and possibly with accretion when calculated at low-tide level.

The evolution and erosional history of the coastline from Borth to New Quay has been described by Wood (1959) while Heywood (1984) has investigated, using cartographic evidence, changes in the south Cardigan Bay coastline over the last century. This latter study indicated that the changes were not consistent either temporally or spatially and that there was an extensive and complex interaction of factors involved.

So (1973) highlighted the adverse effect of human interference with natural processes on coast development and beach changes around Aberystywth and nearby Tanybwlch. A later paper by Wood (1978) discussed present-day coast erosion at Aberystywth, particular reference being made to a fall in beach level and the undermining of the north promenade.

Wood (1978) contended that the building of a new promenade at the turn of the century inadvertently cut off a source of beach material from the south. In a recent report to Ceredigion District Council, Wood (1983) recommended replenishing the beach with some 2000 tonnes of pebbles but warned that the only long-term solution would be the construction of an underwater breakwater of large rocks.

Consulting engineers Lewis and Duvivier (1960, 1967, 1973), in numerous reports to the local authority on sea defence works and beach conditions, have referred not only to this deficiency in supply of materials to the beaches but also to the rapid breakdown of the parent rock. This process of gradual attrition, almost inherent it seems with the local Aberystwyth Grits, could be responsible for the loss of a substantial portion of potential beach fill offshore.

1.5 Aims and organisation

The original statement of the project outlined an investigation into the physical processes responsible for erosion along the south Cardigan Bay coastline, special reference being made to the stability of coastal till sections.

No complete quantitative study of the total coastal system has yet been attempted, partly because of the complex integration of sub-aerial and marine processes and partly because of the diverse roles played by marine processes themselves - both in direct cliff erosion and debris-forming by undercutting and the removal of the same debris, together with protective beach material, by sediment transport movement both longshore and normal to the shore.

It is only when one considers all the processes operating at one place at one time in moulding the coastal landscape that the inherent problems in geomorphological research become apparent. 'Geomorphology is, and perhaps always will be, one of the most difficult of the physical sciences' (Linton, 1964, p.58).

Whilst it may be idealistic to expect a complete quantitative understanding of the coastal system it is perhaps realistic to attempt to solve specific problems and to establish empirical relationships between process and change. Certainly such a quantitative approach provides data which can lend itself to statistical analysis providing all relevant parameters are measured. The question then arises - which parameters are relevant or not?

This study will attempt to postulate a predictive model of the inherent coastal system by quantifying the major factors responsible for erosion and determining a statistical relationship (if any) between these factors.

Apart from the largely theoretical and laboratory work of Sunamura (1977) there has been relatively little work on the mechanisms of erosion and sediment removal by wave action at the toe of a sea cliff. In addition the beach profile and particularly the amount of beach material at the cliff base has received limited attention (Robinson, 1977; McGreal, 1979). Particular reference is given in this study therefore to the role of wave action on unconsolidated cliffs of glacial drift and to the effectiveness of the gravel beaches as buffer zones. The distribution of wave energy along the coast is identified by means of computer modelling and by field experiments making use of a wave dynamometer and pressure transducer developed in the Physics section of the Department of Science at the Polytechnic of Wales.

The structure of the work falls into the following distinct phases though not necessarily chapters:

(i) Theoretical modelling of predicted onshore and longshore wave power using a wave refraction model developed at Queen's University, Belfast, and based on May's (1974) WAVENRG computer programme for estimating the distribution of energy dissipation in shoaling waves. This model is used to identify potential zones of erosion and deposition as expressed by sediment cell boundaries.

(ii) Positioning of such boundaries in terms of beach morphology, the presence of 'high' and 'low' beach sediment volumes being indicative of zones of net deposition and net erosion respectively (Tanner, 1974a) The longshore variation in beach morphology is established by topographic profiles taken at fixed distance intervals from temporary beach marks established above high water level, together with beach sediment sampling and testing where necessary.

(iii) Measurement of long-term retreat rates for a 20km section of coastline together with contemporary retreat rates for local areas of low-lying till and boulder clay slopes. Variation in cliff material facies and their geotechnical properties is examined and related to the measured coastline recession.

(iv) Quantification of the beach, cliff and environmental factors which may account for spatial and temporal variations in erosion rates and their statistical analysis in terms of importance.

CHAPTER 2.

THE PHYSICAL PROCESSES OF COASTAL EROSION - AN HISTORICAL PERSPECTIVE OF THE LITERATURE

2.1 Introduction

Coasts have been a major interest to man throughout most of his long history and the phenomenon of coastal erosion has been recognised from early times and been extensively documented from many parts of the world and from varying coastal environments.

Active interest in coast erosion and defence in Britain dates back at least to the medieval period when the Cistercian monks of Furness Abbey were known to have constructed dikes and embankments to prevent flooding of Walney Island on the Cumbrian coast (Phillips and Rollinson, 1971).

The medieval village of Dunwich in Suffolk, once said to be a considerable settlement with monastery, churches and harbour, has virtually been destroyed by coastal erosion. Also in East Anglia the area extending south from Cromer along much of the coast of Norfolk has suffered severe erosion which was first described by Hewitt (1844). Perhaps the best documented area is the Holderness coast of East Yorkshire, where erosion of cliffs of glacial drift has been going on at least since Roman times (Sheppard, 1912).

The first thorough compilation of the British coastline,and still the definitive work to date, was produced by Steers (1946,1973). Although these texts were essentially physiographical treatises where the coastal morphology was examined in relation to geology and structure, references were made to the rate and effects of erosion in specific areas where land losses had been severe.

The Royal Commission on Coast Erosion (1911) gave figures that indicated the extent of erosion, and accretion, on the coasts of the U.K over an average period of 35 years. Evidence was derived from a comparison of the various editions of the 6 inch to 1 mile Ordnance Survey maps and although in detail the figures may not have been completely accurate, they did show more land gained from the sea than lost to it.

Nevertheless coastal erosion has been, and remains, a serious problem in many areas, not only in Britain but world wide. More recently a National Shoreline Survey issued by the U.S. Army Corps of Engineers (1971) showed that one quarter of all the U.S. shoreline was experiencing significant erosion. Komar (1976) has suggested that if Alaska's coasts are excluded, this proportion is raised to 43%.

Much publicity has been given in the last few years to the problem of the world's vanishing beaches and its implication for coastal retreat (Bird, 1984). A global survey set up by the International Geographical Union (IGU) has discovered that more than 70% of the total length of sandy coastline around the world has retreated at a rate of at least 10 cms per year in recent decades, with a third of this total receding at more than a metre per year (Gribbin, 1984). The commission's definition of sandy coastlines embraces about one-fifth of the total coastline but does not include rocky coastline or cliff which has only a fringe of sand at its foot.

At a time when the conservation of natural resources is regarded as of increasing importance, considerable attention has also been focused on the recession of sea-cliffs in connection with coastal zone planning and management. (Brown et al, 1978; Griggs and Johnson, 1979; Kuhn and Shepard, 1979,1980; Boukuniewicz and Tanski, 1980; Lee, 1980; Nordstrom 1984,1985).

It is apparent from the accumulated literature about coasts and from the works of earlier writers that the problems of coastal erosion encompass a wide range of facets. Indeed, current studies reflect the inter-disciplinary nature of research work in this field,research which spans the fields of geology, engineering, biology, mathematics, oceanography and geomorphology. Lithologically,studies range from unconsolidated glacial sediments through the more typical soft rocks to granites and basalts and in scientific approach from flume tank experiments and instrumentation to stratigraphy and the more conventional geomorphological direction.

The breadth of investigations concerning coastal erosion discourages a complete listing and this review will be primarily limited to those studies which delineated the processes investigated and the techniques used in this work.

2.2 Qualitative Approach

Published work on coastal erosion has tended to be largely descriptive in nature and many provide lists of the various processes by which cliffs are eroded by the sea and are of a qualitative or semi-qualitative nature. Such studies are invariably subject to personal bias and as Trenhaile (1980,p2) stated 'although mechanical wave erosion is accomplished by a number of processes, the relative importance of these has usually been referred from morphological evidence which may be ambiguous'. The first part of this review lists in chronological order some examples of this approach.

Shepard and Grant (1947) provided a list of factors involved in wave erosion of rocky coasts in southern California:

(i) hardness of rock
(ii) planes of structural weakness
(iii) coastal configuration
(iv) solubility of rocks and rock cement
(v) height of cliffs
(vi) nature of wave attack

Muir-Wood (1971), describing the engineering aspects of coastal landslides, provided perhaps the most comprehensive list of the principal factors affecting stability. This paper was an attempt to identify and understand the factors involved and, most importantly, to understand how they operated in association. It concluded that the most efficient solution to coastal instabilities was one which treated the problem in a composite manner rather than one which provided separate countermeasures to each individual factor.

King (1972) only considered the various marine processes responsible for cliff foot erosion:

(i) corrosion - chemical weathering by salt water
(ii) corrasion - mechanical weathering by abrasion

(iii) attrition - breakdown of debris formed by erosion

(iv) hydraulic action - pressure variations by waves causing block removal.

The last process is probably the most effective agent of marine erosion, particularly where shock pressures are exerted by waves as they break directly against the cliff face in such a way that pockets of air are enclosed (Bagnold, 1939; Denny, 1951).

Where cliffs descend straight into deep water, or if the waves break before they reach the cliff, then obviously no shock pressure will be induced.

Komar (1976) identified hydraulic pressure by wave impact as the principal process of marine erosion and, in providing a similar list to that of King (1972), also added biological action and sub-aerial processes such as weathering, ice wedging and rain wash.

McGreal (1977) ranked in hierarchial fashion the processes operating to produce recession on a glacial drift coastline in County Down, Northern Ireland.

(i) landslide activity - largely seasonal

(ii) marine activity

(iii) sub-aerial wash

(iv) surface weathering

(v) creep

(vi) wind action

McGreal (1977) drew particular attention to the modes of cliff failure and discussed stability relationships involving angle height relationships for the slopes and their geotechnical properties.

Clarke (1979) and Davies(1980) listed the following six processes that amplified the four given by King (1972).

(i) quarrying by wave action on loose rock

(ii) abrasion: wave induced currents moving sand and shingle against the cliff face

(iii) water layer weathering: more relevant to shore platform erosion than cliff erosion

(iv) solution of calcareous rock
(v) rock weathering
(vi) bio erosion.

Emery and Kuhn (1980) included most of the above processes but added the human factor, be it minor, for example, erosion by human feet, or major, as in mass movement due to shorefront construction. Man's influence on marine erosion has also been emphasised by Williams and Davies (1980) in their study of remedial cliff blasting at Llantwit Major in South Wales.

2.3 Historical assessment of recession rates

Studies of particular sections of coast have provided an historical assessment of recession rates from which processes have often been inferred. Greatest rates of erosion have been recorded from areas where active clifflines are formed in unconsolidated material. This approach is invariably subjective and can sometimes lead to erroneous conclusions of both rates and processes. Some examples of this approach, with salient points, are listed below by geographical location.

North Yorkshire

Agar (1960) examined the length of North Yorkshire coast from the Tees estuary to Ravenscar for physical evidence of changes which have occurred in the past 10,000 years. The present rates of erosion were established by comparison of the 1892 1:2500 O.S map with special resurveys at selected points. The average cliff foot rate was 4.88m/century and the cliff top rate was 2.13m/century indicating a steepening of the cliffs. More rapid erosion was measured for the areas of glacial drift (28.0m/century) than for those of solid rock.

Agar (1960) was concerned with cliff recession in relation to lithology and arranged the rocks in order of decreasing resistance as follows - sandstones, sandy shales, boulder clays, sands and gravels.

Robinson (1976,1977) made some successful measurements of the rate of erosion of cliffs and adjacent wave-cut platform, the latter by means of a micro-erosion meter developed by High and Hanna (1970). Using this device he found that corrosion was the main erosion process on the platform ramp and rates varied between 3.94×10^{-3} cm per tide and 1.13×10^{-3} cm per tide depending on wave energy and the depth of overlying beach material. Robinson (1976, 1977) noted that cliff erosion was between 15 and 18 times faster on cliffs fronted by a beach which contradicted the efficiency of the beach as an energy dissipator as proposed by most other coastal workers.

Robinson's interpretation of the evolution of this part of the Yorkshire coast also differed considerably from Agar's (1960) possibly because the latter did not fully consider the isostatic movements which have taken place during and since the Ice Age.

North Humberside

On the Holderness coast Valentin (1954) compared ground measurements with those obtained from 1852 1:10,560 scale O.S maps to obtain retreat rates over a 100 year period.

While the average rate has been about 1.8m/yr, Valentin's work showed great variation of erosion rates along this coast which seemed to bear little relationship to cliff height but more to the variation in drift material type forming the cliffs and to the position of coastal defences which resulted in a considerable increase immediately downdrift.

Pringle (1981), on the same coastline, correlated phases of accelerated cliff erosion with the presence of low beach in the southward drifting beach system, emphasising the fact that deposited beach material on the backshore serves to protect the base of cliffs from direct wave attack, storm wave energy being expended upon the beach.

East Anglia

Cambers (1975) applied the classic concept of scale in geomorphology as proposed by Schumm and Lichty (1965), to three coastal cliff erosion systems on the east coast of England. The areas studied were all lengths of unconsolidated Quaternary cliffs, two of which are in Norfolk and Suffolk, the third the Holderness cliffs in Yorkshire.

The systems were described in terms of location, dominant processes and erosion rates. Retreat rates were measured over a 70 to 100 year period by comparison to the 1:10,560 (6 inches to 1 mile) Ordnance Survey maps. For Norfolk, map comparison provided a retreat rate from 1880 to 1946, brought up to date (1967) using aerial photographs to plot the cliff top position. Similarly for Suffolk, map comparison gave the retreat rate over a 70 year period. For Holderness, Valentin's (1954) data were used (see North Humberside).

The existence of dynamic equilibrium conditions was emphasized and the relative importance of the catastrophic and moderate storm event was discussed and shown to be a function of the time scale under consideration.

Suffolk

Williams (1956) recorded 12m of recession on cliffs of glacial sand 12m high and 27m recession on cliffs 3m high on a mile long sector of the Suffolk coast at Covehithe during the famous 1952 storm surge,when the loss of material in a 24 hour period was estimated at some 300,000 tonnes. This is an extreme example of very destructive waves with an abnormally high water level acting on unconsolidated cliffs.

Because of the intermittancy of such extreme events, and lateral variations in their effects, average rates of cliff retreat can be extremely misleading. It is interesting to note that this very high loss in the Covehithe area compared with a relatively low loss near Dunwich, an area which has suffered so much historically. This further emphasised the vaguaries of temporal and spatial variation in coastline erosion.

Near the same location, measurements by Durbridge (Steers et al., 1979) showed that 9m of cliff disappeared between 19 March 1977 and 11 March 1978, most of this being attributed to the storm surge of 11 January 1978. During 1979-1980 erosion was less marked (4.6m) and appears to have shifted southwards.

The cliffs hereabouts are not prone to sub-aerial erosion in that they give rise neither to landslides nor to flowing but yield in local small falls and more or less continous crumbling.

Sussex

May (1977), from an analysis of 6 monthly surveys of the cliff top made by Hailsham R.D.C, measured an average yearly rate of recession of chalk cliffs at Birling Gap between 1950 and 1962 of 1m. This represented an areal loss of 3264m^2 over 12 years, 97% of which was removed in winter periods and 42% in two particularly severe winters. This not only emphasises the severity of winter storm waves but also suggests that severe falls produce a great deal of debris which, for a limited time, forms a defence of the cliff foot.

Northern Ireland

Long-term evidence from map sources suggest mean annual retreat rates of between 0.21 and 0.84m/year in sediments of glacial origin near Kilkeel, County Down (McGreal, 1979). Spatial variations in these rates were considered to be independent of environmental conditions and were instead a function of site, beach and geotechnical factors.

Temporal variations (particularly the cohesive strength of the deposits) in rates were largely explained by changes in beach-profile level and by the presence or absence of protective toe structures.

Isle of Man

Erosion problems along the northern coast of the Isle of Man have been investigated by Joliffe (1980). Lengthy stretches of glacial till cliffs between Gob-ny-Creggan in the west and Gob-ny-Rona in the east are eroding, notably where the higher Bride Hills are being truncated. Classic sub-aerial/marine cliff retreat is accompanied by a variable coastal sediment budget, such that a general pattern of coastal erosion and accretion tends to be obscured by a shifting pattern of sediment distribution.

Cliff erosion, beach form and offshore conditions are considered to be closely interrelated and,as this coastline is virtually unmodified in terms of conventional protection works and is a unified dynamic coastal system within itself,Joliffe (1980) has suggested that any physical intrusion would have an adverse affect.

2.4 Model Analysis

One of the few attempts to measure both the erosive process and the rates of cliff recession so that a true quantitative model could be prepared is the series of studies by Sunamura and Horikawa (1969,1971), A model for predicting the rate of short-term bluff recession was derived from wave-tank experiments. Two major factors were considered - the attacking force of the waves at the foot of cliffs and the resisting force of the cliff material. Other important factors such as water-level fluctuations (Kolberg, 1974; Birkmeier, 1980) and the amount of beach material at the cliff base (Robinson,1977;McGreal,1979) were ignored.

On the basis of these wave-tank experiments the following relationship was established by Sunamura (1977,p613).

$$\frac{dx}{dt} \propto F,$$

where $dx/_{dt}$ = erosion rate, F = erosive force of waves which was defined as being proportional to In (fw/fr) where fw = attacking force of the waves and fr = resisting force of cliff forming material.

Due to the complexity of the phenomena involved and the difficulty of measurement, no suitable quantitative index for fw has yet been determined in actual field situations although the shock pressure due to breaking waves has been the subject of numerous investigations, notably by Mitsuyasu (1967), who has described a laboratory method using pressure gauges of very high frequency.

Similarly, although the cliff resisting force fr is principally a reflection of the mechanical strength, this in turn for rock is related to the complexities of geologic discontinuities such as jointing, faulting and stratifications and for other soils to particle size distribution, density and fabric.

Strength could be expressed in terms of compressive, tensile or shear strengths but since these indices are closely related and not independant of one another, any one could be considered representative. By relating fw and fr to wave height at the cliff base and to the compressive strength of the cliff material respectively, Sunamura (1982) reduced the previous equation to

$$\frac{dx}{dt} = k \left(c + \text{In} \frac{\rho g H}{S_c}\right)$$

where H is the wave height at the height of the cliff base, S_c is the compressive strength of the cliff-forming material, ρ is the density of water, g is the gravitational acceleration, c is a non-dimensional constant and k is a constant with units of $[lt^{-1}]$.

By applying this model to two eroding Tertiary cliffs on the Pacific Coast of Japan where data was available for erosion rates, material strength and wave climate, Sunamura (1982) showed that only the larger but rarer waves caused cliff erosion and that the erosion rate at each site was greatly affected by the frequency of occurrence of waves higher than a certain critical height.

This form of modelling is important in that it can predict in quantitative terms the time and scale of geomorphic events. It is flexible in that many sites and conditions may be modelled, the main disadvantage being that such models often require considerable time to set up, can be expensive and are subject to serious problems of scale (Kamphuis, 1975). Uncertainties also remain about the validity of results obtained from any modelling procedure for, as Pitty (1982,p59) has suggested, "artificialities do limit the applicability of any findings to natural situations".

A more efficient approach to the monitoring of coastal systems appears to be numerical modelling, which utilises the speed and flexibility of computers to assess the impact of wave activity over large sections of shoreline. Computer modelling of wave refraction began in the mid-1960's (Wilson, 1966; Dobson, 1967) and the technique has been widely used and developed by many researchers for large-scale investigations into predicting variations in wave power and consequently the variations in erosion or erosive potential, along a coastline.

The concept of littoral sediment cells existing longshore was developed by May and Tanner (1973) in their 'abc....' model and new combined refraction - morphogenetic models have been developed in the late 1970's (Noda et al, 1974, Shian and Wang, 1977, Felder and Fisher, 1978 and Dalrymple et al, 1980) which attempt to use wave information obtained from wave refraction analysis as the input to multi-dimensional models of beach and foreshore.

Whilst these later models may be much finer detailed, it is the wave refraction model of May (1974),combined with beach sediment movement, which is arguably the most successful and has been used by numerous workers - Goldsmith, (1976), to establish critical links between continental shelf hydraulics and shoreline processes; Greenwood and McGillivray (1978), in modelling the littoral drift system in the Toronto area of Lake Ontario; Davidson-Arnott and Pollard (1980) to identify potential sediment transport patterns in Nottawasage Bay, Ontario; Lowry and Carter (1982) to delimit littoral power cells on the barrier coast of southern County Wexford; and Bowden and Orford (1984) to establish residual sediment cells on the coastline of the Ards peninsula, Northern Ireland. In the latter study, results showed that a 30km section of the Ards Peninsula, County Down, was dominated by eight major cells each one associated with an ordered change from net erosion to net deposition of beach sediments. Comparison of this theoretical pattern with the actual observed erosion and deposition showed first order agreement, any discrepancies being accountable.

2.5 Geotechnical aspects of coastal erosion

The character of any coastal form is dependant on the material of which it is composed yet relatively few research projects have used material as their major point of focus. It is the practising civil engineer who has contributed most in this field, and most work has been confined to failures in non-glacial clays.

In the U.K., Ward (1962) recognised four different forms of landslip movement in cliffs formed from the weaker sedimentary strata along the east and south coasts - rock falls in chalk caused by frost action and undermining; shallow surface slides in stiff-fissured clays, boulder clays, sands and gravels; deep-seated rotational slips in clays, involving shore upheaval; and slips brought about by internal water erosion of fine sands interbedded with clays. Zenkovitch (1967) also recognised the importance of sub-aerial processes, especially landslide activity, as major processes in coastal recession of the Odessa coast of the Black Sea, where retreat rates of 1m/yr^{-1} were recorded in cliff sections of Pontic clays, shell limestones, Quaternary clays and loess.

Kazi and Knill (1969) analysed the geotechnical properties of the Cromer Till between Happisburgh and Cromer in Norfolk to explain the various processes with included tensile block failures, active mudflows and deep-seated,non-circular slips.

In the Gault clays of Folkstone Warren, Hutchinson (1969) identified two main types of failure - large multiple rotational landslides (type M) and smaller failures of a rotational character (type R) - as well as a third failure mechanism in sliding or falling of large masses of chalk.

From a study of differing rates of erosion in London Clay cliffs bordering the Thames estuary, Hutchinson (1973) examined the influence of the one major variation between the cliffs - the intensity of marine erosion at their toe. He distinguished three strongly contrasting modes of behaviour:

Type 1, where the rate of marine erosion is broadly in balance with the rate of weathering:

Type 2, where the rate of erosion is more rapid than the rate of weathering, and

Type 3, where the rate of erosion is zero.

Hutchinson (1976) also described landsliding in cliffs of Pleistocene deposits on the Norfolk coast between Cromer and Overstrand where he attempted to relate the observed mass movements in the cliffs to their geology, hydrogeology, geotechnical characteristics and exposure to marine erosion.

Hutchinson's (1973) classification scheme and associated concepts have been applied to eroding coastal slopes in other types of overconsolidated sediments. Recent geomorphological investigations in Denmark and Northern France (Prior, 1973,1977; Prior and Eve 1975; Prior and Renwick 1980) have revealed the presence of excellent examples of Type 1 coastlines. These are developed upon Eocene "plastic" clays in Denmark and on very active slopes in Jurassic clays in Normandy, France.

Increased erosion of coastal bluffs along the Great Lakes of Canada/USA has resulted in much recent research work by planners and engineers, with a need for concise geotechnical classification. Bluff erosion results from the complex interaction of nearshore hydraulic conditions and the erodibility and instability of bluff materials. Quigley and Gelinas (1976) have described the soil mechanics aspects of shoreline erosion in general terms using examples from the literature and from current studies of till bluffs along the north shore of Lake Erie. They categorised three major morphological types of slope retreat and demonstrated the validity of Hutchinson's evolutionary sequence of Type 2 cliffs. In an integrated programme of field and laboratory investigation of six active bluffs along the western shore of Lake Michigan, Edil and Vallejo (1977) concluded that the most important processes in initiating slope retreat are toe erosion by wave action and physical degradation on the slope face. These processes, in turn, trigger rotational slides, solifluction and mud flows which modify the slope geometry and eventually cause the retreat of the bluff top.

Edil and Haas (1980) determined the geotechnical properties of Lake Michigan bluff materials, which include glacial tills, and related these to the failure phenomena seen in the bluffs. Two criteria proposed by Edil and Haas (1980) - the unstable circle and the critical circle method of analyses - were utilised from Leary's (1970) computer programme analysis of some hundred bluff profiles.

In response to demands on various levels of government for some long-term solution to the problems of erosion (in the Canadian Great Lakes) there have been numerous studies of rates of shoreline recession (eg. Bird and Armstrong, 1970; Boulden, 1975; Carter and Guy, 1980; Buckler, 1981), and of the processes operating on the bluffs (eg. Quigley et al, 1977; Edil and Vallejo, 1980; Bryan and Price, 1980). Quigley and Zeman's (1980) paper reviewed the hydraulic and geotechnical controls that most affect instability and erosion rates and made recommendations with respect to shore-line mapping strategy.

Foreshore erosion by wave action has been proposed by Philpott (1984) as the controlling process in bluff erosion, rather than direct wave attack on the toe as implied by Sunamura (1983).

Kamphuis (1987) has also explained the recession of glacial till shorelines along Lake Erie in terms of wave-foreshore interaction, the controlling factor being primarily the foreshore erosion rate. He derived a theoretical expression based on many simplifying assumptions and also by analogy with earlier longshore sediment transport research, which stated that recession rate should be proportional to incident wave power to the exponent 1.4

However it would appear that along much of the Great Lakes the foreshore is geotechnically closely related to the lower layers of the bluff and is normally covered with only small amounts of sand and gravel in discontinuous thin deposits. The reaction of both foreshore and toe to wave action are therefore inevitably closely related.

It follows from this brief survey of the literature that the emphasis of research into coastal erosion has moved from the descriptive, qualitative approach into a more quantitative modelling of the erosive process.

The aspect of coastal slopes which has received most attention is the erosion of basal segments which is only one part of the interaction between processes that are responsible for cliff form and recession. Whereas the complexities of the coastal system may still defy exact description and full understanding, geomorphological research is becoming more sophisticated both in equipment used and in the analysis of the quantitative data obtained.

CHAPTER 3.

THE EVOLUTION AND EROSIONAL HISTORY OF THE SOUTH CARDIGAN BAY COASTLINE

3.1. Physical setting

The study area lies to the south of Cardigan Bay on the west coast of Wales and encompasses the 20km of coastline between the village of Llanrhystud (GR 530699) in the north and the seaside resort of New Quay (GR 390600) in the south. Fig 3.1.

In plan form the coastline shows a series of open crenulate shaped bays opening towards the west or north-west. The alignment of the coastline is essentially S.W - N.E and the influence of wind on wave and tidal activity is therefore limited as, with the exception of a 12^{o} arc opening to the Atlantic Ocean in a W.S.W. direction, all waves are generated internally in Cardigan Bay and St. George's Channel (Fig 3.2).

3.2. Structural geology

The uniform sweep of the coastline of Cardigan Bay is principally a reflection of its parallelism with the Caledonian strike of the rocks (George, 1975). The late-Palaeozoic era in Wales culminated in the Caledonian earth movements which produced the Teifi anticline running N.E - S.W across Central Wales and the coastal syncline to the west. On a local scale this massive uplift left the rocks considerably folded and shattered with implications for their resistance to erosion and weathering.

Most of the area is dominated by cliffs of the Aberystwyth Grits of upper Llandoverian age which provide spectacular rock-exposures along the coast. The grits form a crescent-shaped outcrop extending for some 40km from north of Aberystywth to 6km south of New Quay (Fig 3.3). The maximum outcrop width is about 12km. They have been described by Wood and Smith (1958) as a typical turbidite series with a characteristic lithology of rapidly alternating bands of hard, fine-grained sandstones or siltstones (greywackes) and softer, rudely cleaved mudstones.

Ramsay (1846) was interested in the general seaward inclination of the land surface above the line of cliffs, stating that this great

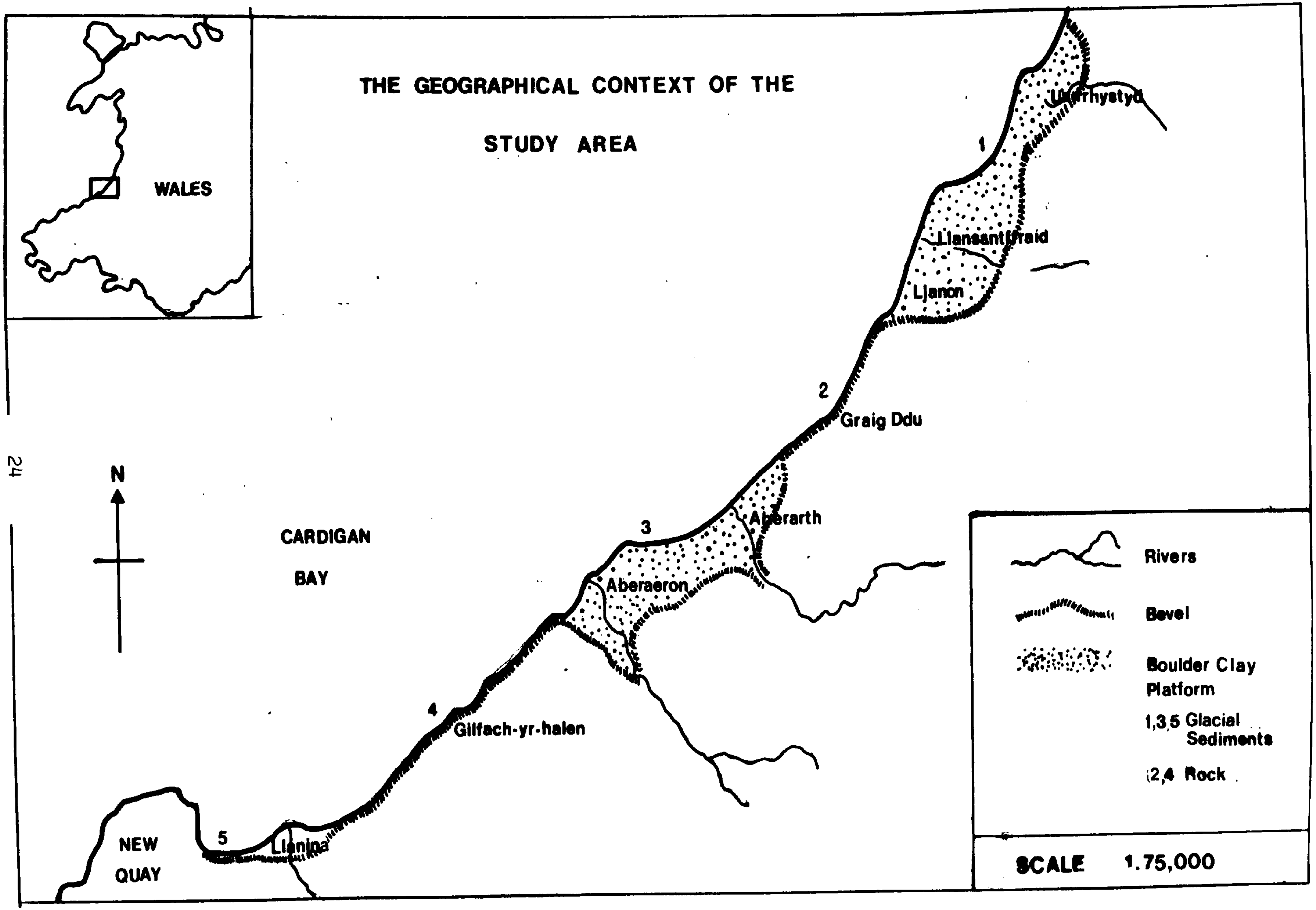

THE GEOGRAPHICAL CONTEXT OF THE
STUDY AREA
WALES
N
CARDIGAN
BAY
Llanrhystyd
1
Llansantffraid
Llanon
2
Graig Ddu
Aberarth
3
Aberaeron
4
Gilfach-yr-halen
5
Llanina
NEW
QUAY
Rivers
Bevel
Boulder Clay
Platform
1,3,5 Glacial
Sediments
2,4 Rock
SCALE 1.75,000

FIG. 3.1.

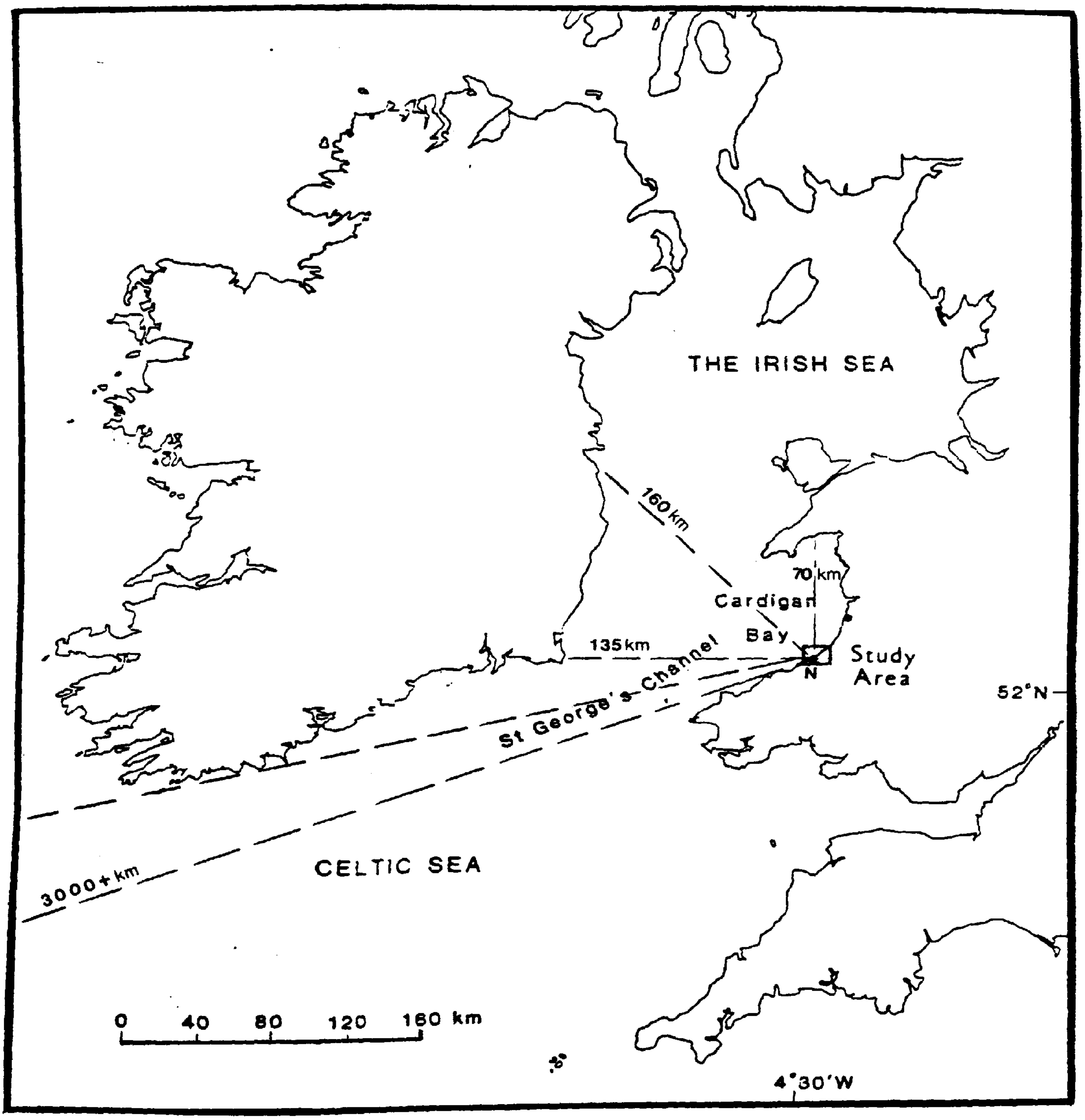


FIG 3.2. Location of study area within Cardigan Bay showing fetch rose

plain was "bounded by distant inland hills, easily comparable to many an existing line of lofty coast". Keeping (1881) extended Ramsay's observations, recognising the existence of two denudation surfaces in Cardiganshire, a concept elaborated by Jones (1911) who named them the High Plateau and the Coastal Plateau.

Wood (1959) has described this coastal platform, which is 122 - 183m above sea level and rises gently inland, as being the remains of cliffs cut by marine erosion and degraded by sub-aerial weathering at several times in the past.

3.3 Quaternary geology

Williams (1927) was the first to give a concerted description of the drift deposits of the coastal region of Cardiganshire although Keeping (1882) made some observations on the glaciation of Central Wales in general while Jehu (1904) made reference to the drifts of Western Cardiganshire. In his paper, Williams (1927) attempted to show the relationships which existed, during the glacial period, between the local Welsh Ice and Irish Sea ice-sheet.

The limit of upper Devensian glaciation in Wales had been established by Charlesworth (1929), (Fig 3.4),who described his limit as 'conjectural' (p 344) due to the weakness of the field evidence. Wirtz (1953) accepted the evidence for local ice in northwest Wales and drew an eastern limit to the Irish Sea Ice running from near Criccieth in Lleyn across Cardigan Bay to near Cardigan (Fig 3.4). Subsequently Mitchell (1960) and Synge (1964, 1970) put the southern limit of the Irish Sea ice in the east glaciation on the north coast of the Lleyn Peninsula, assigning all drifts in Cardigan Bay to older glaciations. More recently Mitchell (1972) revised his opinion accepting the Wirtz interpretation.

John (1970), partly on the basis of radiocarbon dating, proposed that ice covered all of the area shown on Fig 3.4. Bowen (1973a), however, has moved Charlesworth's limit southward (Fig 3.4 again) to take cognizance of later re-mapping work.

An investigation conducted between 1970 and 1974 by the Institute of Geological Sciences together with the Department of Geography, University College of Wales, Aberystwyth, established the succession

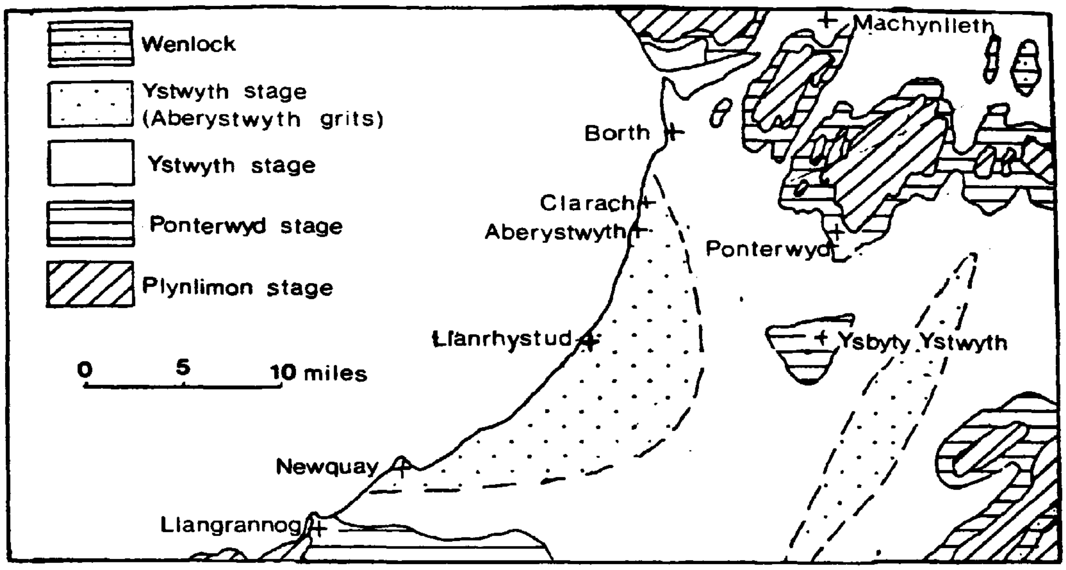


FIG. 3.3. Geological map of north Cardiganshire (principally after O. T. Jones)

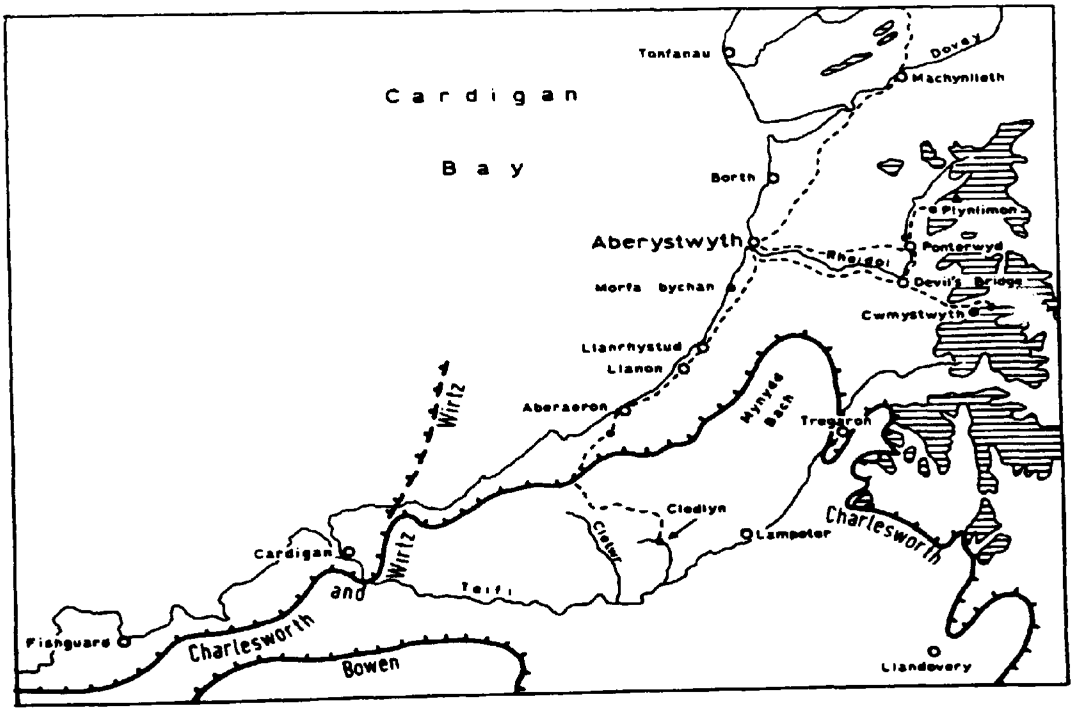


FIG. 3.4. The west coast of mid Wales showing proposed ice limits for the last glaciation (after Watson, 1977).

of Quaternary sediments to the South Irish Sea.

The sequence of events has been described by Garrard (1977). In the Devensian the South Irish Sea became glaciated by a large continental ice sheet flowing southwards from Scotland towards the southern entrance to St. Georges Channel. Local ice was restricted to the peripheral area only (Fig. 3.5). Ice movement southwards was restricted by physical features such as the Lleyn Peninsula and West Pembrokeshire. Welsh Ice, in the form of local piedmont glaciers, fanned out from the mountains of north and central Wales onto the old sea floor of Cardigan Bay before the arrival of Irish Sea - a fact borne out by the stratigraphic position of their assorted sediments.

On land, the junction between Welsh and Irish Sea glacial drifts appears to be near Llanina, between New Quay and Cei Bach bays. The coastal area to the south west was once covered by Irish sea ice while the local Welsh drifts to the north have been the subject of much contention as to their origin.

At Morfa Bychan, north of Llanrhystud, three units of head occur at the base of an unusually high and steep coastal slope. The middle unit, a clay-rich deposit containing striated stones, has been considered by Watson and Watson (1967) to be almost exclusively periglacial of Wolstonian (Riss) age. Wood's (1959) interpretation, that it was boulder clay redistributed by solifluction at the close of the last glacial period, has been held more likely by Bowen (1973a, p218) in view of the "steep coastal slope which would have readily promoted slipping of unconsolidated glacial drift".

Similar deposits at the base of the steep coastal slope at Aberarth, believed to be head by Watson and Watson (1967) have been interpreted as glacial by Mitchell (1972) as they had previously by Williams (1927).

3.4 Geomorphology

As the physical characteristics of the cliff material exposed along the coast forms an integral part of the present study, it is considered necessary to describe in some detail the morphology of the coastline and the distribution of the various cliff facies. For this

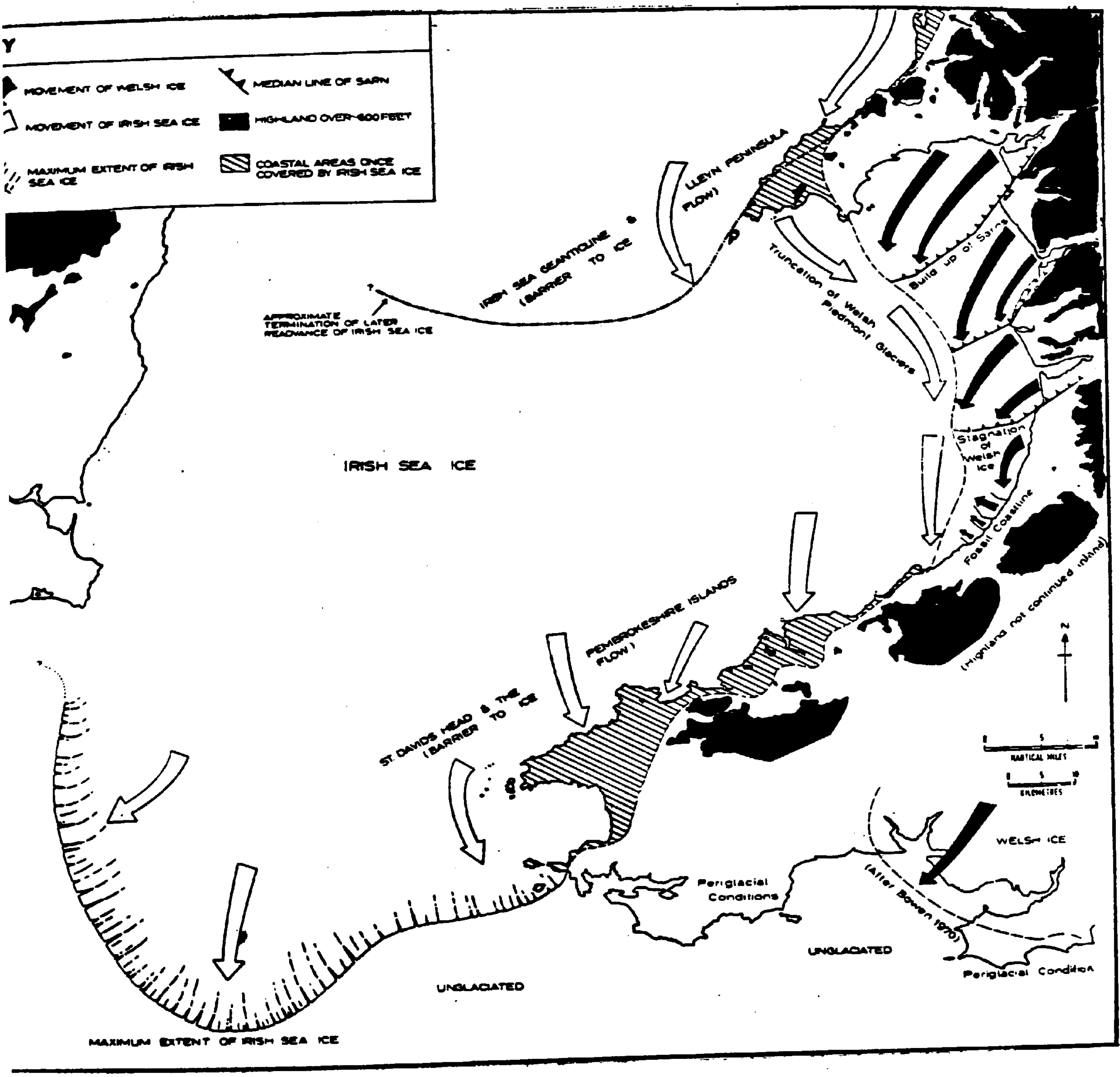


FIG. 3.5 *West Wales and the South Irish Sea during times of maximum Devensian Glaciation. (after Garrard, 1977)*

purpose the coastal region can be conveniently divided into five sections indicated in Fig 3.1.

Along approximately 2km of the shoreline, erosion is conterbalanced by coastal protection structures in the form of sea walls, riprap barriers and revetment works together with some beach restoration and nourishment. The remainder of the section is about one-third hard-rock cliff and two-thirds embayed or backed by a coastal platform.

Generally the hard-rock cliffs are from 15 to 25m high but within the two low-lying embayments cut into the Coastal Plateau at Llanon and Aberarth exposed faces of glacial sediments are no more than 3 to 4m maximum in height. It is arguable therefore whether the latter can be classified as cliffs in the true sense of the word.

The Oxford English Dictionary defines a cliff as "a perpendicular or steep face of rock of considerable height......" or, in modern use, ".... a perpendicular face of rock on the sea shore". What is perhaps confusing is the range of scale of true coastal cliffs. Pethick (1984) has contrasted the 600m black lava cliffs of Tenerife with the 0.5m high cliffs cut into salt marshes in Western France, but, since both are vertical, or near vertical, faces cut by marine erosion, he has considered that a sea cliff should be regarded as a relative landform which can be defined as a marked break in slope between hinterland and shore.

3.4.1 Llanrhystud - Morfa Mawr

To the south-west of Llanrhystud, the coastal platform gives way to the first of two low-lying boulder clay platforms. The villages of Llanon and Llanrhystud are situated on this platform which is generally below the 30m (100ft) contour, some 6km long and rather more than 800m wide.

The coastal bevel described by Wood (1959) is prominent (Plate 3.1), its lower margin lying at some 15m O.D while below it the surface of the boulder clay platform declines seawards to below high water mark. Near Llanrhystud a storm beach seperates the agricultural land from the sea, extending south from the mouth of the River Wyre for some 2km (Plate 3.2).

PLATE 3.1 Llanrhystud north beach
Profile 1 is at concrete ramp in foreground

PLATE 3.2 Llanrhystud storm ridge (Jan 1984)
showing overwash

To the south of the storm ridge low-lying cliffs of clast-dominated till material form the first of several minor headlands which is probably the result of an old fan structure laid down by the river Peris. These till deposits are continuously exposed in low coastal cliffs (3-4m in height) for the next 3km.

Watson (1968) has attributed a periglacial origin for these embayment sediments, being the result of the solifluction of head slope material during the Weichsel. For some 600m to the north and 400m to the south of the river Clydan the cliff face is 3.5 to 4.5m high and shows typical periglacial structures of well-developed involutions and vertical stones. Coarse fluvial gravels have been deposited around the mouths of the two rivers, becoming thinner and finer to the north and south, the greatest thickness being just north of the Peris (Plate 3.3).

3.4.2. Morfa - Aberarth

High cliffs of solid rock separate the Llanrhystud platform from the Aberaeron platform. The coastal bevel described by Wood (1959) and sloping at some 32°, is transected by nearly vertical sea cliffs of the Aberystwyth Grits (Plate 3.4).

The cliffs have a seaward slope of 77 - 88° and rise to a height of some 25m O.D. at the base of the coastal bevel. The strike of the beds is nearly parallel to the coast and they dip at 27° inland.

North of Aberaeron the cliff base is occupied by steep banks of boulder clay. Two different deposits are discernible in this section. Williams (1927) defined a buff-coloured lower boulder clay overlain by drift very similar to that which constitutes the greater part of the Llanrhystud platform. Fine earth pillars have been formed by surface water running down the rock/clay interface and dissecting the boulder clay lying on it (Plate 3.5).

3.4.3. Aberarth - Aberaeron

The 3km of coast between Aberarth and Aberaeron is formed by another conspicuous remnant of the drift platform. The average width of the platform is about 400m and slopes gently towards the sea from

PLATE 3.3 5m high vertical cliffs of till at the mouth of the river Peris

PLATE 3.4 Coastal bevel and cliffs of the Aberystwyth Grits near Morfa

its inland boundary, which coincides approximately with the 100ft (30m) contour line.

The best exposures of the drift are seen in cliff sections immediately south of the groynes and recent revetment works at the mouth of the river Arth (Plate 3.6). Here the deposits, which are clast-dominated attain a thickness of 5m above present beach level. However, elsewhere along this section the cliffs are never this high and in places around the Aberaeron headland the low cliffs are completely obscured and overriden by shingle and artifical fill. (Plate 3.7).

3.4.4. Aberaeron - Cei Bach

South of Aberaeron the coastal bevel swings seaward at Pen-y-Gloyn headland (Plate 3.8) before, some 400m to the south-west, the solid rock goes behind boulder clay slopes which continue as far as Cwm Cilfforch.

The most important exposures of glacial material within this section occur at the mouth of the Afon Cwinten at Gilfach-yr-Halen where this latter stream has carved a channel through the glacial deposits, nearly 30m deep (Plate 3.9).

There is a further small pocket of boulder clay in the cliffs on the south side of the mouth of the Afon Drowy but otherwise this section shows the high castellated cliffs and slopes typical of the Ceredigion coast as a whole.

3.4.5. Cei Bach - New Quay

The solid rock cliffs capped by the coastal bevel curves around behind the boulder clay of Cei Bach and New Quay bays to form the slope behind New Quay itself. The boulder clay forms a fairly high, irregular platform, in some places over 400m wide, and is exposed at the base of the cliffs along practically the whole length of the two bays (Plate 3.10).

In Cei Bach bay the low cliff sections are very much overgrown and disturbed by old landslides (Plate 3.11). The clay is generally homogenous and unstratified, buff-coloured, often distinctly mottled with large irregular blotches.

PLATE 3.5 Aerial view of glacial deposits north of Aberarth showing extensive gullying

PLATE 3.6 Glacial deposits south of Aberarth

PLATE 3.7 Coastal protection works at Aberaeron north beach

PLATE 3.8 Aberaeron south beach and Pen-y-Gloyn headland

PLATE 3.9 Glacial cliffs at Gilfach-yr-halen

PLATE 3.10 Boulder clay cliffs at the eastern end of New Quay Bay

PLATE 3.11 Low cliff sections and groyne system at Cei Bach

The clay at the western end of New Quay bay is a coherent deposit of boulders, often striated, in a bluish grey clay matrix and is exposed in cliff sections some 25m high (Plate 3.12). Near the lifeboat station at New Quay this boulder clay overlaps and comes to rest on a shattered surface of the local rock.

3.5 Offshore morphology

Perspective views of the bathymetry of the area are shown in Figs 3.6 and 3.7. Of note is the deep water 'trawling ground' which runs the whole length of this stretch of coast at a depth of greater than 10 fathoms. According to Jones (1971) the shoreward slope sediment of the trawling ground is composed of poorly sorted coarse gravel which suggests it acts as a sediment trap for fine sand and coarse silt.

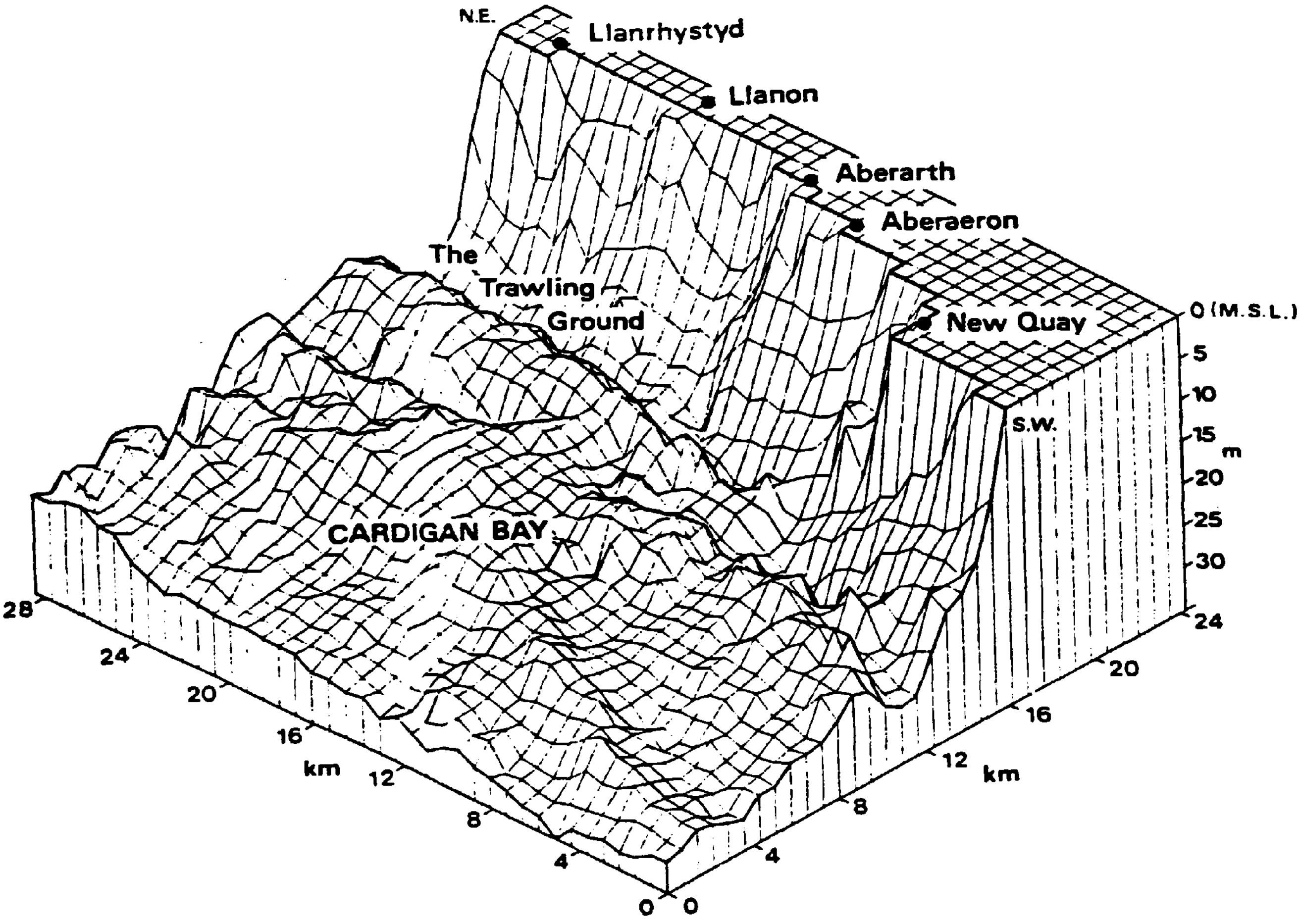
The 6,3 and 1 fathom lines all follow the trend of the coast interrupted by headlands such as Pen-y-Gloyn and features such as Cadwgan reef, which is a morphological continuation of the Llansantffraid fan axial line extending some 2 to 3km offshore.

The offshore area largely consists of loose stones which are moved around by wave action to give a continuous change in the morphological features. Renowned in Cardigan Bay, and complicating the submarine topography, are the 'Sarns' which extend roughly normal from the shore as ridges of boulders, cobbles and pebbles. They are considered to be the most prominent morphological features to remain from the Devensian episode of glaciation, and represent the maximum lateral extent of the local Welsh glaciers. Subsequently western extensions of the sarns became truncated by the Irish Sea Ice, which incorporated and removed Welsh morainic material along its contact.

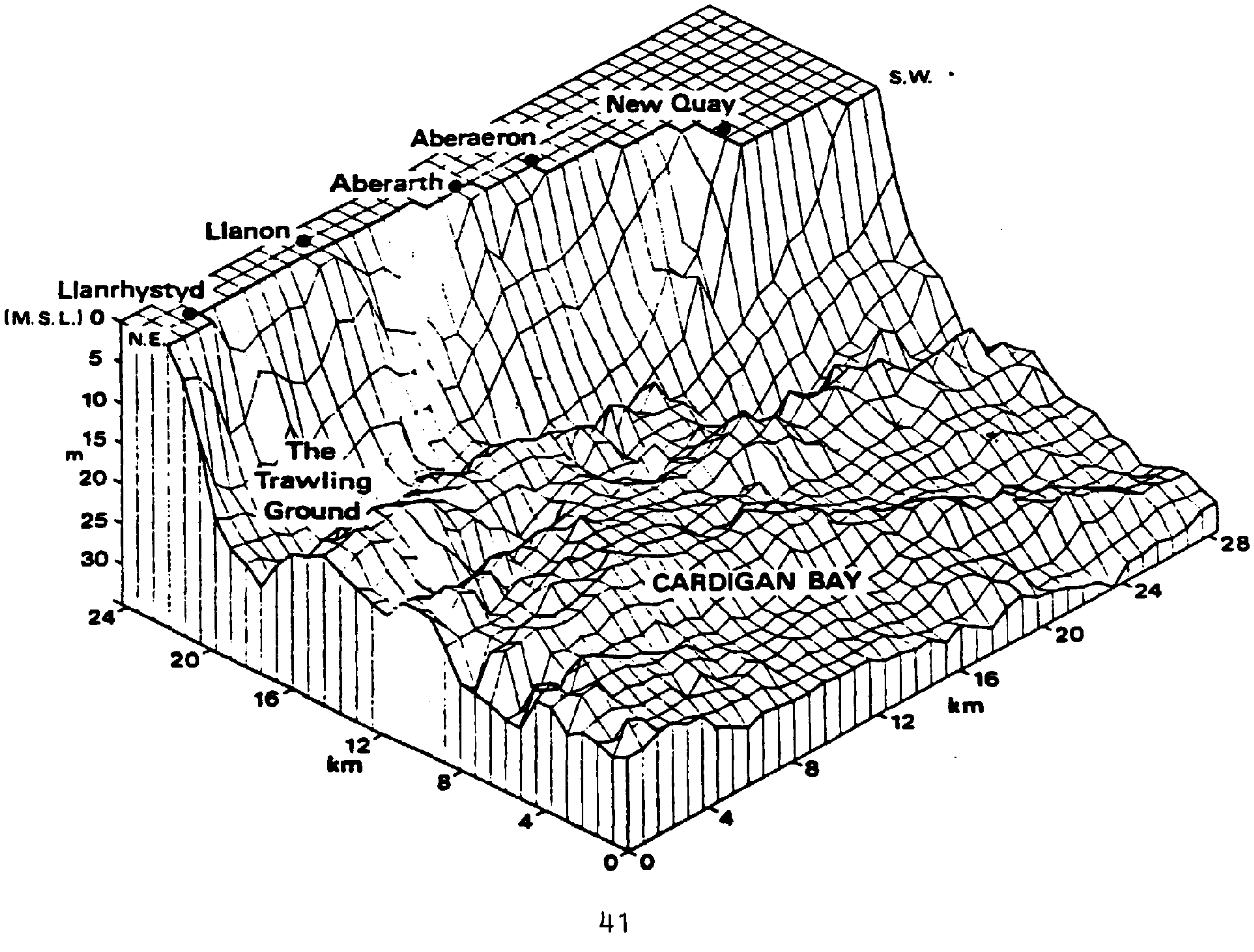
The ones within the study area are the smallest of the five sarns in Cardigan Bay, Sarn Dewi off Aberarth is only about 400m long while Sarn Cadwgan, a mile further south is about 1.5km long.

The nature of the heavily clasted till material which has given rise to the extensive area of loose stones offshore has also produced the beach material. Beaches front virtually all the sections of glacial till. They are generally wide (>30m) and, apart from the sand beaches of New Quay and Cei Bach, consist primarily of shingle although there are

PLATE 3.12 Exposed boulder clay cliffs at New Quay



Figures 3.6 & 3.7: Perspective views of the bathymetry between Llanrhystyd and New Quay, Dyfed.



pocket beaches of sand in the larger embayments at Llanrhystud and Llanon.

3.6 Erosional history of the south Cardigan Bay coastline

3.6.1. Extent of post-glacial marine erosion

Wood (1959) has suggested that the post-glacial rise of sea level continuously renewed marine attack on the boulder clay spreads of the Cardigan Bay area and,by a combination of successive erosion and drowning of the margins, the sea advanced inland probably several kilometres. Haynes et al (1977) have shown that sea level was some 22m below O.D. about 8700 years ago.

Although there seems to have been only a minimal relative submergence between land and sea along western coasts during the past 6,000 years, there has been oscillation above and below its present level (Fairbridge, 1961).

Tooley (1979) indicated the importance of secular changes of sea-level surface in the coastal erosion of low-lying cliffs formed of unconsolidated sediments. The important aspect of this changing sea level, with reference to the Cardigan Bay coastline, has been the exposure of successive areas of the boulder clay cliffs to wave action in and near to the breaker zone.

In areas of stiff boulder clay, if the present slopes are projected seawards, the amount of erosion since the sea attained its present level is several hundred metres. In other areas no erosion has occurred at all, as at Trenewydd Fach and near Llanrhystud, where the drift surface falls below present high-water mark.

3.6.2. Coastal erosion during historic times

Records of early coast erosion are fragmentary. Evidence for the loss of some coastland has been suggested by Ptolemy's map of the second century. The existence of a former extension of land in Cardigan Bay has been popularised by the legend of Cantre'r Gwaelod, the traditional account being that the present-day Cardigan Bay as far as Sarn Cynfelin once constituted an extensive low-lying plain known as Cantre'r Gwaelod which was overwhelmed by the tide with the help of favourable gales through the negligence of a drunken gate-keeper who did not close the floodgates of the embankment.

The first record of the inundation of this land seems to be in the Black Book of Carmarthen which belongs to the early twelfth century,while Meyrick's (1810) History of Cardiganshire gives A.D 520 as the fatal year.

Much of the recession of the coast in the more recent period has been initiated by storms. So (1972) has listed twelve damaging ones in the period from 1744 to 1964 and has suggested that the record of thirteen storms leaving imprints on the coast in the first 65 years of the 20th century gives a probable future frequency of one storm event every five years.

3.7 Coastal changes during the last century

One means of understanding present-day erosion is to examine in detail, when, where and why erosional events have occurred in the past.

Although one of the aims of this study is to quantify the erosion process through a field investigation, this data from the study period must be related temporally to avoid the possibility of the data being anomalous. Thus the field investigation was supplemented and placed in proper prospective by an historical analysis.

3.7.1 Choice of historical technique

Of the current methods of historical analysis of shore lines, aerial photography is the most widely used. However, the Cardigan Bay coastline has not been well covered in terms of aerial surveys and certainly not in time span.

There was no systematic archive of information available and what photographs there were were almost always oblique views of poor definition requiring extensive correction. Scale was usually difficult to estimate, making accuracy poor.

Perhaps the most basic technique for continuous analysis is by comparison of maps or hydrographic charts which show the position of the shoreline. Where available, modern maps are as accurate as field surveys, although the shoreline is not always defined in a systematic way and errors may occur which could be of the order of metres.

William Morris's classical maps of the British coastline include one for Aberaeron - New Quay area dated 1800. Apart from illustrating the headland-bay configuration it is of little value due to its small scale (2" = 1 mile) and obvious inaccuracy of survey.

The first Ordnance Survey maps of the Cardiganshire area were produced between 1809 and 1836,again on the scale of 2" = 1 mile and lacking sufficient detail, since which time they have produced four editions of 1:10,560 scale maps, starting in 1890. Parish tithe maps compiled around 1841 gave an useful insight into the loss of agricultural land for this earlier period, particularly in the Llansantffraid - Llanon area.

The maps selected for the measurement of long-term retreat rates and the ones that form the basis of this study, were the three editions of the large-scale 1:2500 Ordnance Survey maps of the area dated 1880, 1905 and 1974.

Previous research workers, particularly Langfelder et al (1968), have shown that the mean high-water mark (MHWM) of ordinary tides is generally a more adequate and accurate measure of erosional trends than the coastline as such, and it has therefore been used as the indicator of the land sea interface.

Although changes over time of the mean low-water mark (MLWM) would appear of secondary importance and no direct relation between the high and low water marks has been established,it is certain that any change in the high-water mark over time influences that of the low water mark.

From overlays compiled from the three editions of the Ordnance Survey maps precise measurements of both the MHWM and MLWM were made every 200m along the coast (Fig 3.8). The data for the MHWM and MWLM were plotted graphically as total change from 1880 to 1970 (Fig 3.9 and 3.10 respectively).

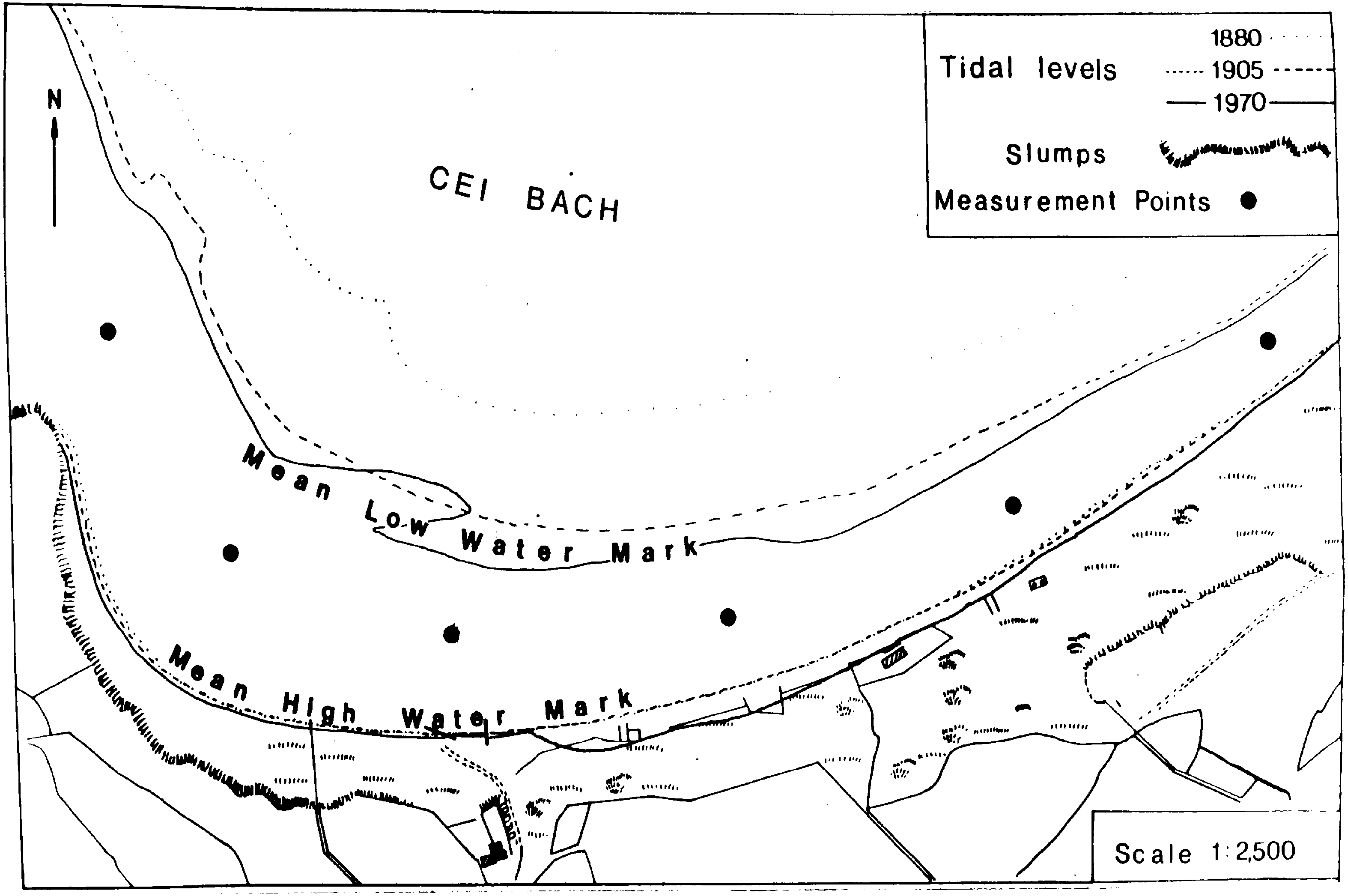


FIG. 3.6. Measurement of changes in MHWM and MHLM from large scale O.S maps

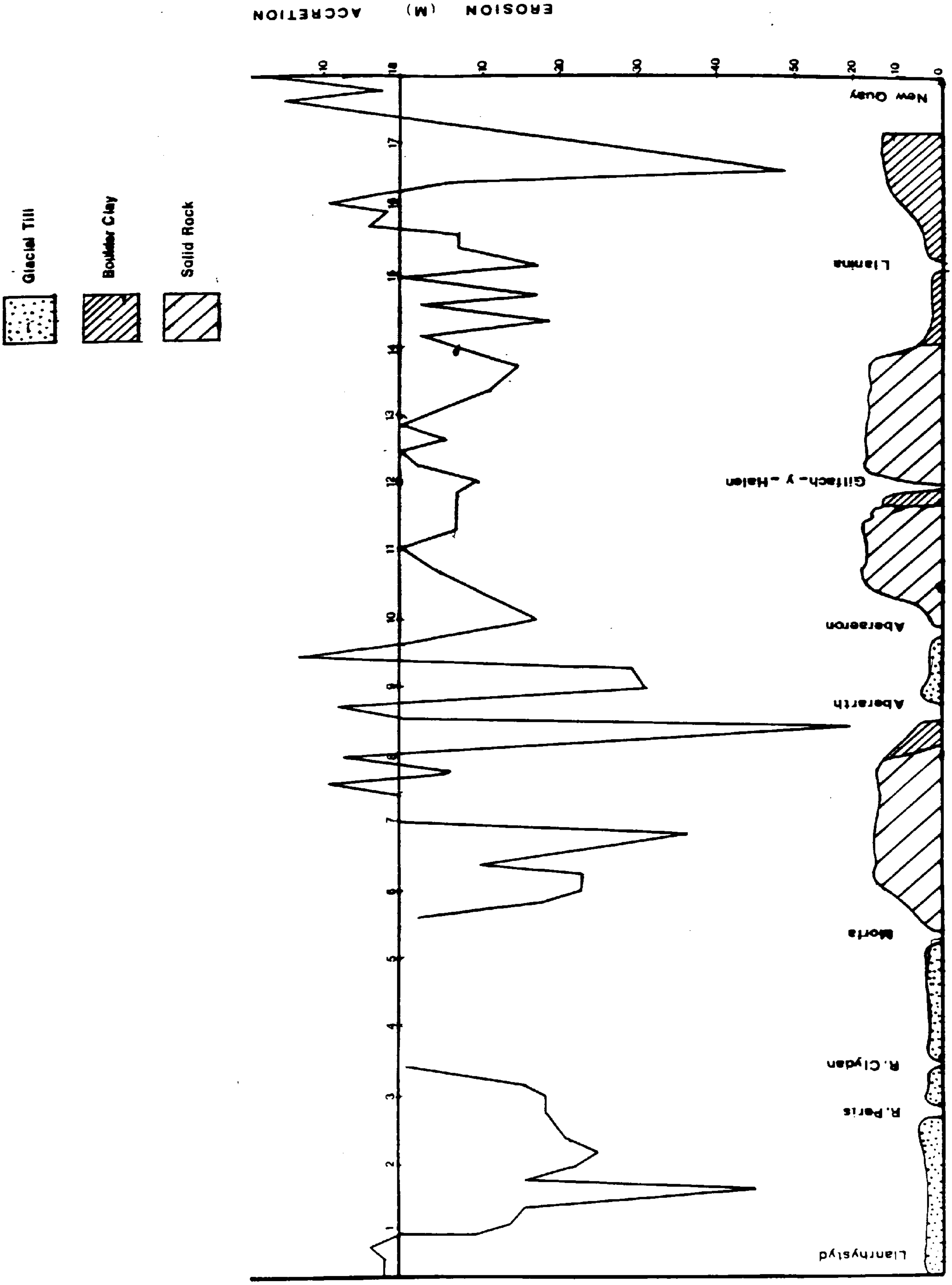


FIG. 3.9 TOTAL CHANGE OF M.H.W.M. 1880 - 1970

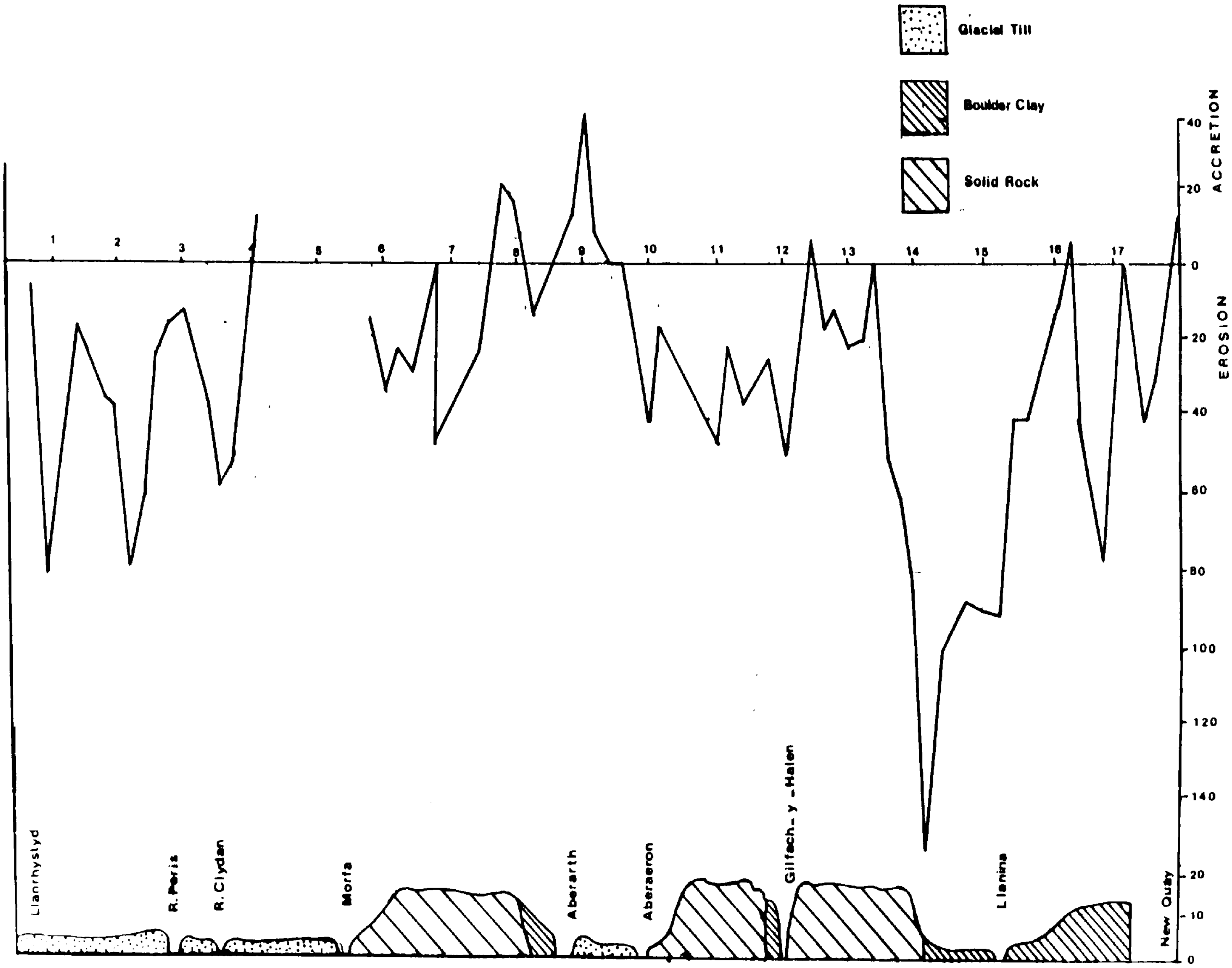


FIG. 3.10 TOTAL CHANGE OF M.L.W.M. 1880 - 1970

3.7.2 Total change of the MHWM 1880 - 1970

Fig 3.9 shows that the coastal section as a whole has experienced change with almost every 200m measuring point showing either loss or accretion. Within the general pattern, some areas show dramatic rates of recession.

Some 300m east of the lifeboat station at New Quay the boulder clay slopes have experienced retreat of some 48m over this period. This must be partly attributed to the circulation around the headland of New Quay itself and partly to the sub-aerial erosion of the in-situ cliff material. The clay appears to weather rapidly in shallow slides which carry the weathered material down the slope to accumulate at the toe. This shallow sliding of the surface layers is exacerbated by run-off water from above although remedial works carried out recently (1984) by the local authority, in the form of cut-off drains and gabions, have alleviated this aspect of the problem.

Significantly, the area immediately to the north of the boulder clay cliffs show slight accretion for some 800m possibly as a result of longshore drift taking the eroded material northwards. Llanina headland shows some erosion while Cei Bach to the north shows sporadic recession of up to 20m maximum. Circulatory tide movements within the bay, together with the presence of numerous groynes and break-waters, tend to confuse the overall picture.

At the northern end of Cei Bach bay the fossil cliff line, described by Wood (1959) and which curves round behind the boulder clay, runs into the high cliffs of the Aberystwyth Grits which continue for some 3.5km to Aberaeron. Although some points along this section show little or no erosion since 1880, the mean erosion rate of 0.06m per annum would appear unexpectedly high, although the indentations in the coastline where the rivers Drywi, Gwinten and Ffos-y-ffin run into the sea may be partly responsible for this average.

As the coastal rock bevel curves inland just south of Aberaeron the south beach at Aberaeron shows a recession of some 18m in the low-lying drift platform. The susceptibility of this till material to erosion is further illustrated between Aberaeron and Aberarth where peaks of 31 and 60m have occurred but where coastal protection works at Aberaeron may have had their influence.

Immediately north of the mouth of the river at Aberarth retreat of 0.65 m/y is recorded for the steep boulder clay cliffs where the material is banked up against the solid rock. Again there are revetment works at the mouth of the River Arth but erosion here is assisted by surface water running down the solid rock slope, dissecting the boulder clay lying on it and forming fine earth pillars.

Further to the north, where the rock surface emerges from below boulder clay, recent erosion has cut into it and a narrow rock platform is visible. Figures for this section indicate a mean recession rate of some 16cm per annum.

At Graig Ddu the coastal level again swings inland and encloses the second low-lying embayment of glacial till. No information is available for the coastal changes between Graig Ddu and the river Clydan at Llanon as no First Edition Ordnance Survey map was ever published for this section. From the river Clydan some 2.5km of cliffs of glacial drift extend around the villages of Llanon and Llansantffraid to Llanrhystud beach. This area shows an average erosion of some 16cms per annum for the study period whilst Llanrhystud storm beach to the north is experiencing accretion.

From the foregoing, it is apparent that considerable erosion has taken place along this stretch of coastline within the last century. Erosion has been particularly high in the two low-lying embayments formed of till and also those areas where boulder clay is deposited on and against the solid rock.

The erratic pattern of erosion exemplifies what has happened in other coastal areas where human intervention has affected the natural process, that is, where coastal protection works in the form of harbour walls, breakwaters and groynes exist in areas of longshore drift. Within the Cardigan Bay area peaks of erosion often occur on the lee or northerly side of these structures.

3.7.3. Total changes in MLWM

The distribution and size of beaches has clearly changed somewhat between 1880 and 1970. Associated with this change has been a decrease in beach width, as evidenced by the decrease in the length of shore fronted by wide (>15m) beaches.

The pattern of change for the MLWM has been more extreme than that for the MHWM (Fig 3.10). The MLWM has advanced inland at a greater rate, generally resulting in a steepening of the foreshore.

Areas of greatest change are to be found in New Quay and Cei Bach bays which have changed substantially in the near shore area, resulting in the advance of the MLWM in the latter of some 135m. It is conjecture as to whether this change can be attributed to coastal protection structures at the southern end of each of the two bays, or whether such embayments go through material phases of change which influence their stability, particularly if the natural system is interfered with. Tidal circulation within the two bays could also have a contributory effect.

North of Cei Bach the cliffed section shows fluctuations in the annual rate of change of the MLWM with river mouths in particular showing increased amounts of recession. There appears to be a deficit of sediment in this area resulting in either a complete lack of beach material or a steepening or constricting of existing beaches.

For nearly 1km north of the river mouth and harbour at Aberaeron the low-lying headland shows a seaward migration of the MLWM. This is related to an accumulation of sediment as a result of the shore protection works in the form of breakwaters and groynes trapping the longshore movement of material. Further north of this area there is a small advance of the MLWM. This sequence is repeated at Aberarth; the retreat of the MLWM is related to the backing up of sediment as a result of groynes fronting the village. Immediately north of the mouth of the river Arth, an advance of the MLWM by some 0.5m per year is indicated.

The coastal stretch between Graig Ddu and Morfa Mawr is again without useful data due to the lack of the 1st edition 1:2,500 O.S map. The remainder of the section shows spatial variation in the changes with peaks of MLWM advance followed by little or no advance. Peaks of advance at Llanon and Llanrhystud correlate with sections of groynes immediately to the south.

The interruption of the longshore transport of sediment by the presence of coastal protection works along the coast is clearly a major control on the position of the low-and high-water marks and has implications for potential back-beach erosion.

3.7.4. Changes in offshore morphology

Fig 3.11 shows the simplified offshore morphology for the period 1880 - 1970, re-drawn from the relevant Admiralty Charts for the area published in 1881, 1938 and 1969.

The deep-water area known as the 'trawling ground' has extended landwards in width during this period as have the 6,3 and 1 fathom lines. This shoreward migration of the depth contour lines has resulted in a gradual steepening of the nearshore area. For instance, a 1 fathom line, only present in 1881 around the headlands of Llansantffraid and Llanrhystud, has by 1938 appeared virtually all along the coast. Considerable change has occurred around Aberaeron where the 1 fathom line has emerged parallel with the shore.

This narrowing of the shallow offshore area and the increased steepening of the foreshore has, according to Stokes' wave theory, the effect of rendering deep water waves more effective for coastal erosion. In reality, it may not be possible to correlate localised areas of erosion with the steepening of the offshore area over time.

3.8. Direct measurement of rates of contemporary cliff erosion

The irregularity of the graphs in Figs 3.9 and 3.10 illustrates the influence of many interacting factors on coastal erosion and the complexity of analysing these factors.

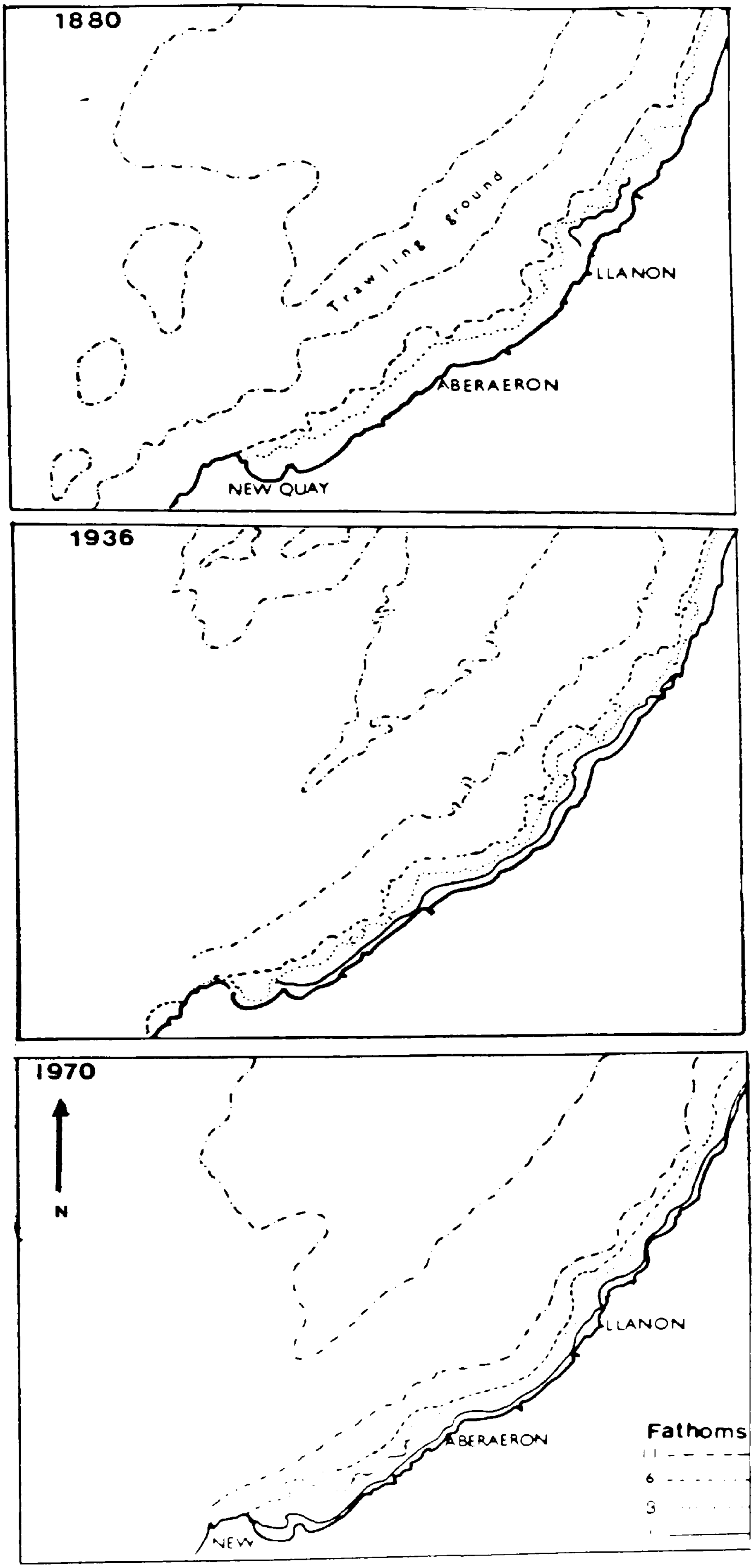


FIG. 3.11

Changes in offshore morphology (1880- 1970)

Each point on the graph represents a positive or negative erosion figure for a particular site and does so for reasons which are specific to that site.

Differences for two points of seemingly the same cliff material in adjacent areas of the coastline may be due to any number of extraneous factors. However, the explanation of such variation must include examination of both variation in longshore coastal processes (delimitation of longterm residual sediment cells and identification of high and low beaches - Welsh Office report No. 2 Feb 1984) as well as in the examination of cliff material facies and associated geotechnical variation.

This study's field survey was instigated to measure the spatial variation in erosion, on a meso-scale (>0.3km), found along the thicker glaciogenic coastal units within the two embayments. Four survey sites were selected for the field investigation - two in heavily clasted material either side of the river Clydan at Llanon, a third in similar material immediately south of Aberarth and a fourth, for comparison purposes, on very shallow banks of glacial till at Morfa Farm headland. The position of these sites along the coast is shown in Figs 3.12a and 3.12b.

It is very difficult to analyse local or small-scale changes to any degree of accuracy without much more detailed information. This information was obtained through a short-term (125 week maximum period) survey of these specific sites by direct measurement from fixed reference points.

Suitable datum points included pegs driven into the ground or, where available, prominent natural features such as walls and fences. The use of pegs, outlined by Brunsden (1974), is a very simple technique requiring little explanation. Measurements were taken approximately every 3 months and, where practicable, immediately after a succession of storm events. A summary of contemporary recession rates is given in Table 3.1.

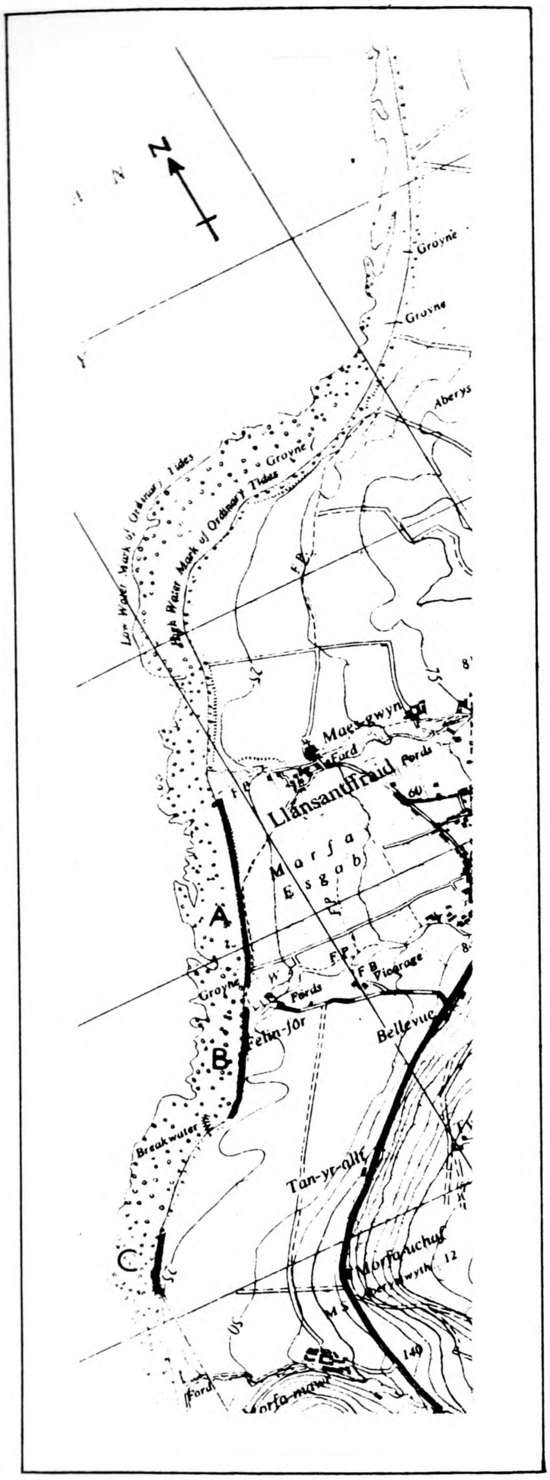


FIG. 3. 12a

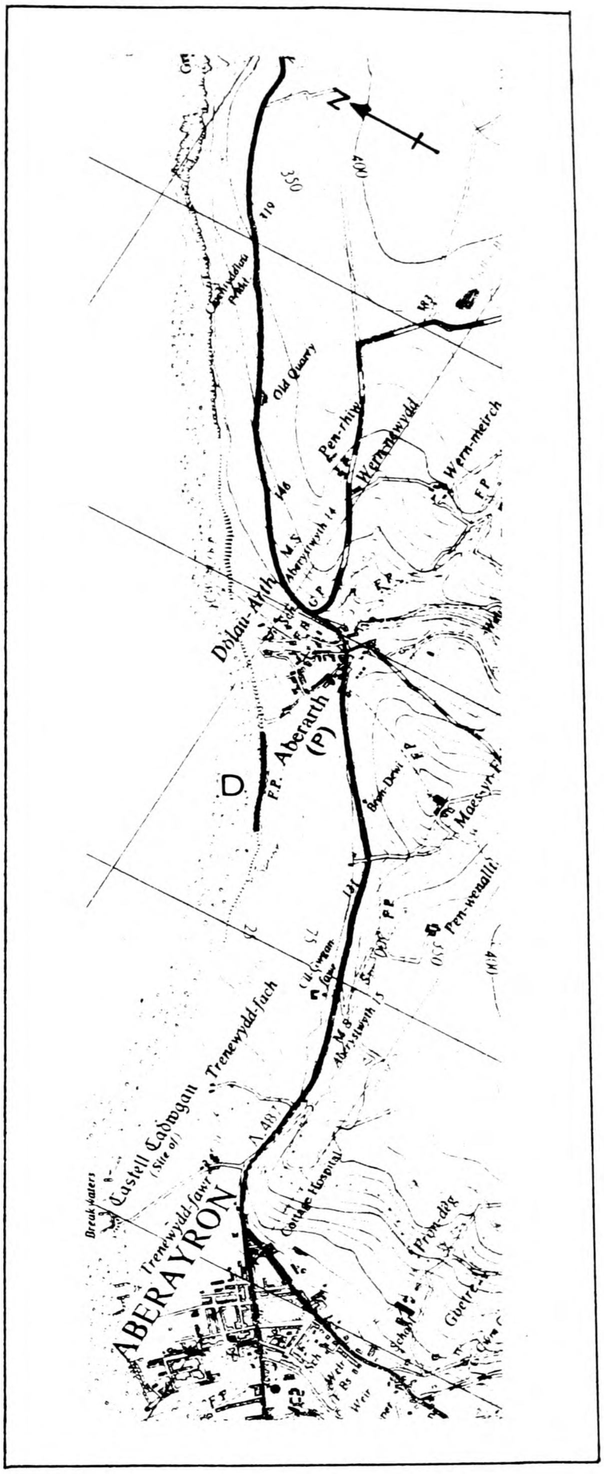


FIG. 3. 12b

1: 25,000 scale maps showing positions of pegline sites A - D

SITE	LOCATION	APPROX LENGTH OF COASTLINE	NO OF MEASURING POINTS	PERIOD	MAXIMUM INDIVIDUAL RECESSION	AS % OF WHOLE	TIMING	MEAN ANNUAL RECESSION (CMS)
A	Llan/st/ff - Llanon	700m	99	Jan'83-Aug'85	146 cms	4.7	Winter 84/85	12.4
B	Llanon (S)	400m	61	Jan'83-Aug'85	107	2.8	Winter 84/85	25.1
C	Morfa	120m	20	Jun'84-Aug'85	52	24.8	Winter 84/85	7.5
D	Aberarth (S)	330m	55	Jan'83-Aug'85	79	8.4	Winter 84/85	6.8
D	Aberarth (S)	120m	19	Jan'83-Sept'84	78	14.6	Winter 83/84	16.8

TABLE 3.1 Summary of contemporary recession rates in glacial sediments

Site A covers the section of coastline between the rivers Peris and Clydan which consists of uniform cliffs of clast-dominated till some 3 to 4 metres high. Erosion is particularly severe at the southern end near the permanent caravan site where a retreat of 1.46m was recorded at one point for the winter months of 1984/5. The problem here is borne out by the local landowner who can recall two separate incidents during the last decade where 2m sections of land were lost as a result of single January storm events. Mean annual recession rate for this section of 12.4cms compares with a rate of 16.3cms per annum for the 90 year period.

South of the river Clydan, Site B, on almost identical cliffs, recorded a mean figure of 25.1cms per annum for the 30 month period. The consistent degree of erosion along this 400m length is indicated by the maximum recorded figure of 107cms representing only 2.8% of the total erosion.

Site C at Morfa Farm represents the only headland chosen in the study. It appears that little erosion has been taking place as the platform slopes down to almost beach level giving only a shallow 1.2m face of till. The mean value of 7.5cms represented 28.4% of the total erosion for the 15 month period.

Site D is the only site representing the Aberarth - Aberaeron embayment and entails some 450m of relatively high (>4m) cliffline south of the revetment works at the mouth of the River Arth. Plates 3.13 and 3.14 illustrate typical failures and collapses along these cliffs.

There is clearly a distinct change in material facies along this section as indicated by the differing annual retreat rates. The higher cliffs of clast-dominated till nearest Aberarth appear relatively stable and show mean erosion of only 6.8cms per annum. Further towards the Aberaeron headland the cliffs reduce in height and the in-situ material becomes more clayey. Figures for this 120m section confirm an increased rate of erosion of 16.8cms per year.

Although quite reliable estimates of erosion have been possible over a period of 30 months from datum pegs, it must be stressed that they give little indication of the precise timing of movement which is

PLATE 3.13 General view of local collapses south of Aberarth (Spring 1984)

PLATE 3.14 View from cliff top of individual failure at chng. 89 + 50 (14.4.84)

important in showing relationships between the erosion process and external factors.

Climate and tidal factors are obviously of importance, as are beach morphology and variation in cliff material characteristics. These will be considered in later chapters.

CHAPTER 4

CLIMATIC AND TIDAL INFLUENCES

4.1 Introduction

Temporal and spatial variations in erosion rates can often be explained by differences in environmental energy input. Tides, waves and currents are all processes which individually or by interaction produce an energy input which can form or modify the coastline.

Wind-generated surface waves are the principal source of input energy into the littoral zone and are mainly responsible for erosion of the coast and for the formation of depositional beach features (Komar, 1976). Perhaps an even more significant type of wave, and one which is seldom seen as such, is the tide. Whilst the range of tides in mid-ocean is small, only some 50cm, they increase in height as they reach the comparatively shallow waters of the continental shelf and particularly within the confines of the Irish Sea and along the embayments on the Welsh coast, where the associated tidal currents may also be increased.

Perhaps in the past undue prominence has been given to the effect of wind waves and tidal currents on coastal landforms and only recently has the importance of tidal range been emphasised (Hayes,1975). Certainly a tidal range coupled with a wave length of say 1000km and a crest velocity of 80km per hour means that huge volumes of water shift position at the coast twice each day and enormous amounts of energy are expended. While most of this energy is dissipated in internal friction, the coastline does adjust to these changes in tidal levels.

In this chapter the result of observations and data on these inputs, which can contribute to both marine and sub-aerial erosion processes, are examined. Climate, waves and tides are considered separately although wind and, to a lesser extent, atmospheric pressure are major influences on the other two. A wave hindcast procedure is used to evaluate theoretical wave heights, periods and effective wave energies for specific storm events based on hourly wind data for Cardigan Bay.

4.2 Climatic data from external source

Climatically the west coast of Wales is typical of a maritime area along the western coast of land masses in the middle latitudes of the northern hemisphere, where the prevailing winds are south westerlies from the ocean which warm the land in winter and cool it in summer.

This moderating influence is reflected in that the average temperature in the coldest month (February) is 5°C and the average in the warmest month (August) is 15°C an average annual temperature range of only 10.5°C. Humidity is high and constant, as might be expected of an oceanic climate, with sea mists and cyclonic rains.

A full synoptic recording station is located at Aberporth (GR 257514) and because of its proximity (16km S.W of New Quay) and coastal situation readings from here are considered applicable to the study area (Fig 4.1).

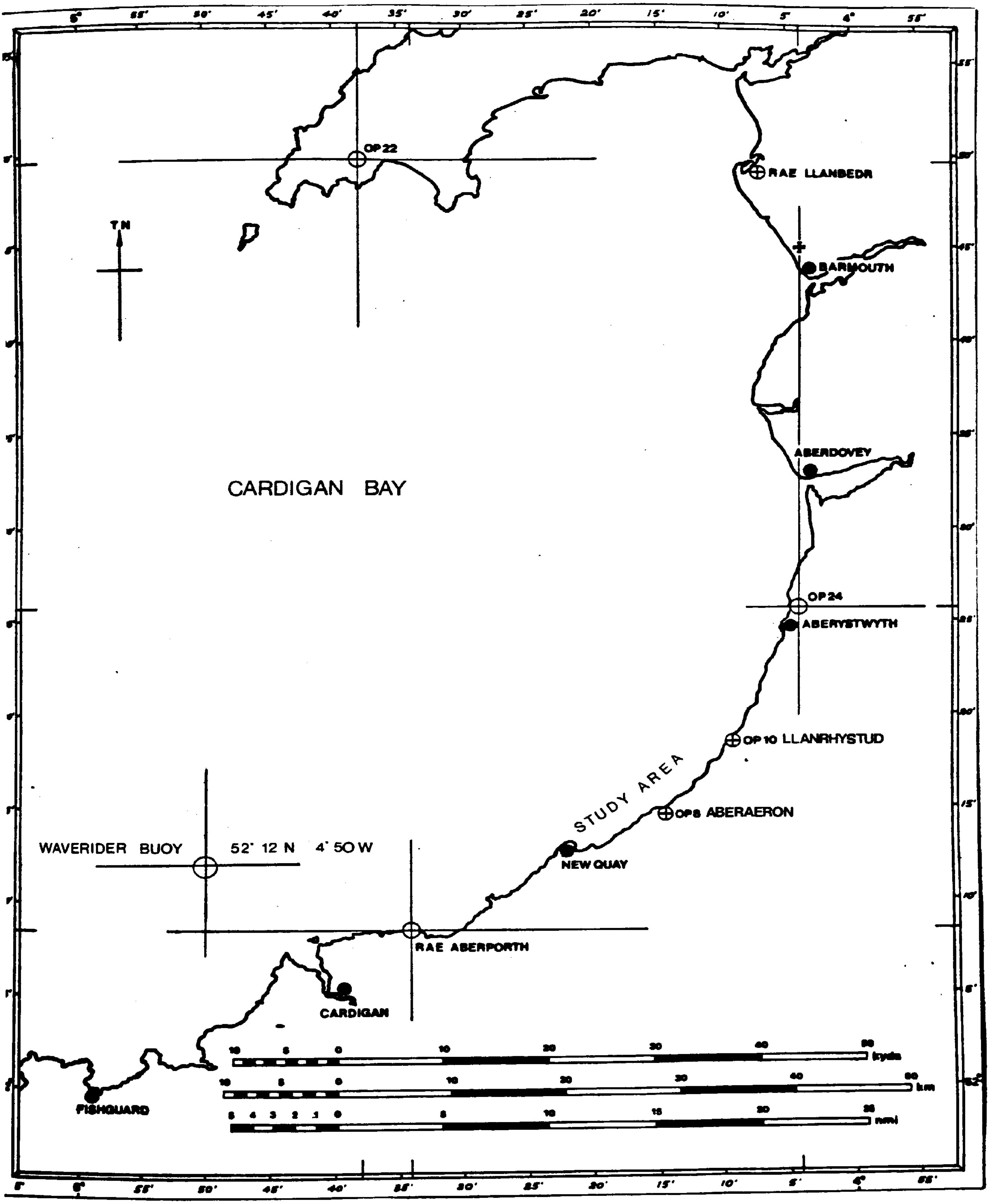
4.2.1 Temperature

Temperature records for the period 1970-1981 and for the study period 1982-1985 are given in Table 4.1. Mean values for this 12 year period are considered representative of long-term averages. Factors such as temperature and humidity are of little direct relevance in affecting cliff erosion although extremes of temperature can lead to drying and cracking and to freeze thaw conditions (See Chapter 9). Frost, however, is relatively uncommon along the coastal strip and on average only 18 days of air frost are recorded during the winter months although the winter of 1984-5 was particularly severe with 35 days of freezing temperatures.

4.2.2 Rainfall

The distribution of rainfall at Aberporth (1970-85) is given in Table 4.2. Total annual figures range from 65.5 to 99.6 cms with a mean value of 85cms. Rainfall occurs throughout the year with maximum falls recorded in the autumn and winter months (Sept to Feb).

When the rainfall during the study period is broken up into seasonal treads (Table 4.3) it is seen that in 1984 a dry spring/summer was followed by an exceptionally wet autumn. The significance of this will be considered in Chapter 9.



IG. 4.1. Sea surveillance stations in Cardigan Bay

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	KEY
70	7.5	6.2	6.6	8.8	14.5	18.5	[illegible]	17.7	16.8	13.3	10.8	7.5	A
	3.1	1.9	2.0	4.2	8.5	11.5	11.3	12.3	11.5	8.6	6.4	3.3	B
	2.2	1.1	0.9	3.2					10.3	7.4	4.9	1.3	C
71	7.7	7.4	7.5	10.7	14.2	14.7	18.4	17.2	18.2	14.9	10.2	9.0	A
	3.5	2.7	3.0	4.7	7.4	9.1	12.3	12.4	11.2	9.1	5.1	5.3	B
	1.9	1.1	1.4	2.1	4.4				8.0	6.7	3.9	3.7	C
72	6.8	7.0	9.1	10.2	12.0	12.9	17.0	16.5	15.2	13.9	9.6	9.2	A
	2.8	2.7	3.8	5.6	6.8	7.7	11.7	11.2	9.0	8.5	5.6	4.7	B
	0.9	1.0	1.1	3.5	4.6				5.5	5.8	3.7	2.9	C
73	7.4	7.1	9.0	9.2	14.2	16.2	16.8	19.5	16.9	12.8	10.1	8.4	A
	3.5	3.2	3.5	4.5	7.9	10.0	11.6	13.2	11.3	7.8	5.9	3.7	B
	2.0	1.7	-0.2	3.1	5.9	7.5			9.0	5.3	4.4	2.2	C
74	8.6	7.9	8.5	12.4	13.0	15.8	16.7	17.1	14.0	10.5	9.3	9.9	A
	3.7	3.1	3.0	5.2	6.9	10.1	11.5	11.1	9.2	6.8	5.2	6.2	B
	2.0	0.9	-0.1	0.7	4.3				7.5	5.1	2.8	3.9	C
75	9.1	8.7	7.2	10.3	12.5	17.0	18.7	19.3	15.6	13.4	9.9	8.3	A
	5.0	2.8	3.0	5.0	6.6	10.5	13.0	13.6	10.0	7.9	5.2	4.6	B
	2.4	-0.5	0.6	2.9	3.4	7.3			6.3	5.1	2.2	2.4	C
76	8.0	7.1	8.1	10.5	13.5	18.9	17.6	20.4	15.5	12.7	7.7	5.6	A
	4.[illegible]	2.6	2.2	4.4	7.6	11.1	13.2	13.5	10.6	7.5	5.2	1.6	B
	2.5	0.2	-0.3	0.7	5.7				8.3	5.5	2.2	-0.8	C
77	5.7	8.2	9.8	7.3	13.6	14.3	18.1	18.0	15.1	14.7	9.0	8.7	A
	1.8	3.4	4.7	4.7	6.8	8.9	12.3	11.7	10.4	9.8	4.8	4.9	B
	0.0	1.6	2.8	3.1	3.9	6.6			8.1	8.5	3.2	3.2	C
78	6.2	5.4	9.0	9.4	13.9	15.2	15.7	16.3	16.1	14.4	11.2	7.6	A
	2.5	1.6	4.0	3.7	7.9	9.8	11.1	11.5	11.2	10.3	7.1	3.3	B
	1.1	-0.4	2.4	1.5	4.7	7.8			7.8	8.3	5.5	0.8	C
79	4.6	4.5	6.9	9.7	11.6	15.5	17.6	16.8	15.7	13.9	10.4	8.9	A
	-0.4	0.3	2.2	4.3	5.4	9.6	11.9	11.2	10.3	9.1	5.7	4.4	B
	-1.7	-1.5	0.7	1.8	4.1				8.5	7.0	4.4	2.6	C
80	5.8	8.7	7.5	10.5	14.5	15.2	16.6	17.7	16.4	11.8	9.1	8.9	A
	1.0	4.3	2.9	5.5	7.2	10.2	11.0	12.5	11.5	7.2	5.5	4.4	B
	-0.8	3.0	1.2	2.4	3.7					5.7	3.6	3.1	C
81	8.0	6.4	9.9	11.2	13.8	15.0	16.5	18.4	17.3	11.0	10.6	5.5	A
	3.6	1.1	5.7	5.1	7.4	9.8	11.6	12.5	10.8	6.5	6.2	0.6	B
	2.5	-0.2	4.4	2.9	5.7					5.3	4.9	-1.0	C
82	6.2	8.1	8.7	10.7	14.5	17.8	17.9	17.1	16.6	12.7	10.6	8.1	A
	2.5	3.0	3.3	5.2	7.4	10.7	12.2	12.0	10.7	7.9	6.4	3.2	B
	1.0	2.1	1.6	2.0	5.3					6.3	5.1	1.4	C
83	9.1	5.3	8.6	9.1	12.1	15.9	20.7	19.7	15.9	13.2	10.6	9.3	A
	4.9	0.5	4.4	3.4	6.8	10.2	13.9	13.1	10.8	8.1	5.8	4.9	B
	3.8	-1.4	2.9	1.6						6.4	3.3	3.5	C
84	7.4	7.1	7.0	12.5	12.2	15.9	18.9	19.9	15.5	13.6	10.2	8.6	A
	2.4	2.2	2.2	5.1	6.4	9.9	11.9	13.2	11.3	8.4	6.0	3.8	B
	1.0	0.6	0.1	1.9	2.7		8.5			6.8	4.1	2.3	C
85	5.0	6.5	7.5	10.8	12.9	14.6	17.4	16.3	17.2				A
	-0.3	1.2	2.3	5.5	7.4	8.7	11.5	10.6	11.2				B
	-2.7	-0.2	0.7	3.9	4.7	6.3							C

KEY: A = MAX; B = MIN; C = Grass MIN, for a given month in a given year.

TABLE 4.1 : MONTHLY TEMPERATURES RECORDS FOR R.A.E. ABERPORTH (1970-85)

TABLE 4.2

MONTHLY RAINFALL FIGURES FOR ABERPORTH (1970-81 & 1982-5)

	J	F	M	A	M	J	J	A	S	O	N	D	TOTAL
1970	97.5	79.2	76.1	67.0	28.1	47.3	57.4	42.6	49.4	108.3	188.1	42.9	88.39 cms
1971	106.9	31.7	62.8	59.4	44.7	116.9	61.4	136.4	42.3	80.0	89.5	48.5	88.05
1972	102.0	88.4	61.1	75.5	65.2	128.5	67.7	32.1	40.6	54.8	91.7	103.4	91.10
1973	45.2	45.8	36.0	44.5	66.7	20.3	75.4	119.9	68.7	55.6	83.5	94.2	75.58
1974	203.2	116.1	47.6	15.9	51.3	54.0	54.2	47.9	124.2	114.0	89.2	78.9	99.65
1975	132.3	31.6	42.0	70.6	23.9	4.3	48.0	47.3	66.8	59.5	69.1	59.9	65.53
1976	48.1	40.5	62.0	19.2	56.6	11.5	13.2	0.8	157.8	155.2	81.1	83.0	72.90
1977	79.3	150.6	56.9	50.4	50.2	54.3	24.9	91.2	27.8	110.6	118.2	78.2	91.26
1978	92.8	74.0	48.0	32.4	14.9	31.1	91.0	61.0	52.0	25.8	71.6	140.0	73.46
1979	91.1	54.2	83.3	68.2	98.3	24.0	13.2	93.3	44.6	158.9	93.7	152.8	97.56
1980	57.9	89.9	91.6	21.4	27.5	76.4	53.9	66.3	75.4	119.3	64.8	82.9	82.73
1981	40.7	52.6	164.5	22.5	70.3	28.1	27.7	24.2	164.8	217.2	51.9	78.0	92.25
MEAN	91.4	71.2	69.3	45.6	52.3	49.7	49.0	63.5	76.2	104.9	91.0	86.9	
1982	67.3	78.3	67.5	18.0	30.5	94.5	53.9	74.5	105.4	107.9	141.2	78.9	91.79
1983	90.8	31.1	71.8	68.0	78.4	42.9	39.5	57.1	93.7	81.8	44.5	122.1	82.17
1984	80.6	52.1	35.3	8.4	44.6	24.9	38.4	40.5	154.2	95.1	145.0	133.6	85.27
1985	71.2	29.7	67.0	62.1	29.3	104.2	70.4	105.4	29.5				

(Figures given in mm except where stated)

DATA FROM METEOROLOGICAL OFFICE, BRACKNELL

TABLE 4.3

SEASONAL RAINFALL DURING STUDY PERIOD 1982-5

	M-A-M SPRING	J-J-A SUMMER	S-O-N AUTUMN	D-J-F WINTER
1982		222.9	354.5	
1982/3				200.8
1983	218.2	139.5	220.0	
1983/4				254.8
1984	88.3	103.8	394.3	
1984/5				234.5
1985	158.4	280.0		
AVERAGE LONG TERM VALUE	167.2	162.2	272.1	249.5

(FIGURES GIVEN IN MM)

Rainfall again as a factor is considered to have only minimal effect on cliff erosion except in those areas of non-vertical slopes of boulder clay or till with little or no vegetation cover where high intensity rainfall may play an increasingly important role in forming rills and small gullies. It may also, in terms of surface run off, increase the erosive effect locally of drainage features such as streams and land drains.

4.2.3 Wind Activity

Because of the orientation of the coastline the most effective winds in terms of erosion potential come from the westerly quadrants. The annual wind rose for Aberporth (Fig 4.2) shows a predominance of on-shore winds both in strength and frequency with at least 40% of all winds coming from the south-west sector. Winds of different strengths follow the pattern of the frequency distribution, nearly all the gale force winds recorded at the station being westerly, usually generated by low-pressure systems. The area receives an average of 35.3 gale force storms a year (Moore, 1968) most of which are concentrated in the autumn and winter.

4.3 Wave climate in Cardigan Bay

Wave energy on a coastline is partly a function of fetch (Schou, 1960). Therefore, in terms of erosion potential, wave energy along the Cardigan Bay coastline is limited by the configuration of the Irish Sea which provides limited fetch in all directions except for a narrow vector to the south west, through St. George's Channel into the Atlantic via the Western Approaches, where fetch is essentially unlimited (Fig 3.2). Fetch to the west and north is restricted by Ireland and the Lleyn Peninsula respectively and ignoring the phenomenon of wave refraction the maximum uninterrupted fetch within the Irish Sea is approximately 230km to the N.N.W.

The wave climate of Cardigan Bay is governed principally by the virtually enclosed position of the Irish Sea and by the influence of the westerly air flows that predominate over the British Isles. Long-period (>9secs) swell waves emanating from depressions in the Mid-Atlantic will only develop through St. George's Channel while short

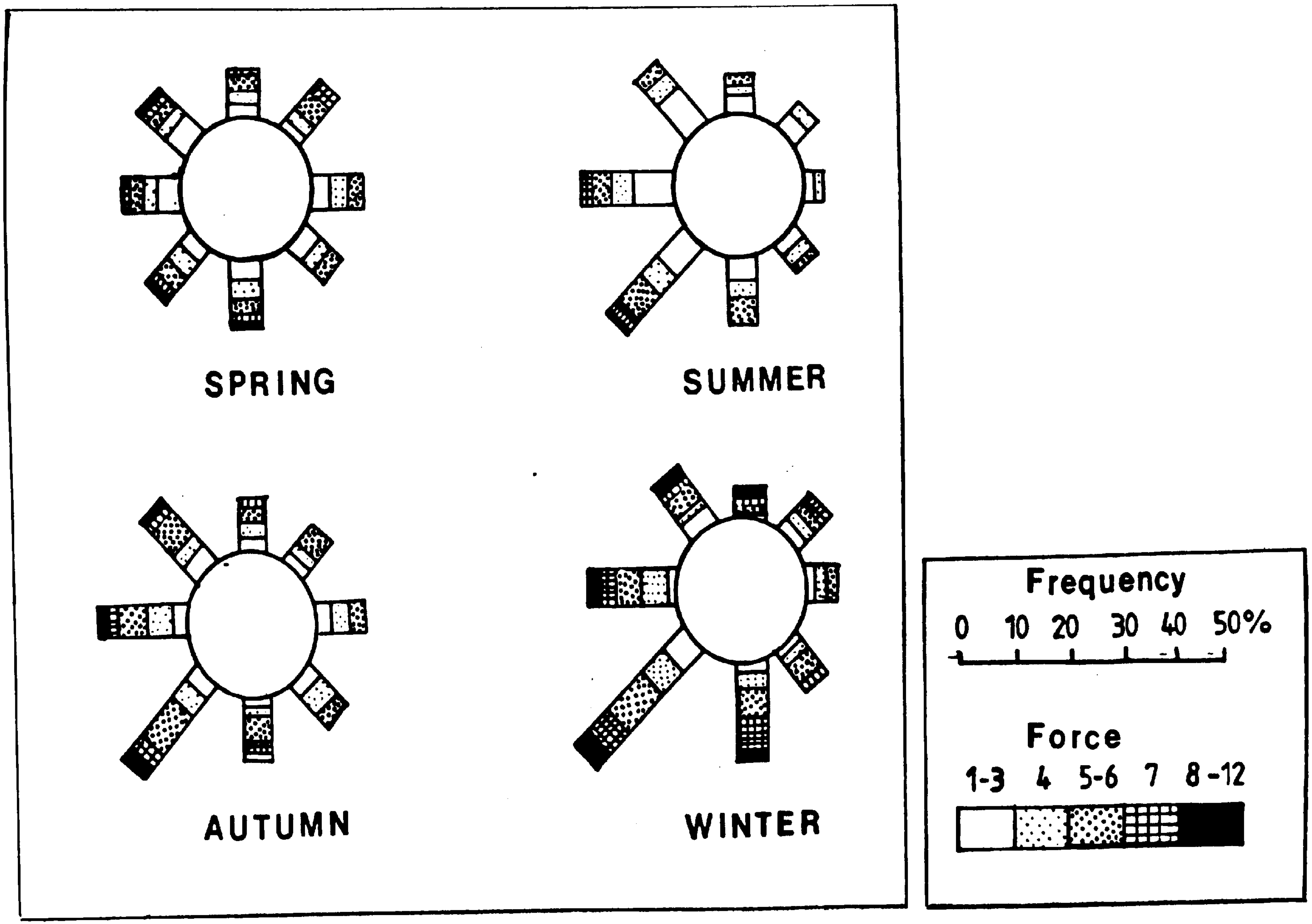


FIG. 4.2. Wind directional frequency and force for Cardigan Bay area (extrapolated from R.A.E Aberporth weather data, 1970 - 1985)

period (<7secs) sea waves will be generated within the Irish Sea, often as a result of westerly and north-westerly winds.

The offshore bathymetry of the Waterford-Wexford and north Pembrokeshire coasts induces reflection and refraction of long period waves. On traversing some 50km of shallow water (<50m) these swell waves are further refracted by the time they reach the study area.

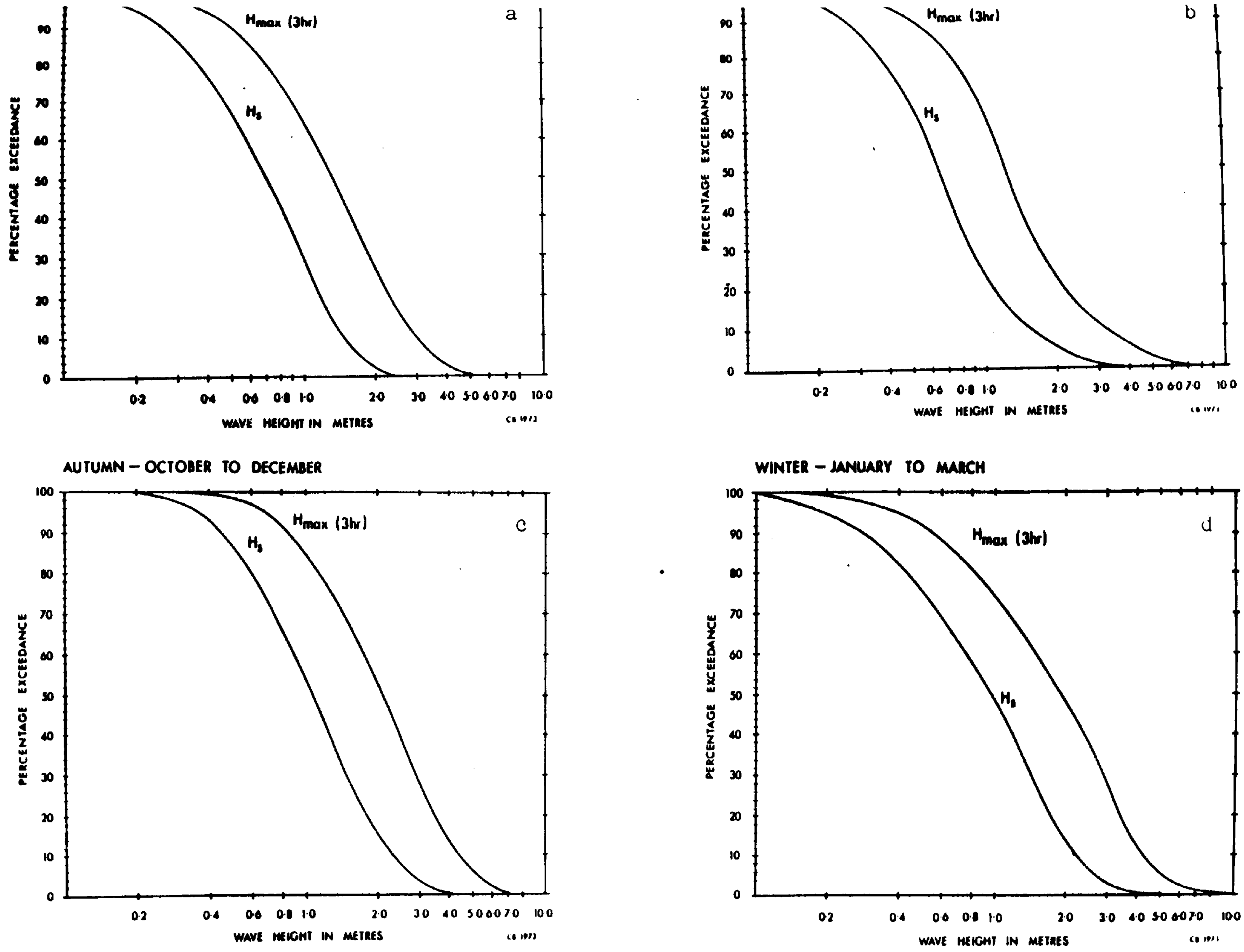
Short-period waves do not start refracting until they come within the same 50m submarine contour which approximately runs from St.Davids Head to the tip of the Lleyn Peninsula, and most refraction occurs within a zone 3-4km offshore (Orford, 1978).

Wave climate data available for south Cardigan Bay is limited. Wave data held by the Marine Information and Advisory Service (MIAS) include only hourly data of sea surface elevation for coastal sites at Aberystwyth (1972) and Aberporth (1974). The most pertinent data for this area has been obtained from an I.O.S. study, based at the Royal Aircraft Establishment, Aberporth in 1973, where waves were recorded by a Waverider buoy placed in a water depth of about 30 metres at 52° 12 N, 4° 50 W, approximately 17km north west of Cardigan (Draper and Wills, 1977). The buoy was in operation from 5th Jan to 31st Dec. and all the records were analysed using Tucker's (1963) method of wave trace analysis to give what was in effect a complete year's wave data.

Examination of the data indicates a predominance of waves in the 7 to 9 second period range with a secondary peak at approximately 11 seconds which probably represents the contribution from deep ocean swell along the 220° - 230° vector.

The highest value of wave height recorded during this period was 6.8 metres on 12th Feb although waves of almost equal height occurred at other times (autumn and winter) in the year (Figs 4.3a-d). The autumn and winter months had, as would be expected, more waves exceeding any given height than the spring and summer months.

For example, in winter the significant height exceeded 1 metre for 48% of the time, whereas in summer this value was exceeded for only 24% of the time.



FIGs 4.3a-d Percentage exceedance of wave height (in metres)

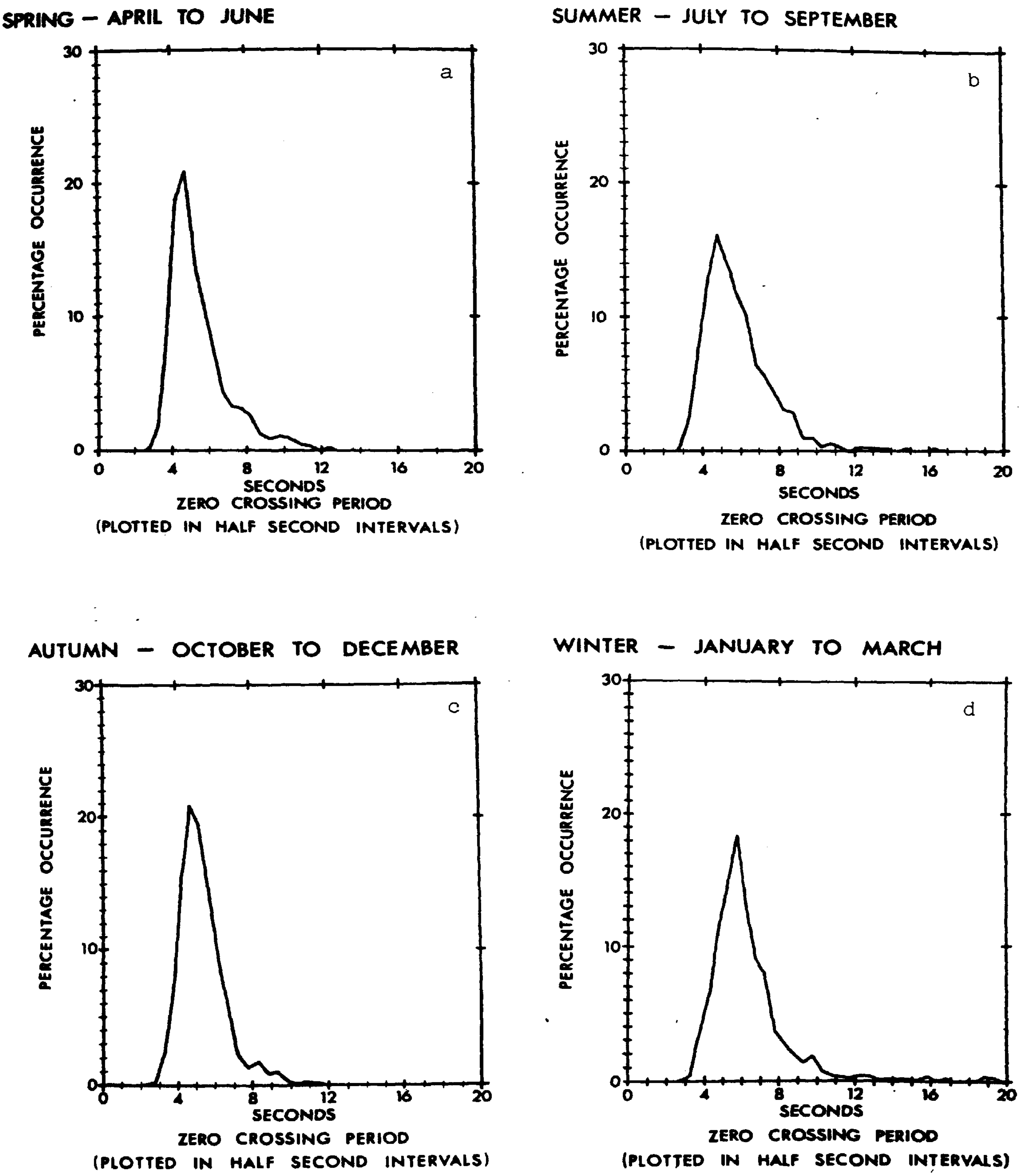
Analysis of the mean zero-crossing period (Tz), (Figs 4.4a-d) shows little seasonal variation. In winter the most common period was about 6 seconds whereas in summer it was about 5 seconds. However, occasionally, the arrival of a very low swell in locally calm conditions gave wave periods in the upper tems of seconds. These swell wave periods (>10secs) are evident in all seasons but particularly between July and September.

The spectral width parameter, E, calculated from Tz and Tc (Tucker, 1961) where $E^2 = 1 - (Tc/Tz)^2$ is restricted to a value between 0.5 and 1.0. This reflects the lack of swell waves due principally to the Irish Sea being relatively small and almost enclosed,thus resulting in a rarity of swell from other areas and indicating a dominance of sea waves within the Bay (Fig 4.5).

The scatter diagram in Fig. 4.6 shows, in parts per thousand the numbers of occurrences of particular combinations of wave period and wave height. It indicates that in 1973 waves most often encountered at this location had a period of between 4 and 5 seconds and a significant height of between 0.4 and 1.2 metres. Within these values wave conditions occurred for 18.1% of the time.

Wave steepness, an important parameter in the dynamics of beach profile morphology (Orford, 1978), is expressed as wave height: wave length. The majority of the waves represented are less steep than 1:18 and no waves >9 secs period have a wave steepness > 1:40.

The long-term prediction of wave height, which is of obvious interest to this study, was obtained by plotting values of H max on both log-normal and Weibull probability paper. The former yields a 50 year lifetime wave height of 13 to 15 metres, the Weibull presentation 13 metres. Allowing for the winds for 1973 over the generating area to be 92% of a long-term average, then it may be reasonable to assume that wave heights measured were 87% of typical conditions based on wave heights being related to the wind speed to the power of 1.5 in the relatively shallow water in the Bay (Darbyshire, 1961). Accordingly, all wave heights should be increased by about 15% and periods by about 4%. This suggests a 50-year predicted wave height of 15 to 16 metres.



FIGs 4.4 a-d Graphs of percentage occurrence of T_z

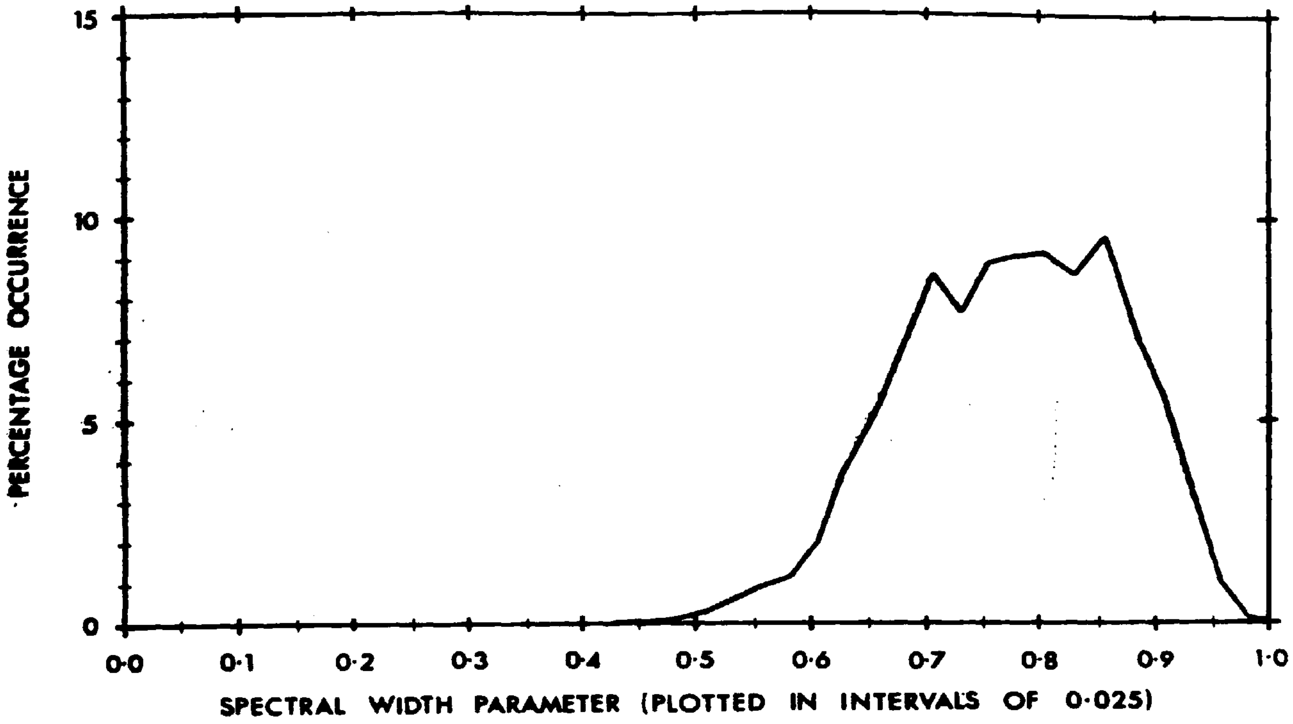


FIG. 4.5 Graph of spectral width parameter for whole year

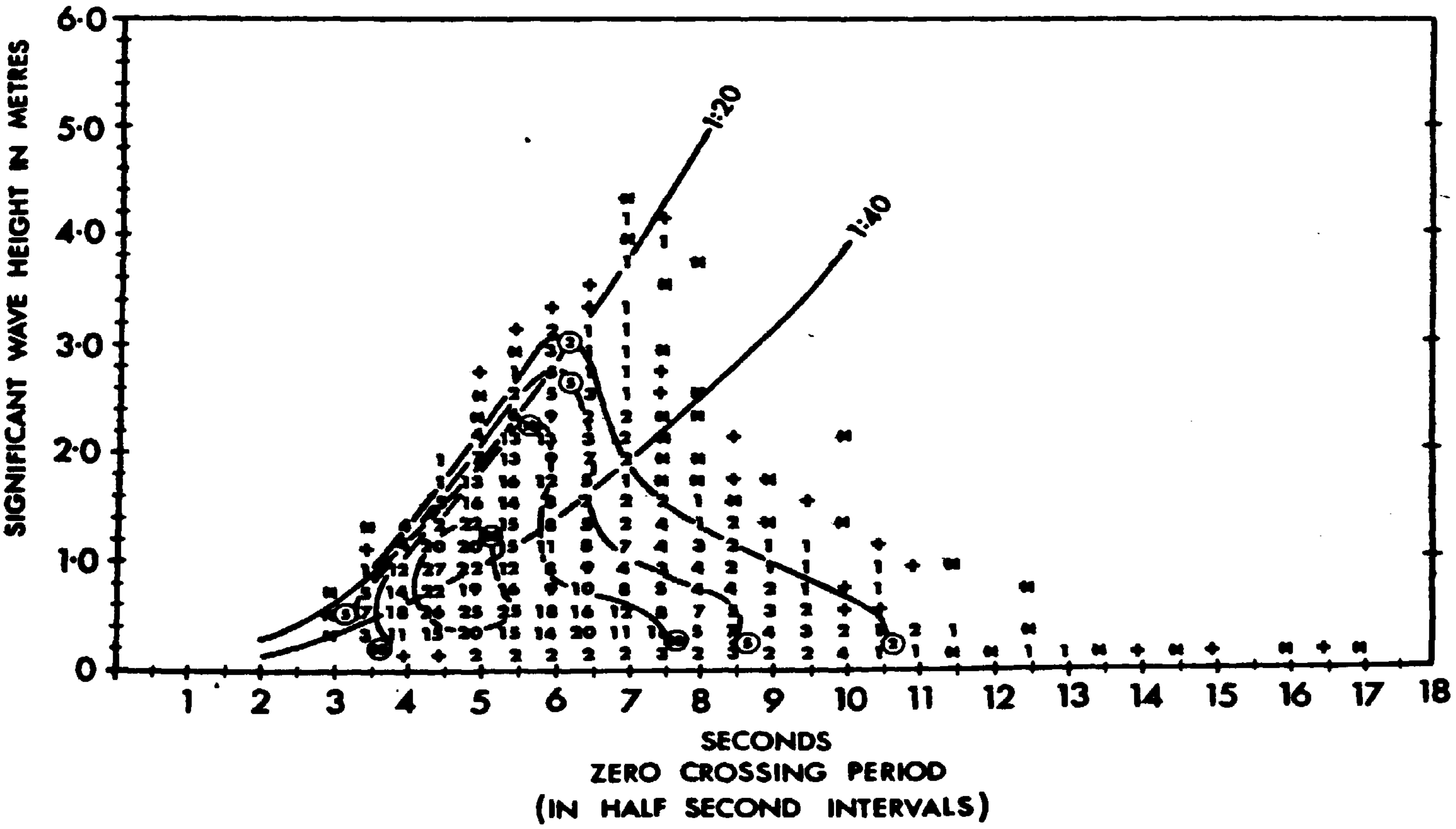


FIG. 4.6 Scatter diagram of number of occurrences (in parts per thousand) of particular combinations of wave period and wave height

Subsequent works by Wills (1983) at the same Royal Aircraft Establishment has provided useful information on wave direction using sea-surface radar plots. Data for Aberporth indicate that the mean angle of approach for swell waves in the south CardiganBay area is 259°, with a standard deviation of 5°. Pure swell waves are often difficult to detect and Wills points out that in storm conditions, wind waves of periods comparable to those of swell waves can approach the coast over an arc extending from south-west to north-west.

Fig 4.7 gives a diagrammatic presentation of the alignment of wave crests at different areas in Cardigan Bay for the period May to September 1983. These wave patterns were obtained from marine surveillance radars located at Aberporth, Constitution Hill near Aberystwyth and Mynydd Rhiw on the Lleyn Peninsula. Wind vectors for the corresponding dates are also shown, although vector lengths have no significance neither do the positions which the vectors are drawn.

Disregarding what Wills (1983) considered to be obvious wind waves and unreliable measurements we have a spread from 232° to 255° averaging 245 degrees for an area of sea off Aberystywth approximately 3 miles by 2 miles and for a spread of wind directions from SW to NW. Measurements for Mynydd Rhiw and Aberporth serve to show the consistent behaviour of swell over widely spaced regions of the Bay. Also,it can be seen that the two measurements for the off shore region at Aberporth agree well with the figure of 259° given previously.

The only source of continuously monitored wave climate data for the Irish Sea at present and the one used in refraction modelling discussed is from Hogben and Lumb's (1967) collection of shipbased wave-data records. Although this source has been criticised by Hansom (1983) for being non-representative, the data contains all the necessary elements e.g. wave height, wave period, wave direction while the time period over which the data was collected (1953 - 1961) contributes to long-term estimates of wave occurrence. This collection indicates a median deep-water wave height of 1.5m for all seasons and a maximum wave neight (H Max) of 9 metres.

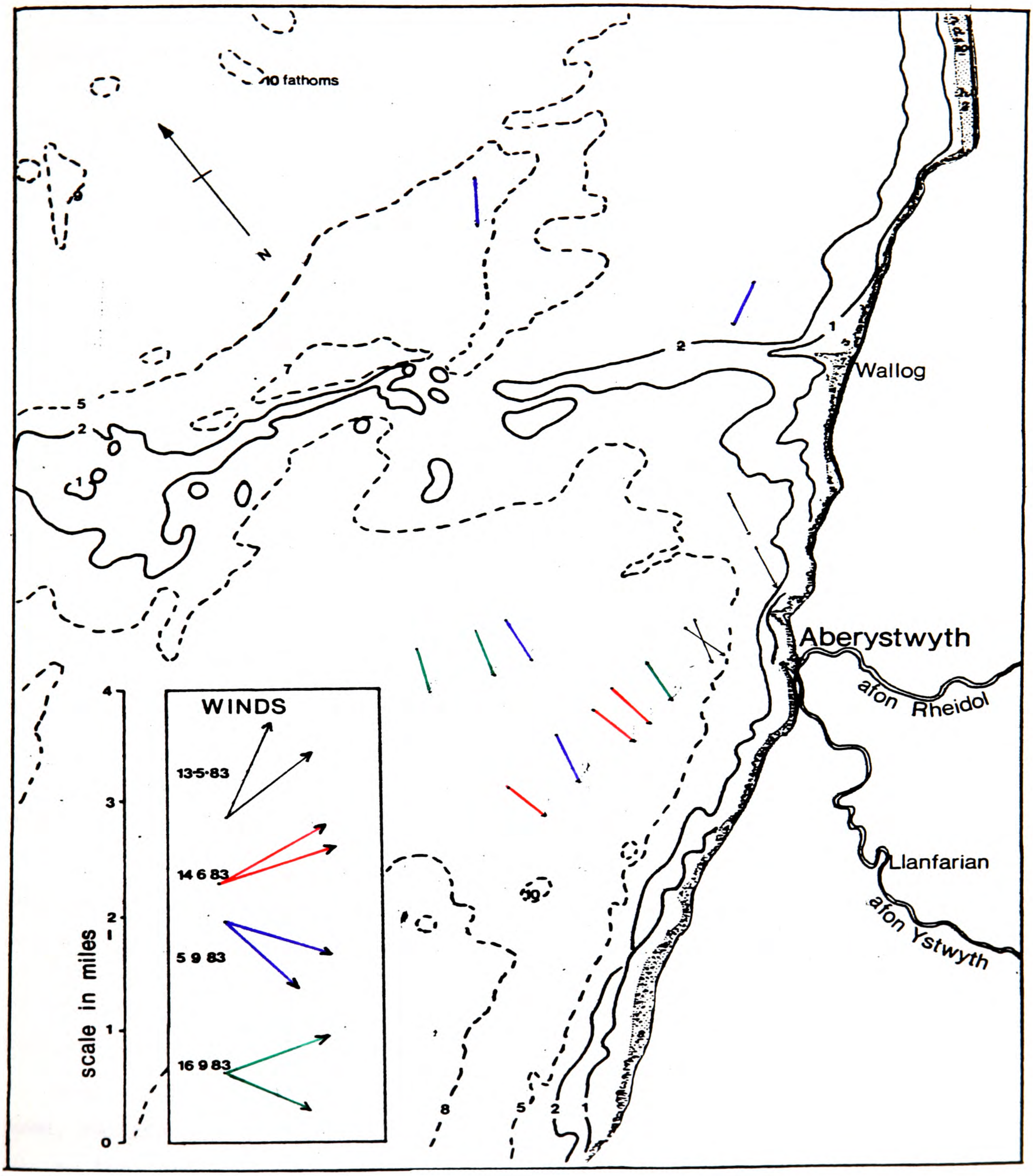


FIG. 4.7 Measured wave crest orientation (after Wills, 1983)

4.3.1 Significance of specific storm events in coastal erosion

In a storm wave dominated environment, morphological change in the coastal zone can be a function of wave energy dissipation and its variation through time (Davies, 1973). As periods of intensive wave activity are associated with storm conditions, the determination of magnitudes and frequency of occurrence of specific storm wave events was assessed in terms of their relative importance.

A wave hindcast procedure,attributed to Sverdrup Munk Bretschneider (S.M.B),was used to produce theoretical wave heights, periods and cumulative wave energies for specific wave events within the Cardigan Bay area,based on hourly wind data for RAE Aberporth.

Wave hindcasting from measured wind data has been used successfully in a number of studies particularly where fetch lengths are restricted e.g. Armon and McCann (1977), Hale and Greenwood (1980), Davidson-Arnott and Pollard (1980).

4.3.2. Storm event criteria

No absolute definitionof what constitutes a storm event exists (Hale and Greenwood, 1980,p76). From the point of view of wave generation and its relative impact on shoreline a number of criteria need to be defined. The generation of wind waves is essentially determined by the speed and duration of the wind and the length of fetch (Komar, 1976). There is,however, a progressionof antecedent meteorological conditions which need to be considered and which often cannot be quantified.

Assumptions have to be made about wind speed and direction. Wind data may have a mean speed but this is an average of gusts and lulls over a range of directions which can be spread more than 45° from the nominal direction. There is therefore a whole spectrum of wind speeds and directions ensuing in a whole range of waves caused by wind drag over the sea.

Other factors need to be considered, such as maximum hourly wind speed, maximum gust, number of hours with gusts of varying strength etc, so that any assessment of the necessary criteria must be subjective.

Hale and Greenwood (1980), in a case study of Kouchibouguac Bay in the Southern Gulf of St. Lawrence, used the following criteria to define a storm event based on hourly average wind speed and direction data:

(i) cumulative average hourly wind speed of 19km/hr or 10 knots will not theoretically generate significant waves greater than 1m in height or 4 second period regardless of length of fetch or duration

(ii) duration of wind speeds knots must be not less than 6 hours

(iii) wind directional variability must be restricted to fluctuation less than 45° from the predominant direction.

In terms of the Cardigan Bay wave climatology, parameters are to a certain degree determined by the aspect of the West Wales coastline and the confines of the Irish Sea. The value of 10 knots adopted in the Canadian study would appear to be conservative when applied to the Irish Sea. Local experience has indicated that westerly winds of Beaufort scale 6 or greater contribute mostly to storm conditions. Force 6 winds of 15 hours duration blowing over a fetch of 140 sea miles induce waves of deep water steepness 0.049 (Roth, 1979). This is twice the figure of 0.025 proposed by Johnson (1956) for destructive waves on beaches and these figures for wind speed and duration would appear to be reasonable thresholds for this area.

From an analysis of the hourly wind speed and direction data for Aberporth, provided by the Meteorological Office, the following criteria were established:

(i) hourly mean wind speed of not less than 25 knots
(ii) duration of wind speeds 25 knots must not be less than 15 hours
(iii) wind direction from within an arc 235°- 025° must not fluctuate more than 45° from the predominant direction

While individual gusts of 70 knots were registered they may not have been significant in themselves as waves take a certain length of time to develop. More important were the number of successive hours which had gusts of similar intensity and the number of hours with gusts of 34 knots or more and 48 knots or more were considered in the assessment.

Storm situations were readily identified in the data from the above conditions.

4.3.3 Storm Frequency

Storm events abstracted from wind data were summarised in terms of the number of events by direction and month for an average year. Fig. 4.8 shows that of the 12 so-called storm events per year, 5 were from the NW quadrant, 3 from the SW, 3 from the SE and 1 from the NE.

Irrespective of direction, January is the stormiest month with a total of 42 storms in the period 1971-85, followed by November with 27, December with 25, March with 23 and February with 21. The three winter months of December, January and February represent 50% of the annual storm conditions.

Winter	(D-J-F)	50%
Spring	(M-A-M)	19%
Summer	(J-J-A)	1%
Autumn	(S-O-N)	30%

4.3.4 Frequency of significant storm events in terms of potential erosion

For the meteorological criteria proposed in section 4.3.2. hindcast storm events were computed using the (S-M-B) significant wave approach (Sverdrup & Munk, 1947); Bretschneider 1951, 1958, 1959, 1970). The relationships representing deep-water wave generation in this technique were defined by Johnson (1950) in the following equations:

$$\frac{C}{V} = \psi_1 \left[\frac{gF}{V^2}, \frac{gt}{V} \right]$$

$$\frac{gH}{V^2} = \psi_2 \left[\frac{gF}{V^2}, \frac{gt}{V} \right]$$

where C = wave celerity, H = wave height, g = gravitational constant and ψ = constant of proportionality derived from empirical data.

Input data of wind speed, direction and duration together with effective fetch length were incorporated into a computer programme developed by Lalande (1975) and modified by Hale and Greenwood (1980)

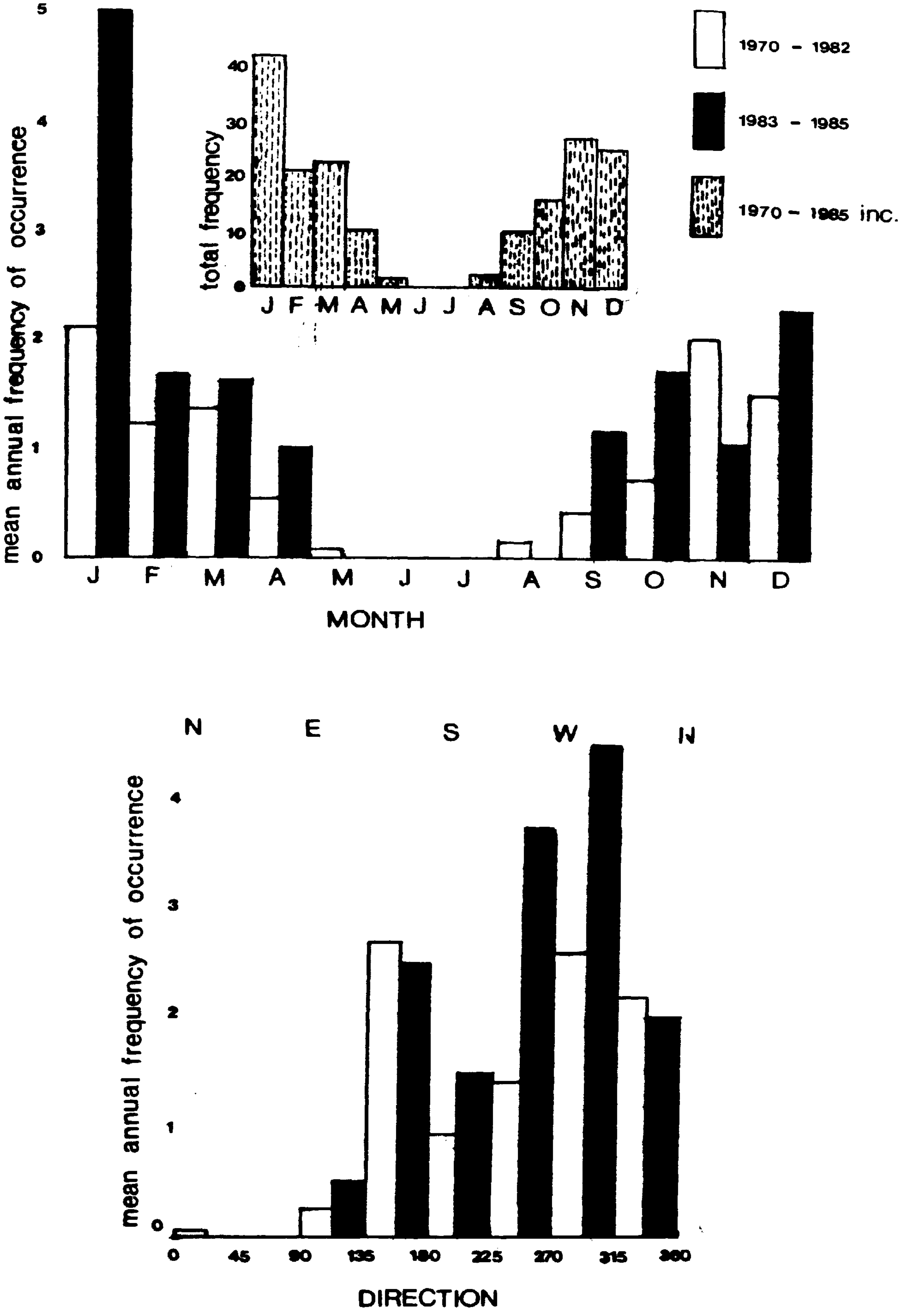


FIG. 4.8 Storm Frequency Distribution by Month and Direction

which provided an hour-by-hour printout of wave conditions from the first hour of the event. Procedures were added to compute the wave energy generated each hour and cumulative wave energy for the storm event. Table 4.4 shows a typical printout for the storm event of 30.1.83. Storm characteristics for the periods 1971-81 and 1982-85 are listed in Tables 4.5 and 4.6 respectively.

These large storm events reveal a consistent general pattern with little annual variability.The frequency of occurrence of 2.0 per annum for the study period (1982-85) is comparable with the figure of 2.2 for the total 15-year period.

In the years 1976 and 1983 there were 4 storms while in 1971 and 1982 no significant storms were recorded. The period September to February accounts for 82% of the total number and the seasonal breakdown, listed below is,as to be expected, almost identical to that for wind data listed in Section 4.3.3.

Winter	(D 3, J 10, F = 3)	16 (48.5%)
Spring	(M 5, A 1, M = 0)	6 (18.2%)
Summer	(J 0, J 0, A = 0)	0 (0%)
Autumn	(S 2, O 4, N = 5)	11 (33.3%)

For the 15-year period (1971-85) storm waves in total, irrespective of wind direction or duration were generated an estimated 7.0% of the time. Waves generated by specific storm events (i.e 15 hours duration from the S.W to N sector) occured only 0.7% of the time.

Storms from the north-westerly quadrant contribute 82% of this figure. This pattern is consistent with depressional movement across the British Isles, particularly in the autumn and summer months. Strong southwesterly winds tend to occur before a front moves in. At the front westerly to north-westerly winds develop, often stormy and cold, becoming north-westerly as the depression moves across Britain to the N.E.

In predicting the potential impact of a storm event on the coast line, the most applicable measure of intensity may be the capacity of the storm waves to do work as expressed by the cumulative wave energy (Hale and Greenwood, 1980).

```
                                                       STORM NUMBER    1
                      DIRECTION OF WIND APPROACH   280.0  DEGREES CLOCKWISE FROM TRUE NORTH      DATE 30/ 1/83
                                                                     ENERGY DENSITY           WAVE POWER
HRLY VEL CUM AV VEL FETCH DURATION  WAVE HT  WAVE PERIOD        FT-LB/FT    JOULES/M    FT-LB/FT/SEC   JOULES/M/SEC
 (MPH)     (MPH)     (MI)  (HOURS)  (FT  CM)    SECONDS

  14.      13.5      81.0   1.0     0.9  26.3    2.01            123.3       548.3          61.4          273.0
  16.      14.9      81.0   2.0     1.3  40.8    2.53            469.8      2089.6         186.0          827.4
  16.      15.3      81.0   3.0     1.7  52.3    2.87           1001.3      4453.8         348.4         1549.6
  18.      15.9      81.0   4.0     2.2  65.8    3.23           2008.8      8935.4         621.1         2762.7
  17.      16.2      81.0   5.0     2.4  72.8    3.41           2725.0     12121.3         800.1         3559.1
  18.      16.6      81.0   6.0     2.6  80.6    3.59           3706.2     16485.7        1033.2         4595.8
  19.      17.0      81.0   7.0     3.0  92.0    3.84           5524.6     24574.3        1439.6         6403.5
  21.      17.5      81.0   8.0     3.3 101.7    4.04           7477.3     33260.5        1851.6         8236.2
  21.      17.8      81.0   9.0     3.5 107.4    4.15           8815.2     39211.6        2123.4         9445.1
  23.      18.3      81.0  10.0     3.9 117.7    4.35          11608.8     51637.9        2669.4        11874.0
  26.      19.0      81.0  11.0     4.3 130.4    4.58          15798.8     70275.8        3449.4        15343.7
  27.      19.7      81.0  12.0     4.6 140.2    4.75          19642.7     87373.9        4135.6        18395.7
  24.      20.0      81.0  13.0     4.7 143.3    4.80          20988.3     93359.8        4371.1        19443.3
  23.      20.2      81.0  14.0     4.8 145.3    4.83          21843.7     97164.5        4519.5        20103.3
  20.      20.2      81.0  15.0     4.8 145.1    4.83          21785.9     96907.6        4509.5        20058.8
  19.      20.1      81.0  16.0     4.7 144.4    4.82          21434.4     95343.9        4448.6        19788.0
  17.      19.9      81.0  17.0     4.7 142.4    4.79          20574.6     91519.2        4298.9        19122.4
  16.      19.7      81.0  18.0     4.6 140.0    4.75          19580.2     87095.9        4124.6        18346.8
  14.      19.4      81.0  19.0     4.5 137.1    4.70          18378.1     81748.9        3911.8        17400.5
CUMULATIVE ENERGY DENSITY IN FT-LB/FT. GREST WIDTH              223486.9
CUMULATIVE ENERGY DENSITY IN JOULES/METRE CREST WIDTH           994108.0
```

TABLE 4.4 Computer print-out of storm characteristics hindcast for 30.1.83 using S-M-B procedure

STORM EVENT NO.	DATE	MAX. WIND SPEED (KNOTS)	DURATION (MINS)	MEAN DIR. (oN)	FETCH (MLS)	WAVE HT (FT)	WAVE PER. (SEC)	CUM. WAVE ENERGY DEN. (J/m)	MAX W.POW (J/m/s)
1	270172	39	35	300	81	4.3	4.58	13.6 E 5	15359
2	270372	34	36	270	81	3.5	4.17	11.6 E 5	9446
3	120273	41	40	280	81	3.6	4.24	13.2 E 5	10322
4	020473	37	15	310	90	3.7	4.28	3.6 E 5	10768
5	160174	42	26	290	81	4.3	4.58	12.1 E 5	15344
6	280174	34	32	330	129	3.6	4.27	9.3 E 5	10265
7	281174	34	21	290	81	3.4	4.11	4.6 E 5	8753
8	161175	35	31	320	117	4.0	4.48	12.6 E 5	13344
9	021275	35	22	340	39	2.5	3.52	2.4 E 5	4147
10	020176	54	18	240	3500+	5.0	4.98	11.3 E 5	22743
11	200176	33	26	260	3500+	3.9	4.44	8.8 E 5	12108
12	090976	37	30	320	117	4.5	4.70	12.7 E 5	17122
13	151076	40	30	320	117	4.5	4.74	14.8 E 5	17803
14	140177	37	28	330	129	4.1	4.54	10.8 E 5	14182
15	141177	46	30	300	81	4.7	4.80	19.2 E 5	19443
16	110178	40	28	360	42	3.3	4.03	6.3 E 5	8175
17	290178	49	35	330	129	6.2	5.51	47.8 E 5	38439
18	140378	34	16	260	3500+	3.7	4.28	3.7 E 5	10571
19	290379	43	36	340	39	3.6	4.16	10.1 E 5	9651
20	171279	38	27	280	81	3.9	4.37	9.1 E 5	11995
21	071080	36	36	270	3500+	4.2	4.68	15.8 E 5	15284
22	281180	37	29	330	129	4.2	4.56	12.4 E 5	14574
23	140181	35	30	280	81	3.4	4.11	7.5 E 5	8766
24	091081	46	18	280	81	4.5	4.71	7.7 E 5	17556
25	281181	39	22	320	117	4.3	4.60	10.3 E 5	15488

TABLE 4.5 Storm event characteristics for period 1971-1982

STORM EVENT NO.	DATE	MAX. WIND SPEED (KNOTS)	DURATION (MINS)	MEAN DIR. (oN)	FETCH (MLS)	WAVE HT (FT)	WAVE PER. (SEC)	CUM. WAVE ENERGY DEN. (J/m)	MAX W.POW (J/m/s)
26	300183	50	19	280	81	4.8	4.83	9.9 E 5	20103
27	060283	42	60	330	129	4.6	4.78	36.1 E 5	18407
28	030983	41	22	250	3500+	4.9	4.94	13.2 E 5	21583
29	091283	44	19	360	42	3.7	4.23	6.3 E 5	10527
30	030184	40	46	290	81	4.3	4.59	23.8 E 5	15475
31	060284	38	34	260	3500+	4.7	4.93	19.7 E 5	20082
32	020384	38	30	320	117	4.5	4.71	16.1 E 5	17341
33	160385	39	17	330	129	4.5	4.71	7.0 E 5	17277

TABLE 4.6 Storm event characteristics for period 1982-1985

Examination of Tables 4.5 and 4.6 reveals the maximum predicted storm occured between 28-30/1/78 and had a significant wave height of 6.2ft (1.9m) and a 5.5 second wave period. A maximum wave power of 38.5000 j/m/sec and total wave energy density of 47.8 x 10^5 jm^{-1} crest width were calculated, indicative of high-energy conditions.

This largest magnitude event was from the north-west quadrant and the dominance of south-westerly winds is further illustrated in Table 4.7 where the wave energies are categorised by direction.

An assessment of the relative importance of storm events cannot be made unless the event can be related to absolute or observed volumes of change along the coastline.

A check on the viability of this hindcasting technique was carried out for several specific wave generating events where some comparative information was available.

(i) 12.2.73

The maximum wave height recorded by Waverider buoy in Cardigan Bay (Draper and Wills, 1977) during 1973 occurred on the 12th of February although waves of almost this height occurred at other times (autumn and winter) in the year.

This agrees with the timing of the most significant storm event, in terms of wave energy, hindcast for 1973, although it must be stated that the predicted values of wave height and period (1.9m and 424 sec. respectively) were appreciably lower than actual (6.8m and 6.79 secs. respectively).

(ii) 14.11.77

A 2-year (1976/7) experimental period into beach changes at Ynyslas, near Aberystwyth, by Williams et al (1981) included one storm of note (14.11.77) when significant volumes of beach material were removed.

Sweep zone diagrams indicated the main profile variation being on the seaward edge of a pebble ridge where 169, 127 and 211 m^3 of material were removed from 3 profiles.

TOTAL WAVE ENERGY $jm^{-1} \times 10^5$	DIRECTION				ALL DIRECTIONS
	(202^o-247^o)	(247^o-292^o)	(292^o-337^o)	(337^o-022^o)	
0 - 10		7	3	3	13
10 - 20	1	6	9	1	17
20 - 30		1			1
30 - 40			1		1
40 - 50			1		1
TOTAL	1 (3)	14 (42)	14 (42)	4 (12)	33

TABLE 4.7 Cumulative wave energy generated by storm events, classified by direction, for period 1971 - 85 inclusive (Figures in parentheses are percentages)

These volumes of sediment moved reflect the total work done by a north-westerly storm with wave energy density of 19.2 x 10^5 jm^{-1} crest width.

(iii) 30.1.83

Although there was no record of its effects on the Aberaeron coastline, there was a newspaper account of the damage caused. "Gale force winds hit many parts of Wales yesterday. Gusts of more than 80 knots were reported by coastguards at St. Ann's Head, near Milford Haven. Ships were battered by huge seas and storm-force westerly winds. Caravans were blown over near Aberystwyth and in the town itself part of the roof of a block of flats was blown off" (Western Mail Reporter, 31.1.83).

In this case, as in many others, it was the popular perception of damage to property or loss of life that gave the storm the status of an extreme event rather than its absolute intensity. Profiles surveyed by the writer subsequent to this storm showed a dramatic lowering of beach levels. (Figs 6.6 a-d). This was particularly evident at Llanrhystud (chng 1 + 00) where the top of the beach face was reduced in level by over 1m.

It is apparent that the moderate-to high-storm events predicted are most important in causing coastal change along the Ceredigion coastline. Without knowing the morphological responses, relating the type or scale of change to the indices of storm intensity is problematic. The likely relationship that exists between total energy and change in the form of quantity of sediment transported will be referred to in Chapter 5 and 6.

Any changes in nearshore configuration associated with storm events may only be effected when such events coincide with periods of high tides. Table 4.8 shows that for the eight events of possible marine erosion during the study period the coincidence of storm climate with high spring tides was rare.

PREDICTED TIDE		HIGH SPRING TIDE	
DATE	HEIGHT m A.O.D	DATE	HEIGHT m A.O.D
30.1.83	2.8	31.1.83	2.8
6.2.83	1.2	31.1.83	2.8
3.9.83	1.4	8.9.83	3.0
9.12.83	1.9	5.12.83	2.4
3.1.84	2.2	4.1.84	2.3
6.2.84	2.1	3.2.84	2.3
2.3.85	2.2	4.3.85	2.3
16.3.85	1.2	9.3.85	2.8

TABLE 4.8 Predicted tides for days of hindcast storm events in temporal relation to high spring tides

4.4 Tides

The study area can be classified a semidiurnal macrotidal environment (Davies, 1964) with a mean spring range of 4.3m and a mean neap range of 1.7m. Fig 4.9 gives a theoretical range of tidal levels for New Quay. Cardigan Bay forms part of the Irish Sea oscillation and tidal ranges increase eastwards since the streams flowing into the Irish Sea through St. George's Channel are deflected by the earth's rotation. Cotidal lines for the Irish Sea (after Doodson and Corkan, 1931) are shown in Fig 4.10.

Tidal currents, produced by the ebb and flow of tides, decrease towards the Welsh coast and spring rates of about 1 knot prevail near land. Tidal streams run regularly across to New Quay and a tidal stream also runs around the bay but is very weak (Ceredigion District Council Tide Tables, 1984).

4.4.1 Predicted Tides

Predicted tidal heights have been obtained from the Aberystwyth Tide Tables which have been compiled and produced by Ceredigion District Council using Holyhead as the calculating Standard Port.

Tide levels for Holyhead are given in Admiralty Tide Tables which are based on continuous observations of the tide over a period of not less than 3 years, the average changes in mean sea level due to changes in meteorological conditions for that period being calculated and included in the predictions.

Predictions for secondary ports such as Aberystwyth and New Quay and other ports in Cardigan Bay are made by applying time and height differences to predictions at Holyhead which as part of the Irish Sea oscillation has similar tidal characteristics.

Tidal levels given in the Tables are referred to Chart Datum of the largest scale Admiralty Chart No. 1482 for the Cardigan Bay area.

In order to determine the manner in which tidal coverage varies along the coastal cliffs it has been necessary to refer all levels to a common horizontal plane Chart Datum, being dependant on the range of the tide, which varies from place to place and has to be converted to Ordnance Datum, Newlyn.

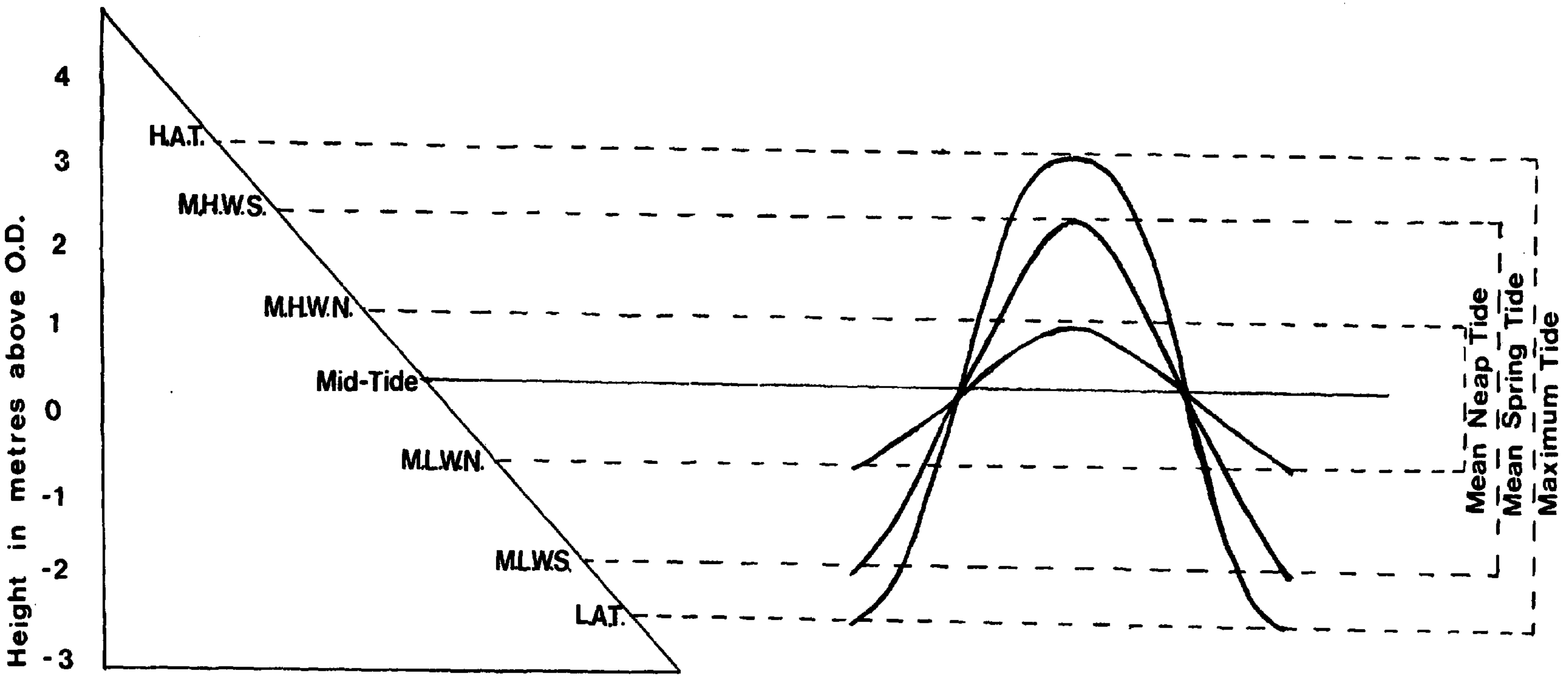


FIG. 4.9 Variation of tidal levels at New Quay (interpolated from standard port of Holyhead)

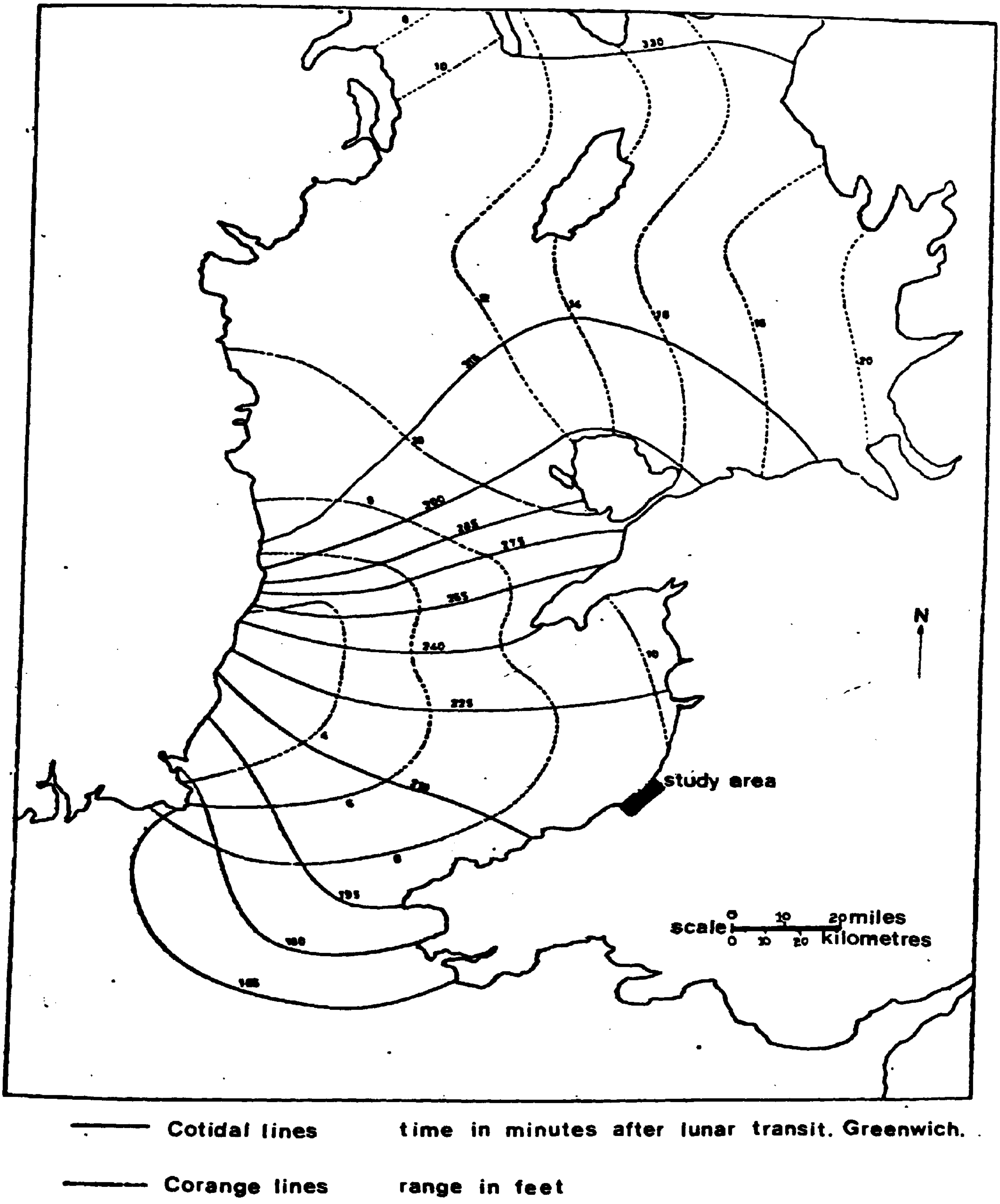


FIG. 4.10 Cotidal lines for the Irish Sea and St. George's Channel (after Doodson and Corkan, 1931)

[Table III, Admiralty Tide Tables, 1983, gives the correction between Chart Datum and Ordnance Datum for the Secondary ports of Aberystwyth and New Quay as + 2.44m].

4.4.2 Actual Tides

Measured levels were obtained from an automatic tide gauge located on the harbour wall at Aberystwyth by the Welsh Water Authority. Recordings, some 700 values in all, were obtained for most of 1980 and for periods in 1982. Fig 4.11 shows a typical tidal-level chart for week 27.10.82 - 3.11.82.

The harbour location may

(i) decrease recorded levels by having a dampening effect on wave action

(ii) increase recorded levels by way of artificial ponding-up of water within a confined space and

(iii) increase levels by flood water from the rivers Rheidol and Ystwyth discharging into the harbour.

However,from discussion with the Harbour master at Aberystwyth and the siting of the gauge on the outer harbour wall, differential effects would appear to be minimal.

The amount of correction for high water at various locations within the study area from the Aberystwyth tidal data is negligible since Llanrhystud at the northern end of the study area is only some 15km S.S.W of Aberystwyth.

From the Tide Tables and the recorded data for Aberystwyth, lists have been compiled showing the deviations between predicted and actual tides. It is seen that high tide is consistently different from the predicted value, the discrepancies in height can be attributed to meteorological conditions.

4.4.3 Meteorological Effects on Tides

As predictions are given for average meteorological conditions it follows that when conditions are not average the actual tides may differ from those predicted. Under extreme conditions these differences can be appreciable.

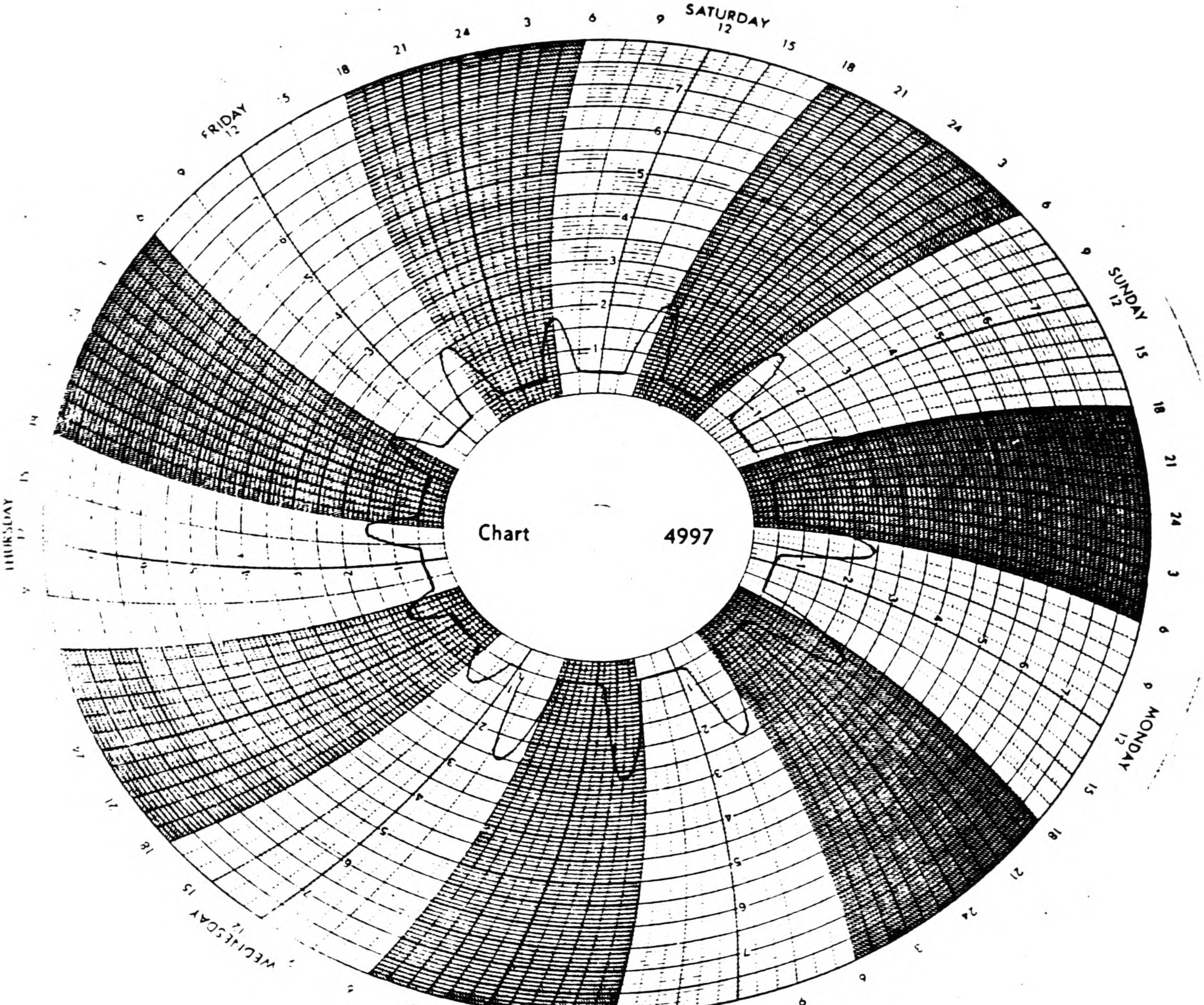


FIG. 4.11 Tidal level chart for period 27.10.82 - 3.11.82 (from Welsh Water Authority automatic tide gauge at Aberystwyth)

Tidal predictions are computed for average barometric pressure. A difference from the average of 45 millibars can cause a difference in height of about 0.3m. A low barameter will tend to raise sea level and a high barameter will tend to depress it. The water level does not, however, adjust itself immediately to a change of pressure and it responds moreover to the average change in pressure over a considerable area. Changes in level due to barometric pressure seldom exceed 0.3m but, when mean sea level is raised or lowered by strong winds or by storm surges, this effect can be important. The converging or diverging of the Irish Sea coastlines may also increase or decrease these variations in sea level.

The effect of wind on sea level and therefore on tidal heights and times is very variable and depends largely on the topography of the area in question. In stating the obvious perhaps, a strong wind blowing straight onshore will pile up the water and cause high waters to be higher than predicted, while winds blowing off the land will have the reverse effect. Seiches and storm surges caused by the passage of an intense depression are very rare in the Irish Sea.

Experience of weather conditions in the area has indicated that strong winds (Beaufort scale 6 or greater) blowing from the south west to north west quadrant,low barometric pressures and, most particularly, depressions approaching the coast rapidly from the west, all contribute to levels in excess of predicted values.

The influence of antededent wind conditions on actual tide levels at Aberystwyth is indicated in Fig 4.12. The choice of meteorological criteria has been discussed in section 4.3.2 and any assessment must be subjective.

The mean hourly wind speed and direction for the previous 24 hours has been calculated and plotted against percentage differences in actual to predicted tide levels.

From Fig 4.12 it is seen that there is generally a wide scatter of results. Winds from the NW and S.E quadrants show no definate pattern with as many actual tide levels above those predicted as there are below. This is perhaps surprising for the onshore winds from the N.W

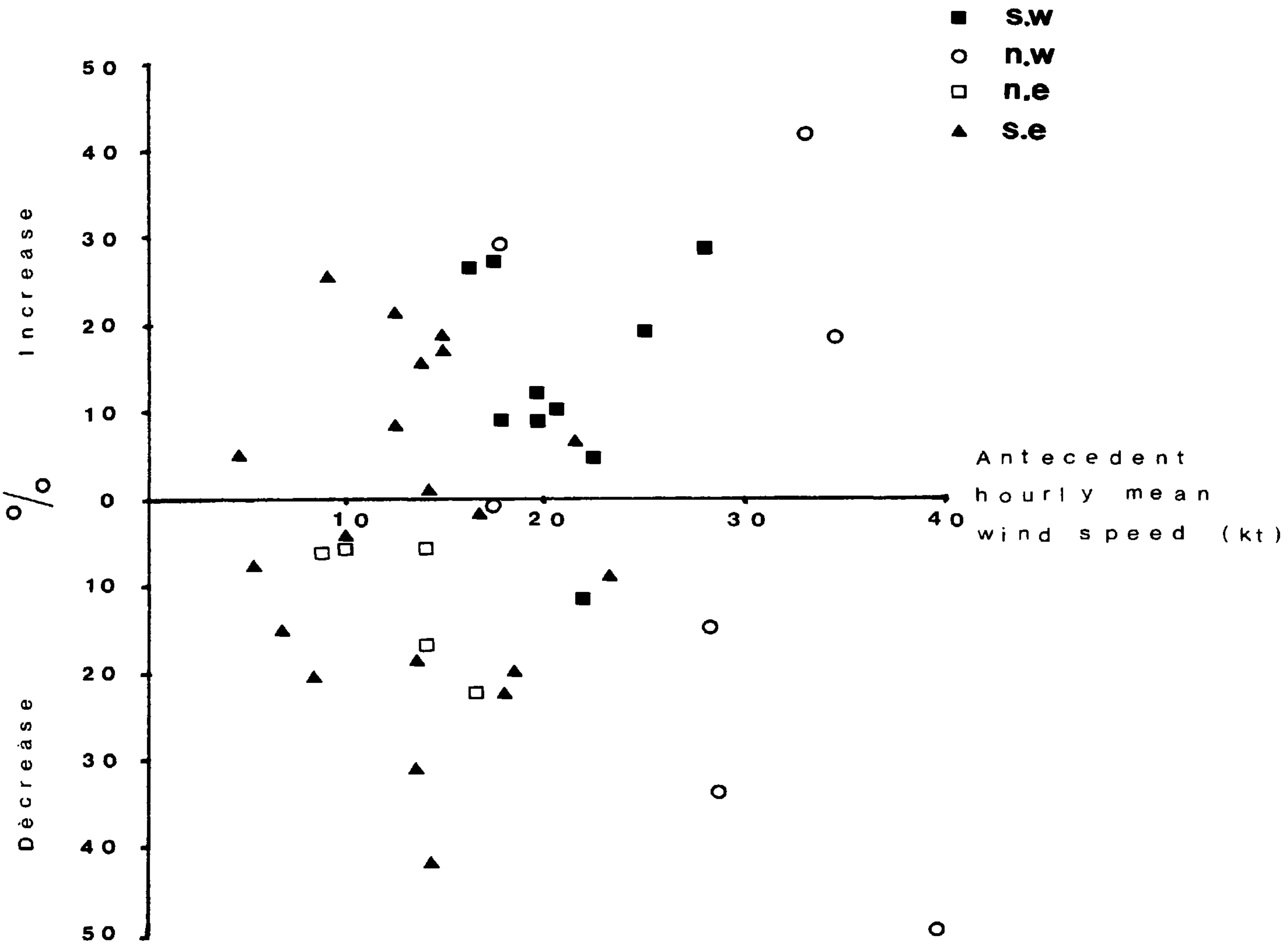


FIG. 4.12 Influence of antecedent wind conditions on actual tide levels in relation to predicted

where a distinct relationship would appear to exist between wind speed and high energy conditions and therefore possible cliff erosion (Table 4.7).

For winds from the other two quadrants there is a suggestion of a linear relationship between wind speed and tidal levels. Increased speeds in onshore winds from the predominant south westerly direction result in a gradual increase in actual tide levels in relation to predicted while north easterly winds show a corresponding decrease.

The role played by waves in pushing tidal levels further up the open beach to a height greater than that recorded by the tidal gauge was investigated by a series of spot levels taken randomly along the coastline. Although there were anomalies there was a general agreement with the Aberystwyth tide gauge in that S.W winds increased and N.E winds decreased the predicted values. It was also evident from these readings that high energy events caused tide levels on open beaches to rise by as much as 150 - 200% above predicted values. Some specific events are discussed below:

3.9.83 Actual high tide of 2.8m A.O.D measured at Llanon showed a 100% increase on the predicted value of 1.4m. Because this was a neap tide, breaking waves still failed to reach the foot of the cliffs and no erosion occurred. Winds for the previous 24 hours were south-westerly gale force, with an hourly mean of 29 knots and gusts of 60 knots, and resulted in an unusually high build-up of seaweed at Llanon (Plate 4.1).

8.10.83 Spring high tide resulted in storm waves breaking on Aberaeron sea wall (Plate 4.2). high tide level on the adjacent south beach was measured at 4.5m A.O.D - a 60% increase on the predicted level. Antecedent winds of Beaufort scale 4 - 5 blowing from 240° did not produce marine attack of the cliff base.

3.1.84 Direct wave attack was observed on the cliffs fronting the caravan site near Llanon during a south-westerly storm (Plate 4.3). High tide level was measured at 5.8m A.O.D - a 160% increase on the predicted value of 2.2m. Winds for the previous 24 hours were south-westerly veering westerly, strong to gale force, locally severe gales.

PLATE 4.1 Build-up of seaweed at Llanon beach (3.9.83)

PLATE 4.2 Storm waves breaking over Aberaeron seawall (8.10.83)

PLATE 4.3 Erosion of cliff base at Llanon (3.1.84)

Although cumulative wave energy, hindcast at 23.8 x 10^5 joules m^{-1} crest width (Table 4.7), made this particular storm event the second highest of the study period, only small individual collapses of cliff material were noted along the section.

27.9.84 The tide of 3.1m A.O.D during the September equinox period was the highest predicted for 19 years. Southerly winds, moderate or fresh but well below gale force, resulted in calm weather conditions at New Quay (Plate 4.4) where actual high tide was measured at 3.8m A.O.D and any erosion was minimal. If wind force had been two or three points higher on the Beaufort scale flooding and erosion could have been extensive.

The foregoing observations further emphasise that marine erosion of the cliffline occurs under a required coincidence of climatic and tidal factors where certain thresholds of tidal level, wind speed, wind direction and storm duration are necessary.

4.4.4 Tidal Coverage

From the predicted and recorded tidal data, tidal coverage of different heights of cliff along the coastline have been calculated and are tabulated in Table 4.9.

While all predicted and recorded tides rise above 0.5m A.O.D, no predicted tide rises above 4.0m A.O.D yet 2.5% of recorded tides do. There are anomalies in the correlation between the two categories of tide but the magnitude and proportion will be correct and they do give an indication of the infrequency with which the tide reaches sections of cliff above 3m A.O.D.

Taking into account the tidal hydrograph in Fig. 4.13 the percentage coverage by tides has been converted into a percentage coverage by time. These duration values - calculated for recorded tides only - are also tabulated in Table 4.9.

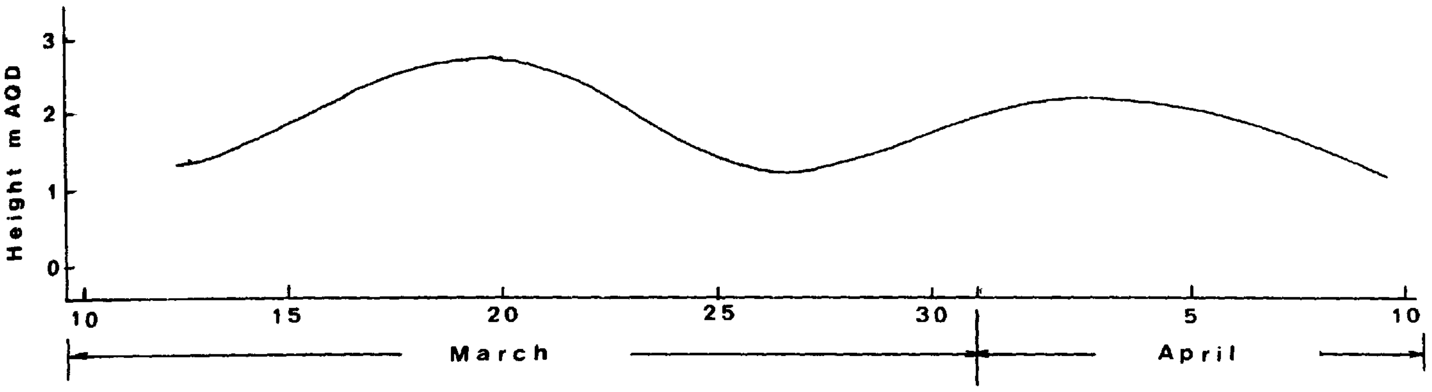
Thus, the areas of beach and cliff at 0m A.O.D are submerged for 52% of the year while those at 3m A.O.D are covered by water for less than 1%. The significance of these figures is that much of the cliffline, even at lower levels, is potentially more subject to sub-aerial rather than marine processes.

PLATE 4.4 Calm conditions at New Quay during highest predicted tide for 19 years (27.9.84)

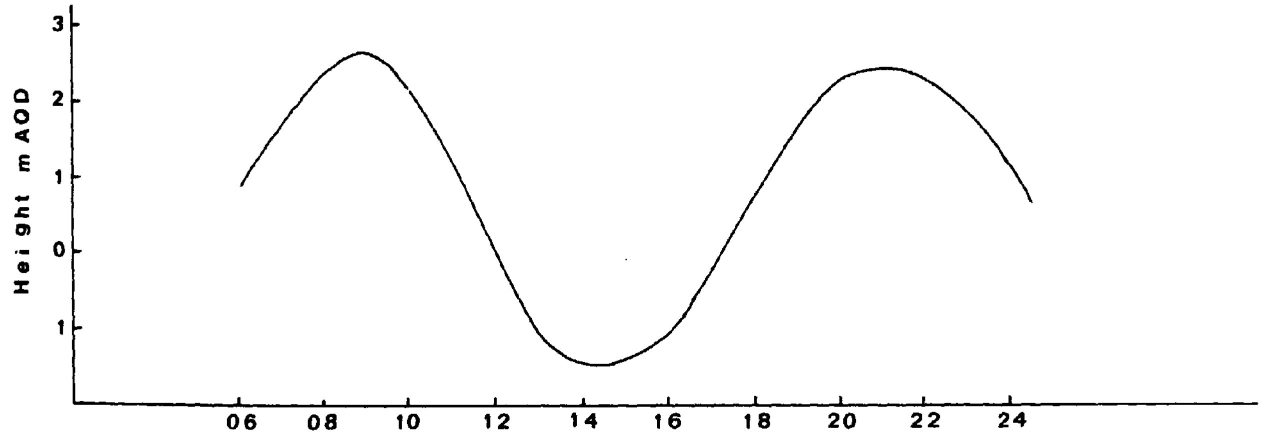
HEIGHT COVERED A.O.D.	PREDICTED TIDES	RECORDED TIDES	DURATION (RECORDED TIDES)
0.0m	100%	100%	52%
0.5	100	100	37
1.0	99	97	21
1.5	76	76	9.5
2.0	40	50	3.9
2.5	14	20	1.7
3.0	1.5	7.4	0.8
3.5	0	-	0.5
4.0	-	2.5	0.3
4.5	-	-	0.2
5.0	-	1.0	0.1
5.5	-	-	0.05
6.0	-	0.5	0.03
6.5	-	-	0.015
7.0	-	0.15	0.006

Sources:- Predicted tides from Admiralty Tide Tables recorded tides from Welsh Water Authority tide recorder at Aberystwyth plus site measurements.

TABLE 4.9 Tidal coverage of different heights



Typical variation in high tide levels over lunar cycle (Mar/Apr.1984)



Tidal hydrograph - Llanon spring tide (7.11.83)

FIG. 4.13

CHAPTER 5.

THEORETICAL PREDICTION OF EROSION ALONG THE CARDIGAN BAY COAST USING COMPUTERISED WAVE REFRACTION TECHNIQUES

5.1 Introduction

The wisdom of using historical analyses, be they by map comparison or wave hindcasting, to project future coastal erosion has been questioned by Hayden (1975). He showed statistically that there are secular changes in world climate which can lead to significant alteration in storm track frequency. Such an alteration in the direction and frequency of storm waves could change the local storm wave climate, when historical methods may give a false indication of future rates of erosion and of traditional areas of shoreline vulnerability.

An alternative method, and the one considered in this chapter, is to use wave refraction techniques to model the response of the coastline to known wave conditions. Any long term variation in wave energy is limited by weighting the model with the occurrence probability of the waves. Such a model can indicate areas of coastline that are vulnerable to higher than normal energy levels (Langfelder et al, 1970; Goldsmith et al, 1974). Since wave action also controls longshore sediment transport (Komar and Inman, 1970),modelling can be used to assess the magnitude of sediment surplus or deficit along the coastline. This in turn can provide an insight into how longshore variations in sediment distribution can control recession rates.

Previous computerised refraction studies have tended to concentrate on large scale, relatively simple shorelines dominated by depositional features. Much work has been done on barrier islands along the exposed east coast of the United States e.g. Stapor (1971) and Goldsmith (1976), while Gulbrandsen (1985) compared the effectiveness of wave refraction technique in predicting erosion for a micro-tidal area such as the Cape Hatteras shoreline (U.S.A) with a micro-tidal area located at Ynyslas Spit near Borth, West Wales.

On a smaller scale, Lowry and Carter's (1982) refraction based study has identified the structure of potential sediment cells in a series of swash refracted bays in south Co. Wexford, while Bowden and Orford's (1984) study of the Ards peninsula in Co. Down, Northern Ireland was the first to use refraction as a means of predicting beach depositional morphology along a crenulated coastline.

Davidson-Arnott and Amin (1983) applied computer modelling of wave refraction and sediment budget techniques to shore erosion problems in S.W. Lake Ontario. Although this work related primarily to problems in the Great Lakes, it should be applicable to all such coasts in rapidly eroding Quaternary sediments.

South Cardigan Bay has an irregular coastline with complicated morphology and embayments formed of such sediments. This chapter deals with a theoretical approach to demarcating longshore residual sediment between New Quay and Llanrhystud, using the wave refraction model of May (1974) and the concept of sediment cell delimitation proposed by the 'abc....' model of May and Tanner (1973).

The spatial position of these cell boundaries dictates the longshore magnitude of beaches (Davies, 1974) and consequently their effectiveness to act as buffers against coastal erosion. The position of such boundaries is identified by means of field surveys and the usefulness of such a theoretical approach is assessed in Chapter 6 by comparing the predicted sediment cell structure with the observed beach morphology.

5.2 Theory of sediment cells and longshore sediment budgets derived by wave refraction

5.2.1 The process of wave refraction

Upon entering shallow water, deepwater waves are subject to the process of refraction, which can cause either a divergence or convergence of the wave energy. Irregular bottom topography can cause waves to be refracted in a complex way and produce variations in the wave height and energy along the coast.

Any offshore or deepwater wave [depth (d) > 0.5 length (l)] with an uniform wave height (H_o) will be spatially altered into a longshore breaker height (H_b). In plan view, progressively shoreward positions of the same relative point on the wave crest trace out a path, known as an orthogonal, which ends at the break-point. Wave energy (E) is proportional to H and given a constant deepwater wave height (H_o) along the wave crest length it can be assumed that the wave energy is constant between equally spaced orthogonal positions.

During refraction the distance between the initially equi-spaced orthogonals becomes non-constant due to the spatial distortion of the wave crest over the variable bathymetry. At the breaker point, assuming that wave energy losses during shoaling have been approximately similar along the wave crest, roughly equal amounts of wave energy are now contained between unequally spaced final orthogonal positions and are expressed in the longshore variation of H_b.

5.2.2 Longshore sediment transport

Although the longshore variation in H_b can be used as a crude index of available energy for understanding variation in coastal morphology, a more productive use of H_b is when it is related to the breaking wave's potential in undertaking work (P) in the form of sediment erosion or transport.

At the breaker point the longshore component of wave power is calculated using the equation

$P_l = (EC_n)_b \sin\alpha_b \quad \cos\alpha_b$ - (Komar 1976)

where P_l = wave energy flux per unit width of wave crest
E = wave energy density
C_n = wave group celerity
α = angle of wave approach to the shoreline
b = denotes breaking condition
and l = denotes a longshore component per unit length of coastline

It has been shown that it is this longshore variation in predicted longshore directed wave power (P_l) and its spatial variability that theoretically correlate most successfully with zones of erosion, transport and deposition in an ideal littoral drift system (Inman and Bagnold, 1963; Tanner 1974a).

5.2.3 Sediment Cells

This system may be divided into a number of littoral drift cells (Inman and Frautschy, 1966; Stapor, 1974) each cell being characterised by an area of net coastal erosion, an area of net coastal deposition and a transport path between them (Tanner, 1974b).

Tanner's 'abc....' model of a simple cell is characterised by five key points designated 'a' through 'e' (Fig 5.1). Certain important parameters vary in a predictable way from point to point. The longshore wave power component P_l is maximum at 'a',decreases steadily in the down-drift direction and is minimum at 'e'. At some position between 'a' and 'e' is an equilibrium position 'c' where the value of P_l is insufficient to maintain the amount of sediment already being transported alongshore.

Two contiguous cells with a common 'a'/'a' boundary result in net erosion and a low beach sediment volume and elevation due to drift moving away from the boundary in both longshore directions; a common 'e'/'e' boundary of two adjacent cells results in net deposition and high beach sediment volume and elevation due to sediment drifting towards the boundary from both directions. An 'a'/'e' boundary between two cells marks the sub-cell boundary within a major drift of constant drift direction and can result in longshore sediment protrusions.

Whilst the concept of sediment cells has existed for some time, computer modelling of such cells from wave refraction is a recent technique which has been used by numerous workers (see literature review).

5.3 Bathymetric and wave climate data used in wave refraction model.

The inner square marked on Fig 5.2 shows the boundary of the bathymetric grid used in the study. This grid extended outside the study area from Aberporth to Aberystwyth and out to a depth of 40m. In theory only waves of period <7s would still be unaffected by such depths but given the shallow submarine shelf of Cardigan Bay, even a grid covering the whole area of the southern Irish Sea would still only partially alleviate this problem.

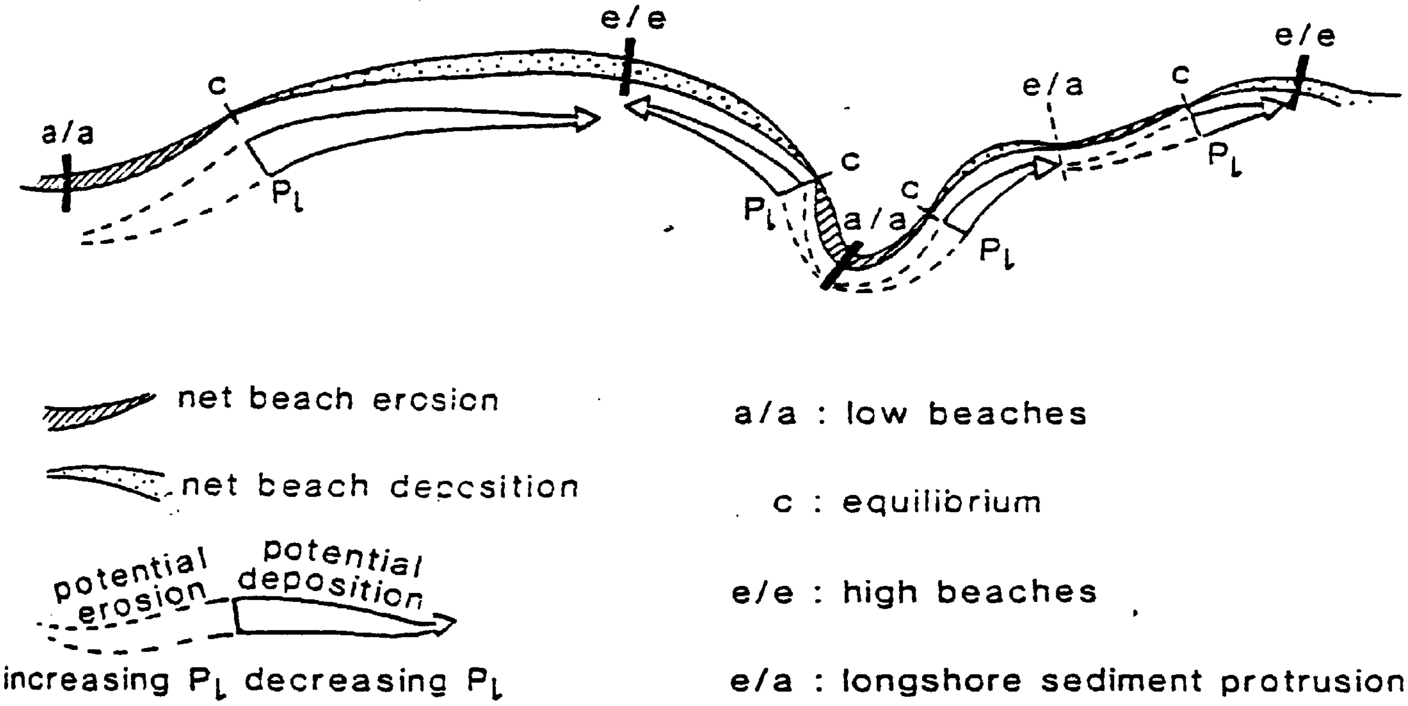


FIG. 5.1 Principal elements of May and Tanner's (1973) 'abc.........' model

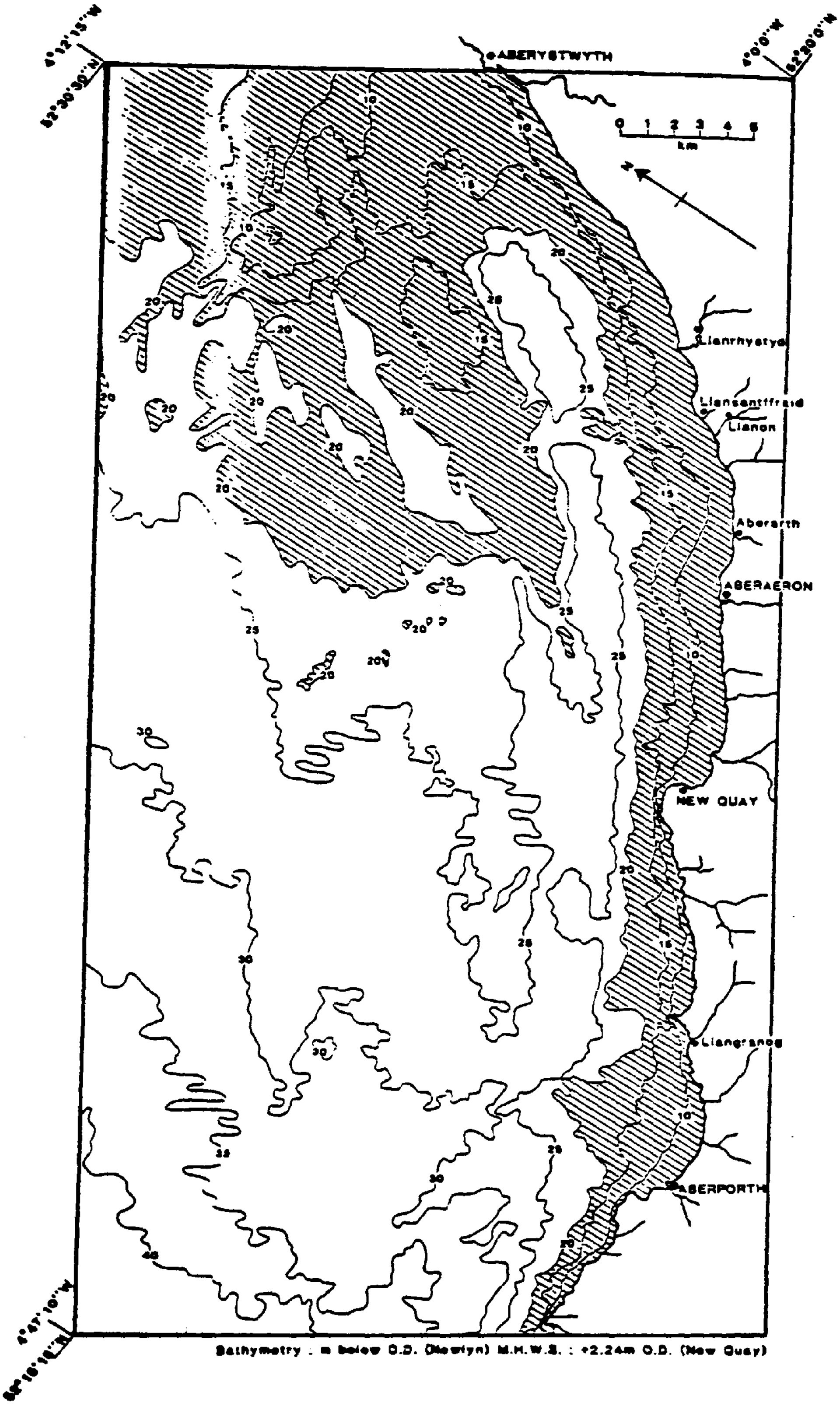


FIG. 5.2 Bathymetry of refraction grid used in the wave refraction model

The rectangular area was subdivided into 130 x 63 equally spaced divisions. Grid spacing interval was approximately 400m and depths were adjusted to a bathymetric datum of mean high water spring tide (MHWS) New Quay.

The most viable source of wave data, and the one used in this study, is given by Hogben and Lumb (1967) from shipbased records. This source includes the required parameter of wave height (H_o) wave period (T) and wave direction (d) necessary for refraction modelling. Table 5.1 shows the recorded H_o and T for the 6 main vectors, from 240° to 030° impinging into the Cardigan Bay coast from a southerly, through a westerly, to a northerly direction.

As the dominance of sediment cells will reflect the duration in any given time unit of the wave conditions which engender them, wave refraction results have to be adjusted by the proportion of occurrence of the given wave conditions. The unit of time selected for this study was a year, so that each value of wave power was multiplied by the proportion of a year that the conditions occurred. For example, a 5 sec wave from 000° N with D = 0.0799319 occurrence would run for 29.175 days in any unit year.

5.4 Wave refraction modelling procedure

The computer programme WAVENRG (May, 1974) was used to simulate wave refraction and to model the potential longshore transport pattern. The programme computes the path of orthogonal wave rays and determines the transformation of wave parameters using linear wave theory as the wave breaks. Orthogonals were generated for each specific wave direction from positions close to the seaward boundary of the bathymetric grid shown in Fig 5.2. The starting positions and orientation were estimated. As slight variations in these starting positions can cause major shifts in termination points onshore Bouws and Battjes (1983) have argued that the wave energy distribution can only be an estimate of reality. They therefore suggest that longshore wave power should be smoothed so that individual peaks of energy can be generalised. Smoothing should only erase local noise elements and not disturb the general pattern of wave energy.

Z	T	H_o	D
030 °N	5	0.79	0.0408163
	6.5	1.12	0.0215419
	8.5	1.50	0.0022675
	10.5	1.50	0.0034013
	12.5	3.25	0.0005668
080 °N	5	0.76	0.0799319
	6.5	1.39	0.0351473
	8.5	1.99	0.0079365
	10.5	1.24	0.0017006
	20.5	0.75	0.0005668
	21.5	0.62	0.0011337
330 °N	5	0.70	0.0697278
	6.5	1.25	0.0362811
	8.5	1.99	0.0124716
	10.5	1.32	0.0034013
	12.5	0.87	0.0005668
	20.5	0.62	0.0011337
	21.5	0.74	0.0017006
300 °N	5	0.81	0.0623582
	6.5	1.27	0.0436507
	8.5	1.60	0.0153061
	10.5	1.24	0.0045351
	12.5	3.74	0.0011337
	14.5	1.74	0.0011337
	21.5	0.70	0.0022675
270 °N	5	0.83	0.0719954
	6.5	1.32	0.0566893
	8.5	2.06	0.0249433
	10.5	2.45	0.0209750
	12.5	1.99	0.0566893
	14.5	4.16	0.0022675
	16.5	5.74	0.0005668
	18.5	1.24	0.0005668
	20.5	0.75	0.0005668
	21.5	0.37	0.0005668
240 °N	5	0.82	0.1145124
	6.5	1.34	0.1150799
	8.5	1.98	0.0640589
	10.5	1.10	0.0340136
	12.5	2.21	0.0232246
	14.5	2.50	0.0090702
	16.5	4.50	0.0022675
	17.5	2.75	0.0005668
	20.5	0.13	0.0005668
	21.5	0.62	0.0011337

Z : wave direction

T : wave period

H_o : Deep water medium wave height

D : Wave direction probability

TABLE 5.1 : Irish sea wave climate (after Hogben and Lumb, 1967)

The computer programme calculates for each orthogonal the x and y co-ordinates at the break point. Breaking is assumed to occur when the ratio of wave height to water depth equals or exceeds 0.78. At this point wave height (H_b), wave power (P_b) and the longshore component of wave power (P_1) are calculated.

To obtain the residual wave power budget values at the shoreline, estimates of wave power for each wave condition were interpolated at regular intervals. A linear function between adjacent shoreline orthogonals was used to establish interpolated values, which were measured at a 0.5 grid spacing interval alongshore (200m). The values of wave power and the longshore component of wave power (the direction of the latter being denoted by '+' or '-' depending on northerly or southerly drift) were computed for each wave run.

A typical graph plot for an 8.5 second wave moving inshore from a 270° (westerly) direction is shown in Fig. 5.3.

The final budget for each interval position was found by summing all of the values at each longshore position, with the net value of longshore power being adjusted for differential drift direction by the change in sign.

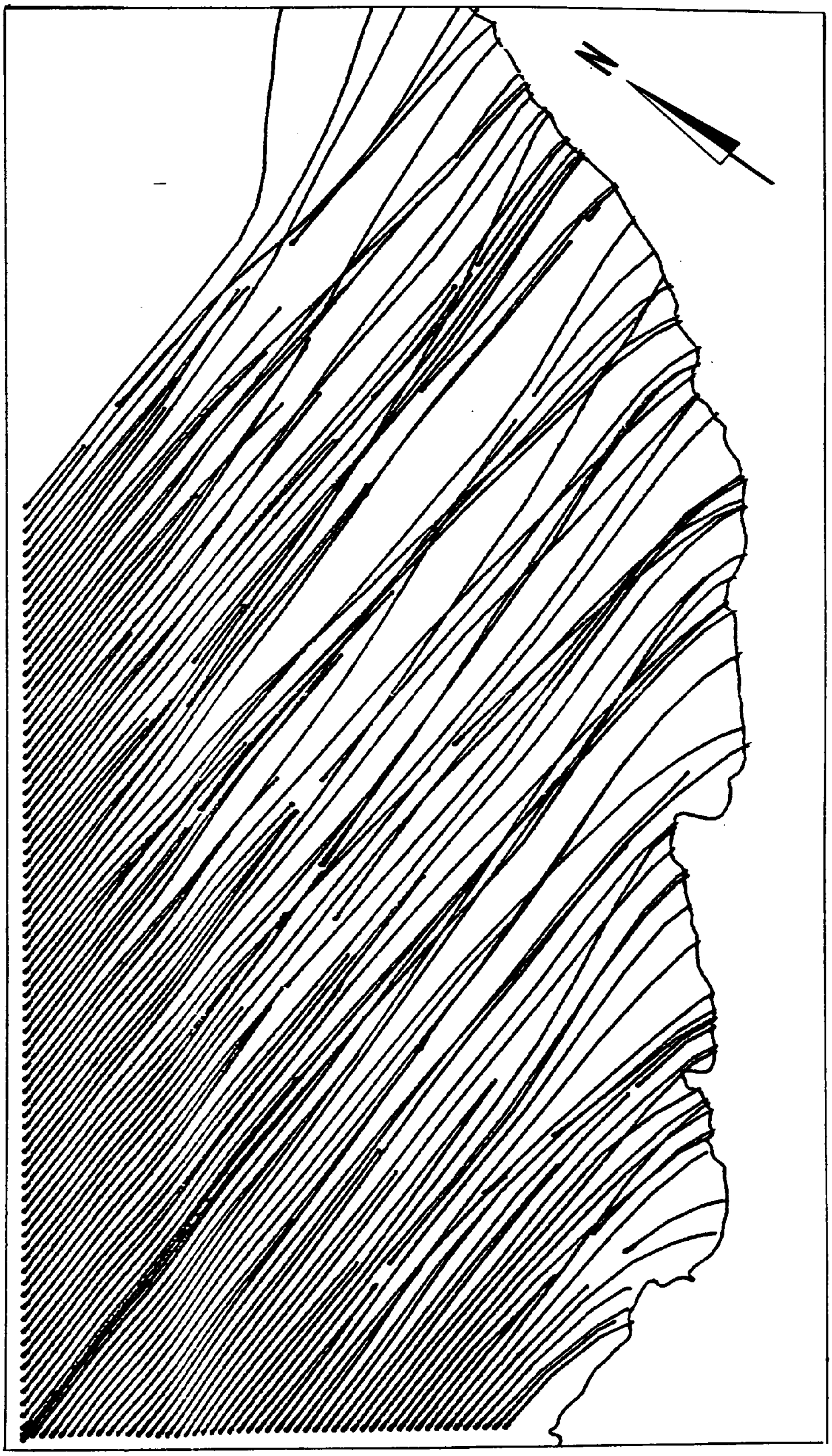
5.5 Model Results

5.5.1 Onshore directed wave power

Fig 5.4 shows the longshore variation in annual total of breaking wave power for each of the 6 wave vectors considered.

In terms of individual wave vectors, the most energetic one is that from the south-west (270°) as would be expected given the St. George's Channel opening to refracted waves from the Atlantic. This vector would also appear to control the overall wave energy along the coastline as highlighted by the pattern of total annual breaking wave power shown in Fig 5.5, where all the vectors have been summed.

A number of distinctive energy provinces occur alongshore. Outside the study area, a low energy zone (4×10^4 mj/m/y) in Aberporth Bay is followed by a high energy zone (12×10^4 mj/m/y) from Llangrannog to New Quay headland. New Quay to Llanrhystud is another low energy



270° N H = 2.06m T = 8.5s

FIG. 5.3 Graph plot for 8.5 second wave moving inshore from a westerly (270°) direction

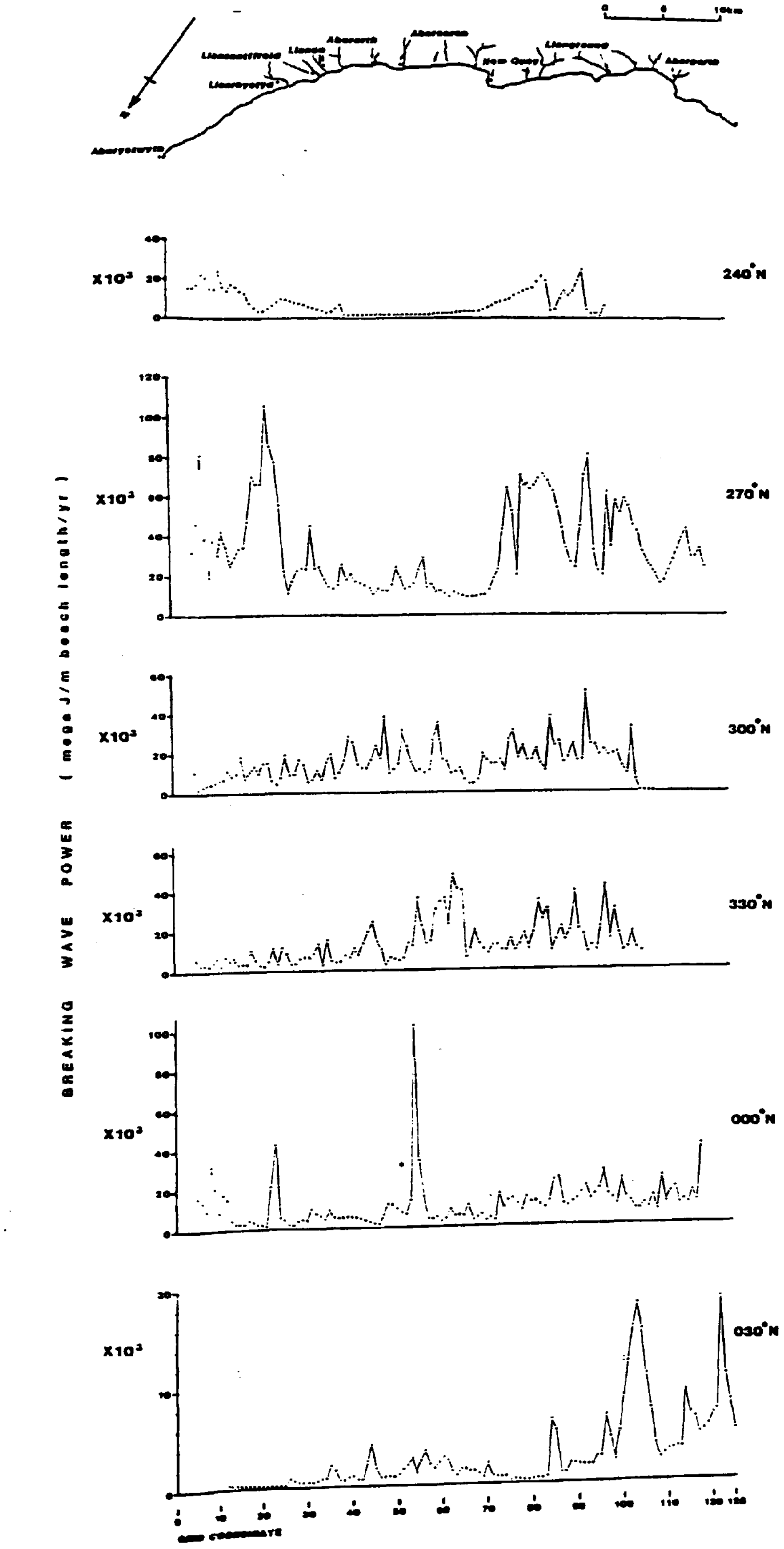


FIG. 5.4 Longshore variation in annual total of breaking wave power, by wave direction

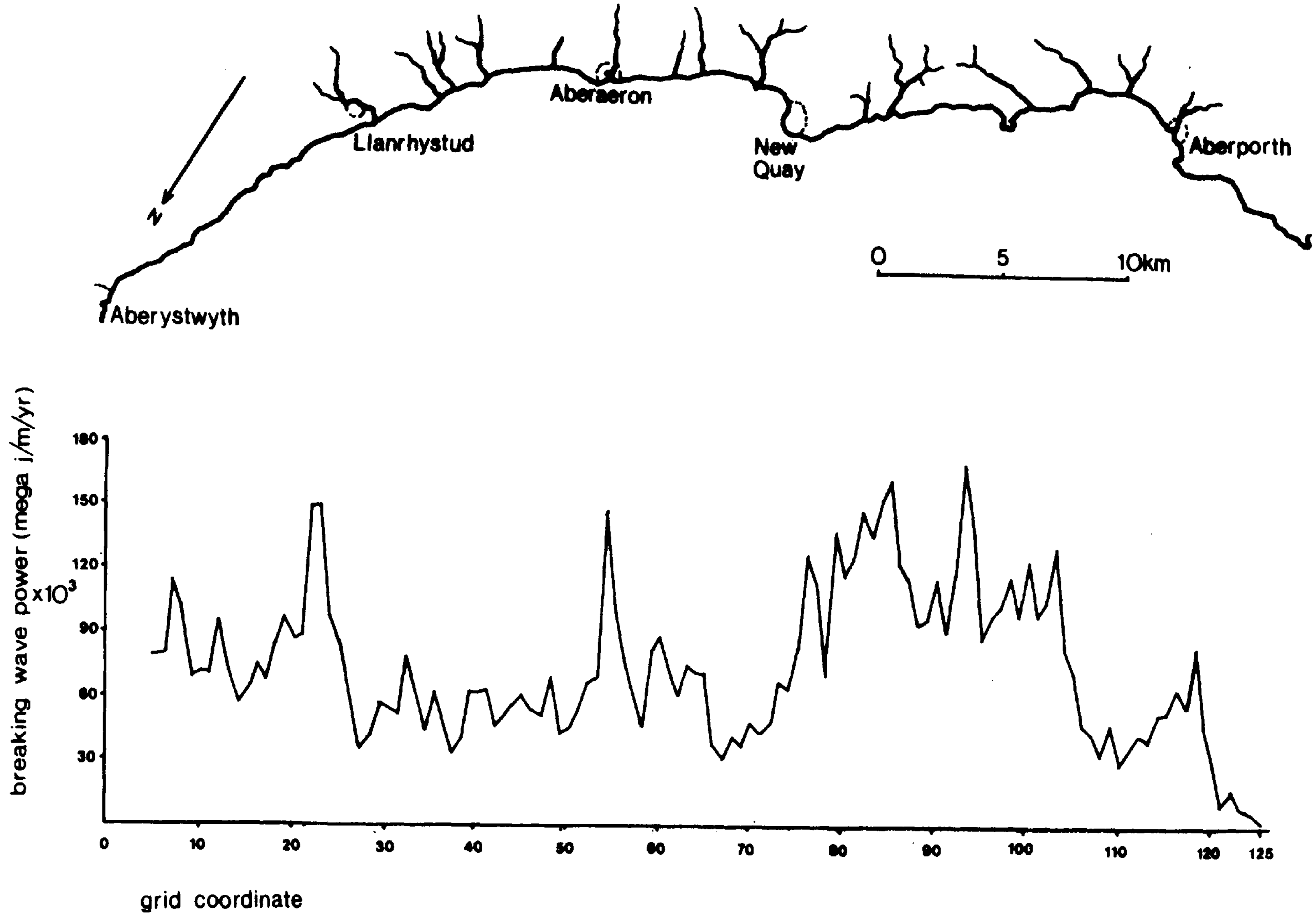


Figure 5.5 Longshore variation in total annual breaking wave power.

zone (5×10^4 mj/m/y), of which two-thirds can be attributed to northerly (000°) waves. North of Llanrhystud, average wave energy increases (9×10^4 mj/m/y) though not to the level achieved south of New Quay.

5.5.2 Implications of variation in onshore wave energy on recession rates

On relatively simple shorelines showing uniformity of cliff height and stratigraphy, rates of erosion would be expected to reflect variations in incident wave energy. Although Cardigan Bay has an irregular coastline with varying topography there should be some correlation between the measured recession rates (Chapter 3) and the longshore distribution of total P_b values (Fig 5.6).

In terms of the overall wave energy grid from Aberystwyth to Aberporth the P_b values within the study area are comparatively low. However, with this low energy regime there are intermittent high peaks and comparisons can be made of the effect of these onshore.

The suggested high recession along Llanrhystud beach corresponds to an intermediate peak of energy while the considerable erosion evident in the till material between Llansantffraid and Morfa corresponds to relatively low P_b values. South of Morfa high peaks of recession in mixed stratigraphy relate to high intermediate peaks of energy.

For similar values of wave power, erosion in the boulder clay cliffs immediately north of Aberarth is on average twice that in the more resistant Aberystwyth Grits further north. South of Aberarth high erosion rates indicated in the low-lying tills again correspond to lower P_b values.

At Aberaeron, any possible erosion represented by the high peak of total wave power is masked by the presence of extensive coastal protection works. Along the cliffs of Aberystwyth Grits south of Aberaeron marginally higher P_b values relate to generally lower rates of erosion in the more resistant gritstone.

At Ceibach and New Quay bays any relationship is confused and although there is a gradual increase in breaking wave power between

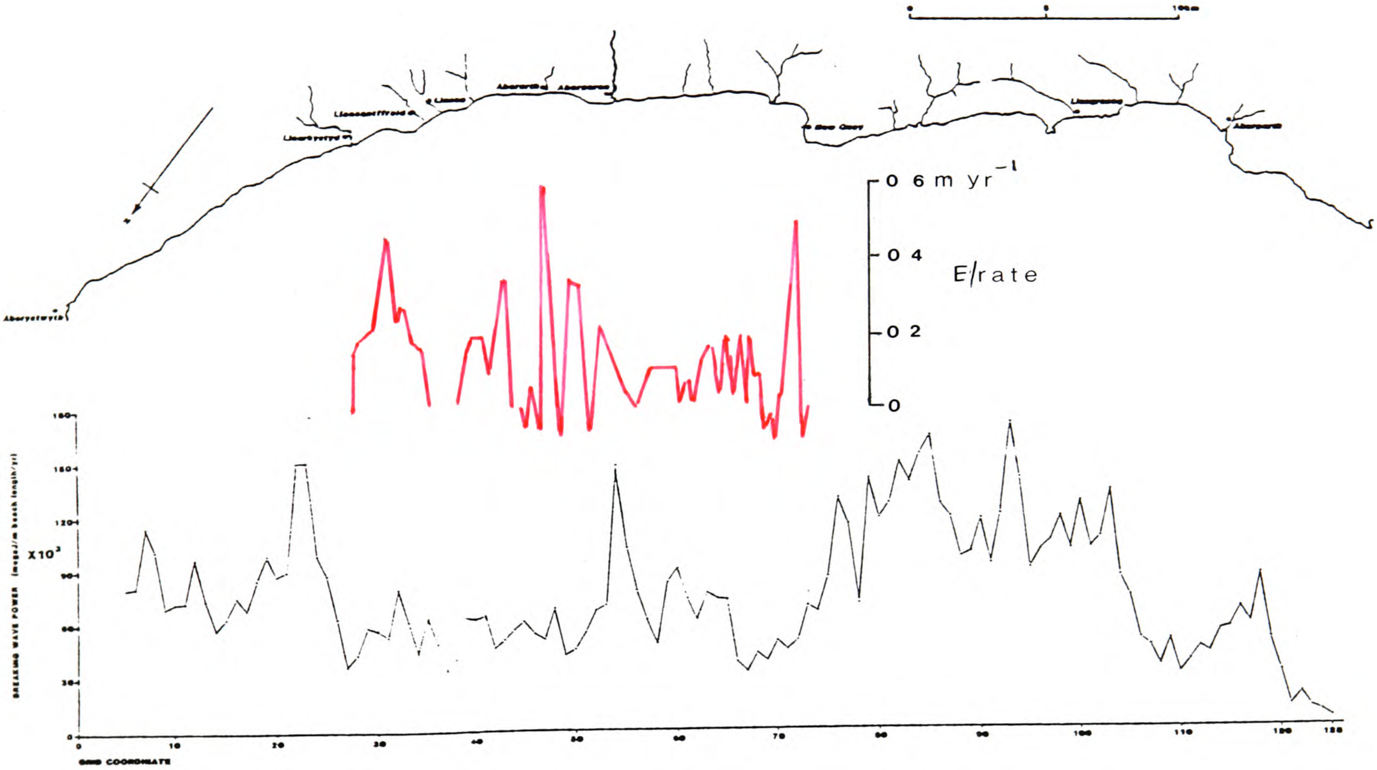


FIG. 5.6 Correlation between measured recession rate and longshore distribution of wave power

Cei Bach and New Quay, it does not explain the massive erosion in the cliffs of boulder clay at New Quay itself where, as at Aberarth, subaerial erosion must be a significant factor and will be considered separately in Chapter 9.

Any agreement between wave energy and recession rates within the study area is very tenuous and there are obviously numerous other controlling factors. At times there would appear to be an inverse relationship between the two. A more logical view, however, is that the weaker Quaternary sediments do not necessarily need the same breaking wave energy to effect the same erosion rates. The role of the inherent geotechnical properties of the cliff material in terms of degree of 'erodibility' will be considered in a later chapter.

Quigley and Zeman (1980) attributed a similar poor correlation with bluff recession in Lake Erie to variations in bluff stratigraphy, erodibility and height, and to the effects of man-made structures. Davidson- Arnott (1984),using a sediment budget approach, found the same lack of agreement between rates of toe erosion and magnitude of incident wave energy for relatively weak Quaternary tills along Lake Ontario.

A factor of major significance in this poor relationship between wave power and rates of recession, although few have recognised it as such, is the protection offered by beach sediments which in turn reflect the variations in longshore sediment transport. It seems likely that comparatively small changes in the volume of beach sediments can influence the rates of cliff erosion and this aspect will be considered in Chapter 6.

5.5.3 Residual cell structure

Fig 5.7 shows the longshore component of wave power translated into a sediment volume using the CERC (1976) transport rate equation

$S_l = 0.32283P_l$

where S_l is the sediment transport rate, (m^3 beach volume/m beach width/day) and P_l is the longshore wave power (j/m/s).

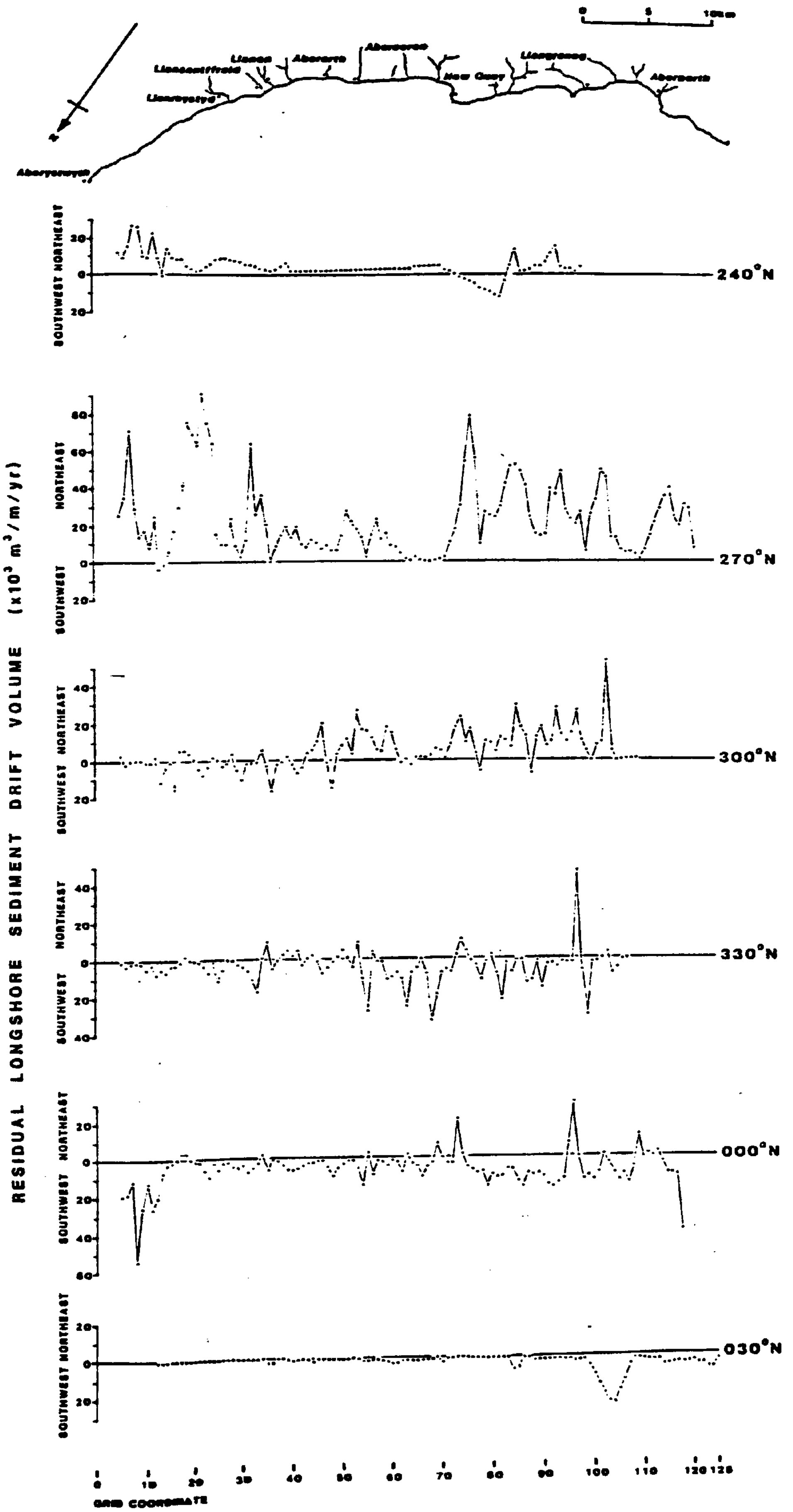


FIG. 5.7 Variation in annual residual longshore sediment drift volume by wave direction for the south Cardigan Bay coast

The constant is based on several assumptions related to sediment density, sediment packing and transport efficiency and is thought to be more realistic than Komar's (1976) figure of 6.85 following the work of Inman and Bagnold (1963).

Each wave vector's contribution to longshore sediment transport is shown with drift direction (Northeast/southwest) indicated. The largest volumes of potential sediment transport relate to the southwest wave vector (270^{O}N) and dominate all the other vector's transport volumes. There is consistent drift direction with strong obliquely impinging waves (north/south) such that the frequency of littoral drift reversals is maximised with westerly or onshore vectors. In general littoral drift is predominantly northeast.

Fig 5.8 shows the summed longshore transported sediment volumes in the time unit of one year together with the resultant sediment cell structures from these values (this data is smoothed during a three-term unweighted moving average).

Positive first differences on the model indicate the potential for increasing longshore erosion and transport capacity, while negative first difference values show a decreasing transport potential and hence sediment deposition. The status of cell boundaries i.e. 'a'/'a', 'e'/'e', 'a'/'e' and intercell zones of erosion and deposition are also shown on the figure. The coastal strip map at the top of Fig 5.8 show the spatial extent of longshore cell sediment deposition plus appropriate drift direction.

5.6 Discussion

The model reveals a number of distinctive features within the sediment dispersal system. Although the area of interest is principally between Llanrhystud and New Quay, the size of the final grid (Fig 5.2) has enabled a 50km length of shoreline to be considered from 1km south of Aberystywth to 4km south of Aberporth. There are 30 distinct cells within this larger area with a mean longshore length of 1.5km. Within the study area there are 15 distinct cells numbered 15 to 29 inclusive running from south to north, most of which indicate separate zones of deposition and erosion (Figs 5.9a-c).

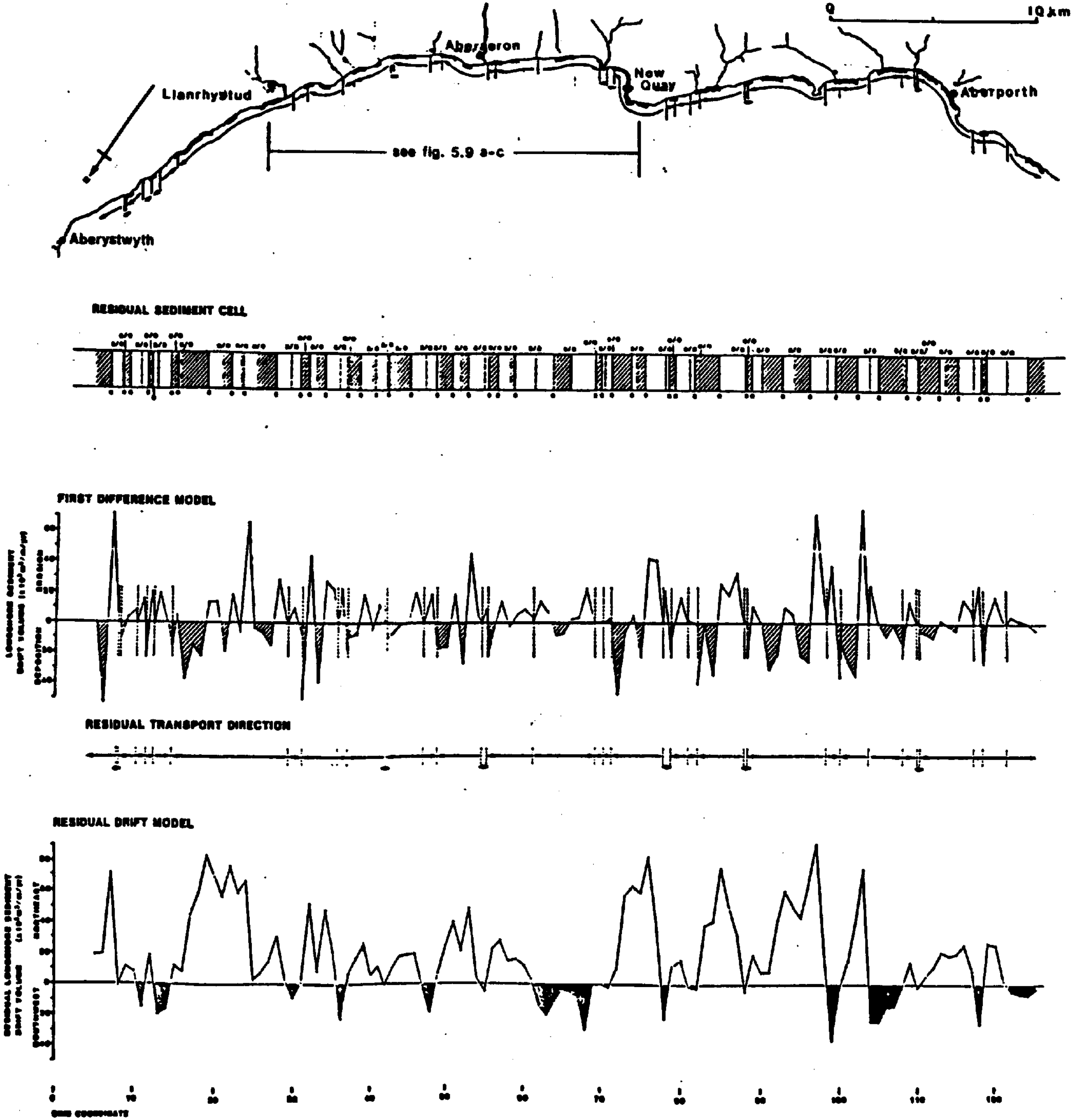


FIG. 5.8 Smoothed residual sediment cell structure for the south Cardigan Bay coast

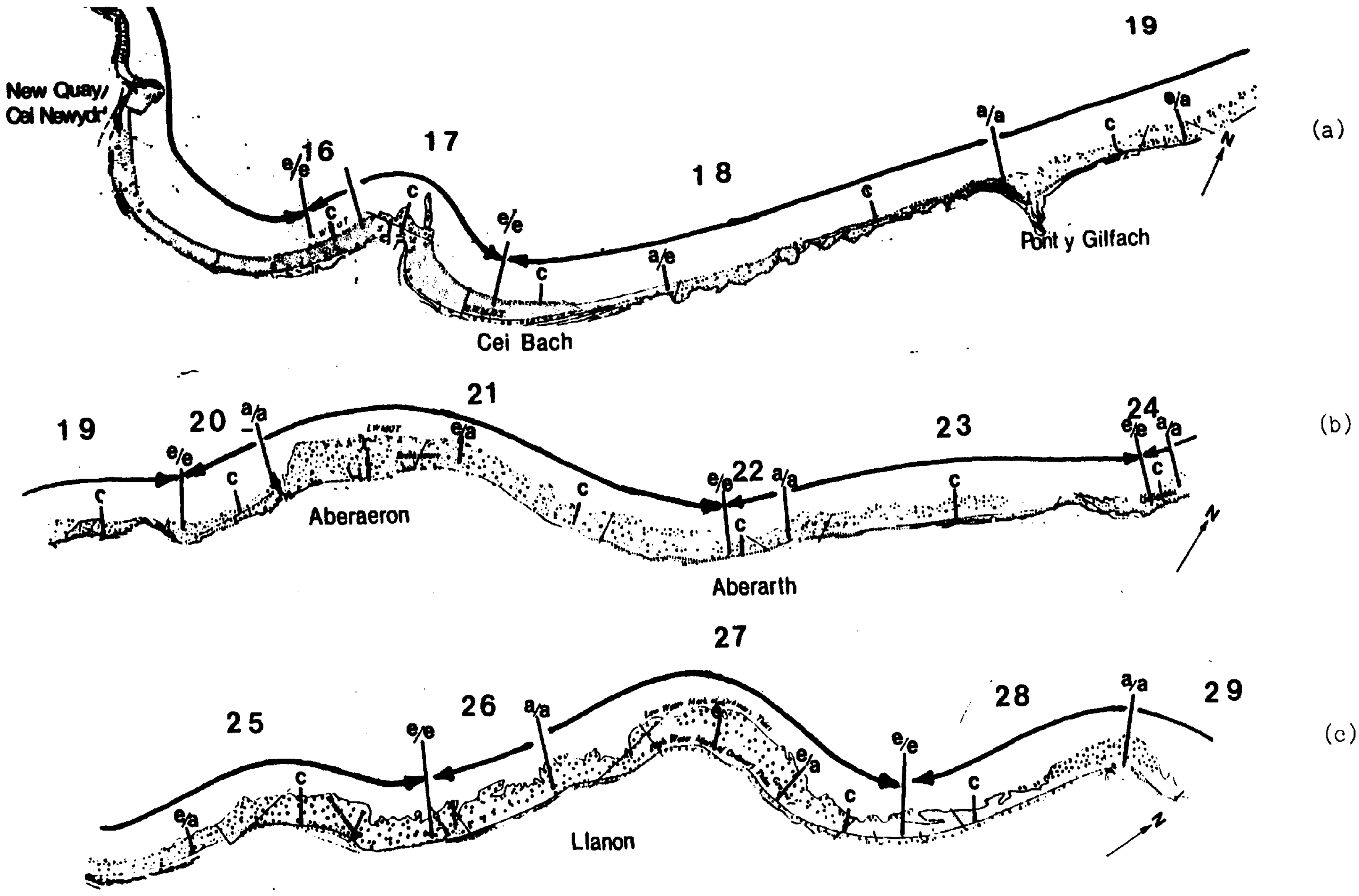


FIG. 5.9a-c Position of sediment cells alongshore (15-29)

The majority of these cells show a north-easterly residual drift direction, the ones showing a south-westerly direction tending to be smaller in length than the northerly ones (generally$<$0.4km) and identified by a single transport value. Numerous cells combine to form higher order cells. There are four such cells between New Quay headland and Carreg-ti-pw, north of Llanrhystud, which comprise some 80% of the coastline, three of which show a progressive north-easterly transport of material (Fig.5.8).

Figs 5.9 a-c identify the position of sediment cells alongshore on a larger scale 1:17,500 scale map of the coastal strip. Cell 15 is the largest single cell and extends some 3km from south of New Quay around the headland to the easterly end of New Quay Bay. Several distinctive zones of net erosion and net deposition are shown within the cell which shows a northerly longshore sediment drift resulting in a potentially high depositional zone along New Quay Bay building up to a 'high' beach at Llanina Point. Cell 17, like 16, shows single distinctive zones of net erosion and deposition within the cell operating in the same northerly drift direction, resulting in a theoretically 'low' beach immediately south of Llanina and a 'high' beach half way along Cei Bach bay (Fig.5.9a). Cell 18 is the largest cell showing a southerly drift of sediment from Gilfach-yr-Halen where there is a potential low beach backed by high cliffs of the Aberystwyth Grits (Fig. 5.9a). A potential erosion zone south of Gilfach is followed by a depositional zone and a sediment bulge (a/e point) near Graig Ddu.

Northwards from Gilfach, cell 19 indicates alternate zones of erosion and depostition with a northerly transport of material resulting in a depositional site and 'high' beach at Aberaeron south. The model identifies a potential erosion stress point at the harbour mouth at Aberaeron with zones of erosion both south (cell 20) and north (cell 21). The littoral drift system in this locality is obviously influenced by man-made protective structures which front the town of Aberaeron for some 1km.

Cell 21 again shows northerly drift of material and a 'high' beach south of Aberarth where it coincides with a southerly drift of material from cell 22. A potential low point at the boundary of cells 22 and 23 coincides with the mouth of the river Arth while cell 23 has a zone of potential erosion followed by one of deposition which extends along a 2km length of high cliffs of the Aberystywth Grits between Aberarth and Morfa.

The size of cell 24 (0.2km) near Graig Ddu again questions its validity and the delimitation of a 'high' and 'low' beach within 200m of one another becomes problematic. Cell 25, which covers the beach around Morfa Farm headland, shows alternate zones of erosion and deposition with an overall northerly sediment drift resulting in a potential 'high' beach at the boundary of cells 25 and 26 which is directly opposite the mouth of the river Clydan. Cell 26 suggests southerly drift of material for 800m from the boundary with cell 27 at the mouth of the river Peris and a theoretical 'low' beach.

Cell 27 extends for some 3km around Llansantffraid headland and shows several sub-zones of erosion and deposition but a net northerly drift of material leading to net deposition and a high beach sediment volume at Llanrhystud storm beach. Net southerly drift is indicated in cell 28 from a potential 'low' beach at the mouth of the river Wyre and net northerly drift in cell 29 which has the maximum longshore transport value of the 15 cells within the study area and extends some 6km northwards from Llanrhystud past the rocky buttress of Carreg-ti-pw towards Morfa Bychan.

5.7 Limitations of model and possible qualifications for its usefulness

There are numerous potential errors inherent in the modelling of such a littoral drift system. The imperfections of the model and the limitations of the theoretical base and interpretation have been discussed in detail by Greenwood and McGillivray (1978). It is sufficient here to list the problems associated with the model in terms of this study.

All refraction programmes are dependant on the quality of the two major sets of input data - bathymetric and wave climate. The lack of British Admiralty charts for Cardigan Bay at scales larger than 1:75,000 means that the grid spacing and therefore the positioning of wave orthogonals may lack sensitivity.

LOW BEACHES ('a'/'a')	chng.	HIGH BEACHES ('e'/'e')	chng.
		New Quay	178
		Cei Bach	166
Gilfach-yr-halen	138		
		Aberaeron (S) beach	116
Aberaeron Harbour Mouth	113		
		Aberarth (S)	89
Aberarth (N)	83		
		Graig-Ddu	63
Morfa Mawr	61		
		Llanon	43
Llansantffraid	36		
		Llanrhystud Storm Beach	14
Morfa Headland	4		

TABLE 5. 2. Predicted longshore position of sediment cell boundaries (chainages given in Figs. 6.2a-g)

Hogben and Lumb's (1967) wave climate data has been criticised by Hansom (1983) for being non-representative of the area as the data comes only from shipping routes in the Irish Sea. Also not taken into consideration are extreme storm events operating in Cardigan Bay which may induce more persistant sedimentation patterns (Bowden and Orford, 1982), although such low frequency occurrences should scarcely affect the distribution of H_o and T in Section 5.3.

The problem of wave energy diffraction and the influence of tidal currents on longshore transport have been ignored although the effect of the latter is thought to be minimal and only affects the sand size sediments.

Because the constant K was unknown for the area the selection of a suitable value in the conversion of P_1 values to actual potential sediment transport was problematic. The value of K must be considered as a constant applicable only to the particular stretch of coastline under consideration and probably reflects the influence of factors such as beach slope, breaker type and sediment size (e.g. Kamphuis and Sayo, 1982; Bruno et al, 1980).

The original cell delimitation for the Cardigan Bay coast made use of Komar's (1971,1976) figure of 6.85, based on the work of Inman and Bagnold (1963). However, sediment volumes by this method were seen to be major overestimates when Canadian studies of high ($>30^m$) unconsolidated cliffs dominated by obliquely impinging waves could only generate total drift volumes of half this amount. (Davidson-Arnott and Amin, 1983). Intuitive use of CERC's (1976) figure of 0.32283 produced a more realistic estimate.

In practical terms, there are limitations to the accuracy of the results presented in this Chapter. For instance, on such a macro-longshore model, the accuracy of the positions of peaks of wave energy projected onshore as potential stress points may be questionable, as will the location of the sediment cell boundaries. Also unknown is how the actual supply and movement of longshore sediment proposed by the model is being affected by coast protection measures, notably the large number of groynes in existence.

By definition any modelling procedure involves abstraction and simplification of the real world state, in this case the sediment budget. It is reasonable to suppose that, as in most sediment budget studies, the actual input data may be order of magnitude estimates. However, it will not alter the overall pattern and,in the context of this study,trends are at least as important as absolute values.

CHAPTER 6.

BEACH MORPHOLOGY

6.1. Introduction

"The beach profile is important in that it can be viewed as an effective natural mechanism which causes waves to break and dissipate their energy. The beach serves as a buffer, protecting sea cliffs and coastal property from the intense wave action" (Komar, 1976, p288).

It follows that if there is a long-term loss of beach material it will increasingly reduce the beach's capability as a buffer and coastal erosion will become progressively more probable. The presence of shingle beaches acting as a buffer against cliff erosion has long been considered as a vital element in coastal stability (Owens and Case, 1908) and the distribution and size of such beaches along the Cardigan Bay coastline may be a major contributing factor to the spatial variability of cliff erosion.

Beaches respond to tide and wave action and a few basic relationships have been established such that exists between wave type and beach gradient e.g Shepard and LaFond (1940), Shepard (1950) and Bascom (1954), and more recently the association between breaker type and beach gradient (Wright et al., 1979,1982).

The profile or cross-section at any time is determined largely by antecendent wave conditions. Low-energy swell waves during "summer periods" build up the berm and beach face forming a steep profile while during "winter periods" high steep waves are normally destructive, eroding the beach face and transporting material seaward. Destructive waves are normally associated with storms and high wind velocities - strong onshore winds generate steep seas as well as raising the tide level above its normal predicted height.

During winter months a rapid succession of storms can result in considerable material being shifted offshore and acute erosion. Where storms are separated by quieter periods the protective berm may not be entirely removed and erosion is minimal. Not only the severity but the succession of storms is therefore important.

The annual change in beach profile is commonly referred to as the winter and summer profile. This terminology, however, is sometimes misleading as seasonal connotations are not always correct and preference is given here to the descriptive terms storm and swell profile.

In addition to onshore-offshore shifts of material,variations in the longshore direction must be considered and the problem of monitoring beach profiles becomes a three-dimensional one.

In the present study a comprehensive field survey was undertaken. The purpose of this survey was 2-fold in that it attempted to identify

(i) by beach profiling and associated sediment sampling, any long-term changes in longshore beach sediments as well as short-term fluctuations which reflect offshore-onshore transport of material

(ii) the presence of high and low beaches, these being the boundaries of sediment cells theoretically predicted by the wave refraction model and listed in Table 5.2 .

6.2 Beach nomenclature

A beach in profile can be defined as the dynamic zone over which sediments may be moved by waves. Komar (1976) used the term littoral to denote this zone and considered it to extend from the upper limit of wave action to water depths of some 10 to 20 metres at low tide.

A more simplistic definition by King (1972) confined the beach to that zone from the upper limit of wave action to low water of spring tides. Although perhaps not as precise a morphological definition it does describe that portion of beach that can be seen and physically measured most easily.

Along most of this section of coastline within the study area, the upper limit of wave action coincides, or nearly coincides,with the base of the cliffs. The beach therefore is easily defined as the area between the base of the cliffs and mean low water mark. Where an area of storm beach intervenes between the high-water mark and the coastline itself then the precise limits of the beach system become more uncertain.

As no standard set of terms exists for describing beach profile features, Fig 6.1 illustrates the terminology used and the variables measured along the beach profile.

The backshore is the zone of the profile extending landward from the top of the beach face to a change in physiography - usually sea cliff or clay slope.

The foreshore is the sloping portion of the beach profile lying between high and low water mark. This term is often synonymous with the beach face but in terms of this particular study is inclusive also of some of the flat portion of the beach profile below the beach face. The foreshore is therefore divided into the UPPER foreshore (steeper section) and LOWER foreshore (flat section), the line of demarcation between them being a sudden change in angle producing a significant 'kink' in the beach profile.

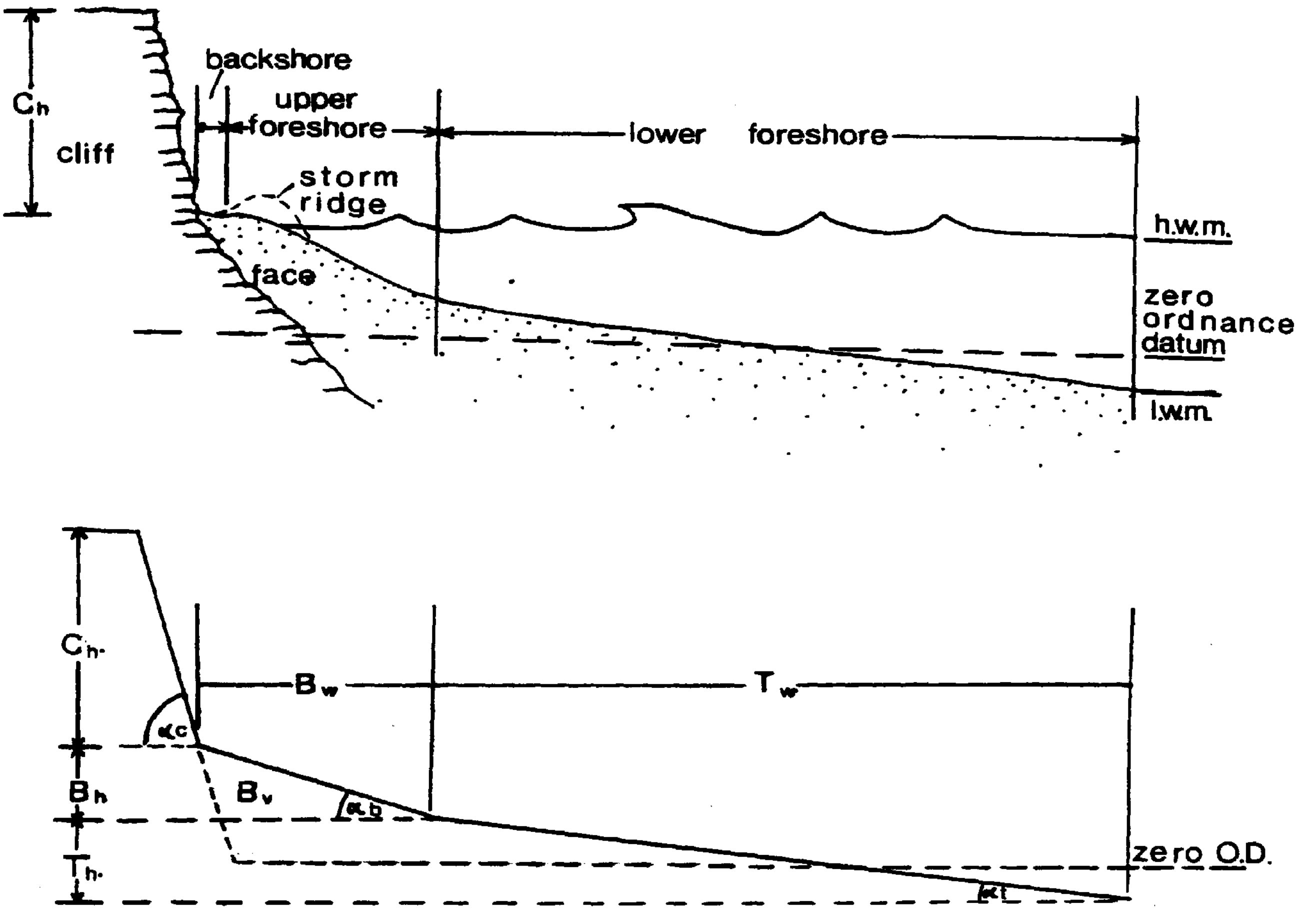
6.3 Beach monitoring - methodology

Beach monitoring has become a very sophisticated technique. Modern methods for monitoring beach movement include photo-radiation (Collins and Madge, 1981) and the use of routine stereoscopic survey and photogrammetric levelling techniques incorporated into computerised systems (Foxley and Shave, 1983).

Any analysis of changes in beach morphology requires repeated sampling in space and time. Initially a survey method had to be chosen with the capability of surveying some 20km of foreshore within a relatively short period of time and within necessary cost limits. Aerial surveys were cost-prohibitive while maps and charts gave only limited information (see Chapter 3).

It was decided at the outset that the only feasible means was the well-tried method of ground surveys by engineering level and staff. For surveys on beaches which were inaccessible or where access was dangerous limited use was made of an amphibious DUKW.

These ground surveys were supplemented by aerial photographs taken from a Cessna light aircraft flying out of Cardiff Airport in July 1983 and again in April 1986. These sorties were carried out at low spring tides at times of the year when average conditions were most likely to



C_h	cliff height
αc	cliff slope
B_h	beach face height
B_w	beach face width
αb	beach face slope
B_v	beach face volume
B_h	beach terrace height
B_w	beach terrace width
αt	beach terrace slope

FIG. 6.1 Schematic diagrams showing nomenclature used to describe beach profiles

exist. However, these aerial surveys could not be used to interpret beach volumes as there was no data base from which comparisons could be made.

For the ground surveys, automatic precision levels (Zeiss model NI-050 and Pentax model PAL-5C),levelling staffs and Fibron tapes were used. The attainable accuracy for these instruments was ± 5.0mm and ± 2.00mm respectively in 1km of double run levelling.

Bench marks at frequent intervals along the coastline were located from National Grid Ten Metre References given in Ordnance Survey Bench Mark lists. Because some of these bench marks were no longer existing or were sited several kilometres inland, a system of temporary bench marks (T.B.M's) was established. The coastline was divided into several zones, the position of the T.B.M's within these zones being largely defined by ease of access and natural features such as headlands or river mouths.

Terminology is that in common use in surveying. Heights above sea level are shown as m A.O.D (metres above Ordnance Datum). Positions alongshore every 100m were set out by tape and ranging rods and are referred to as chainage points. Intervening points between stations are shown to the nearest metre e.g ch. 34 + 75 refers to a point 75m from station 34, 3475m from the starting point. All these chainage points are shown in Figs 6.2a-g and reference is made to them in the following text.

Chainages run from north to south and contrast with the south to north order of sediment cells discussed in section 5.6 and to the assessment of long-term recession made in section 3.7.

The decision to establish the start point at Llanrhystud north beach and to run increasing chainage from north to south was necessary partly because of the availability of bench mark data and partly because the decision to extend the survey south of Aberaeron was only taken some 12 months into the project.

6.3.1 Longshore survey of beach morphology

The longshore survey involved establishing beach profile stations

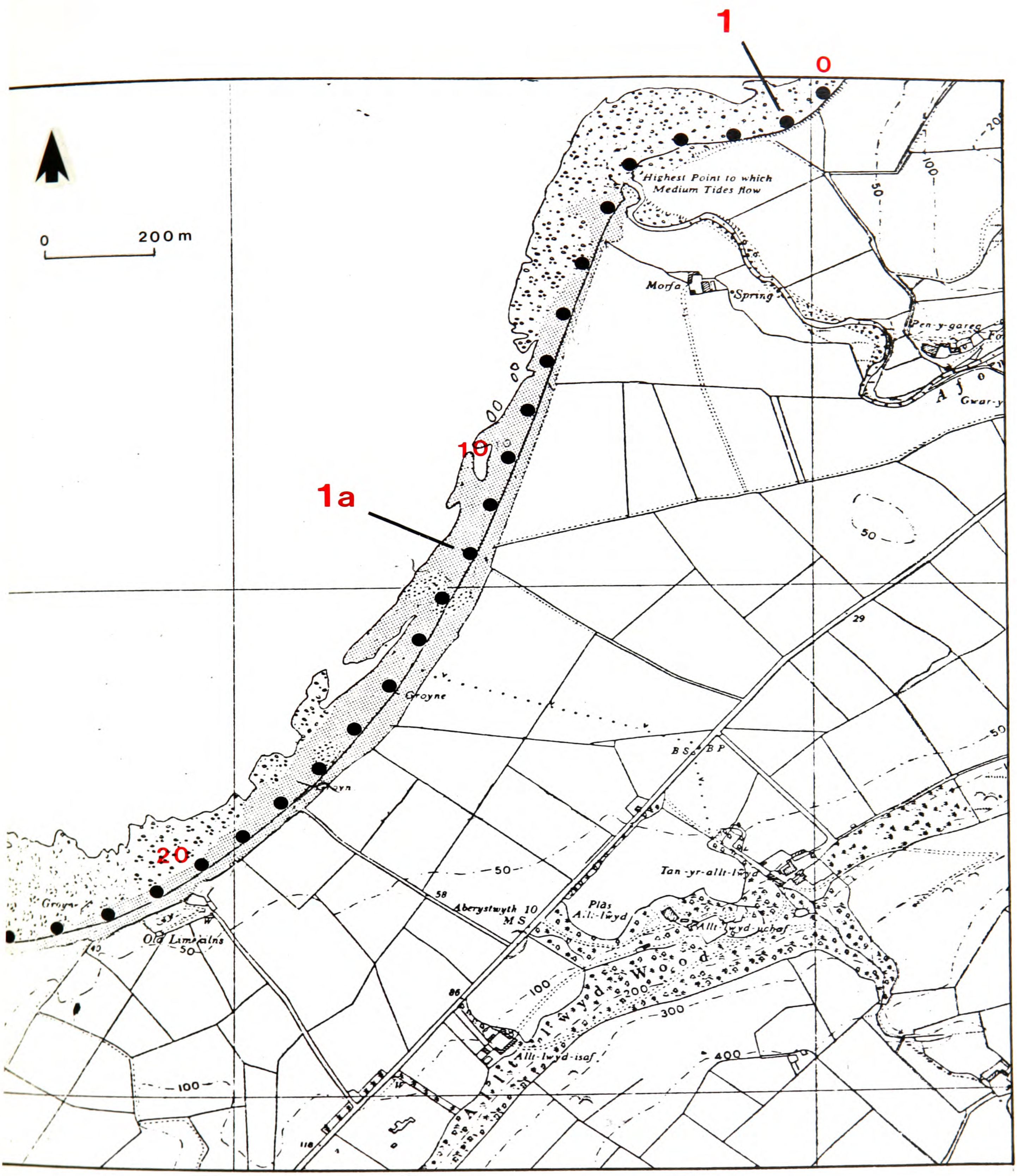


FIG. 6.2a Position of beach profiles in longshore survey (large figures in red indicate specific case-study sites)

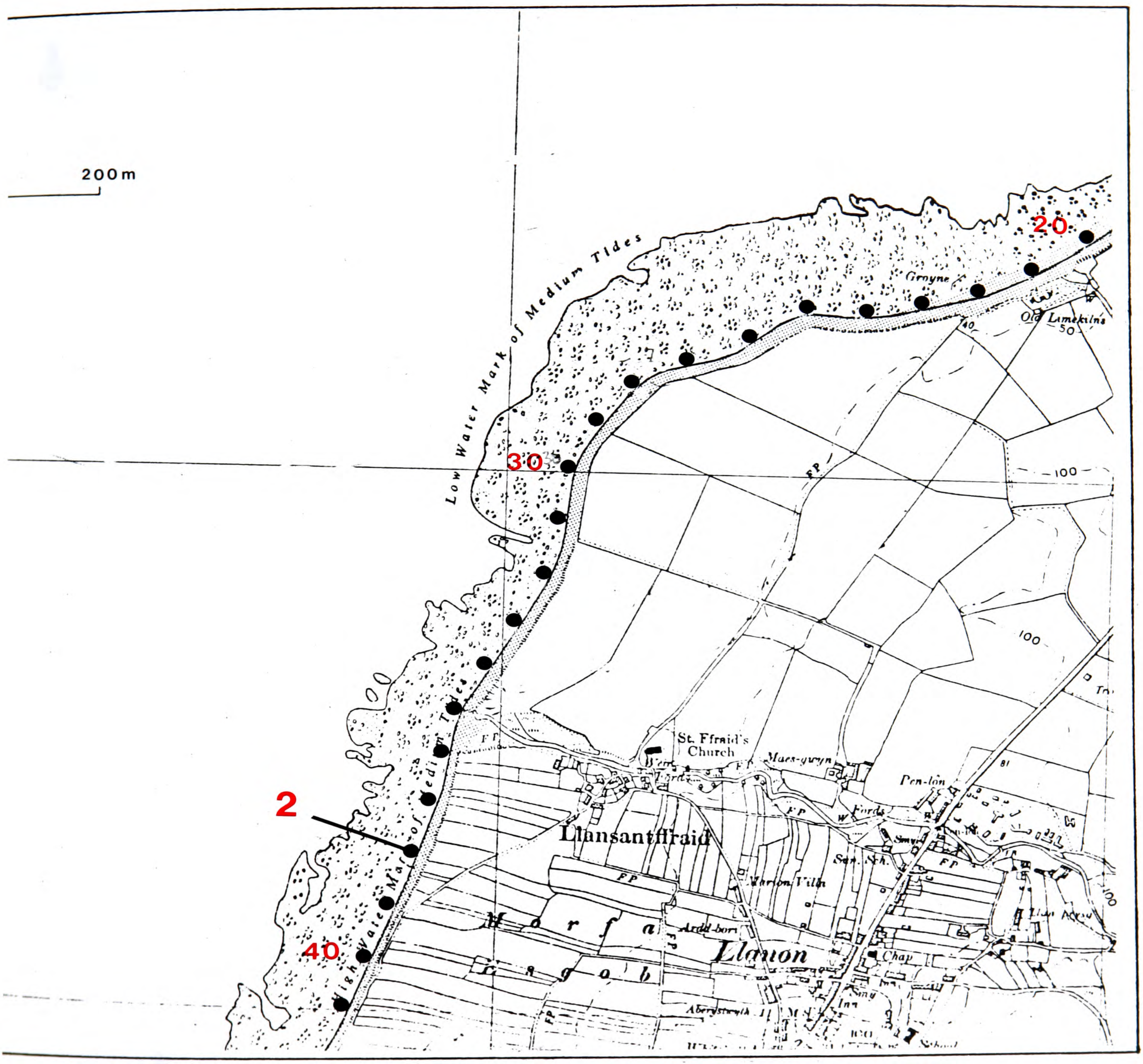


FIG 6.2b Position of beach profiles in longshore survey (large figure in red indicates specific case-study site)

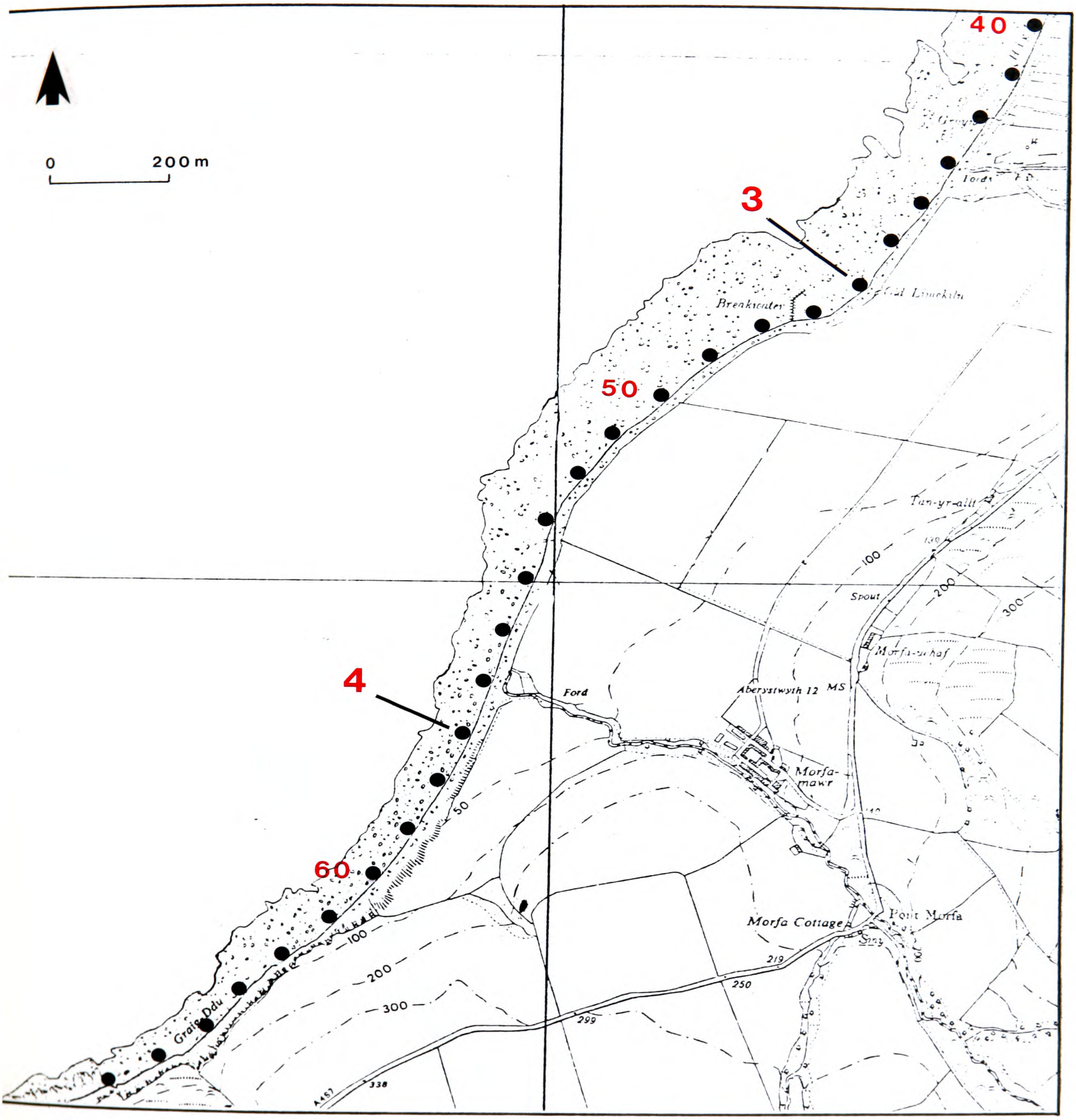


FIG. 6.2c Position of beach profiles in longshore survey (large figures in red indicate specific case-study sites)

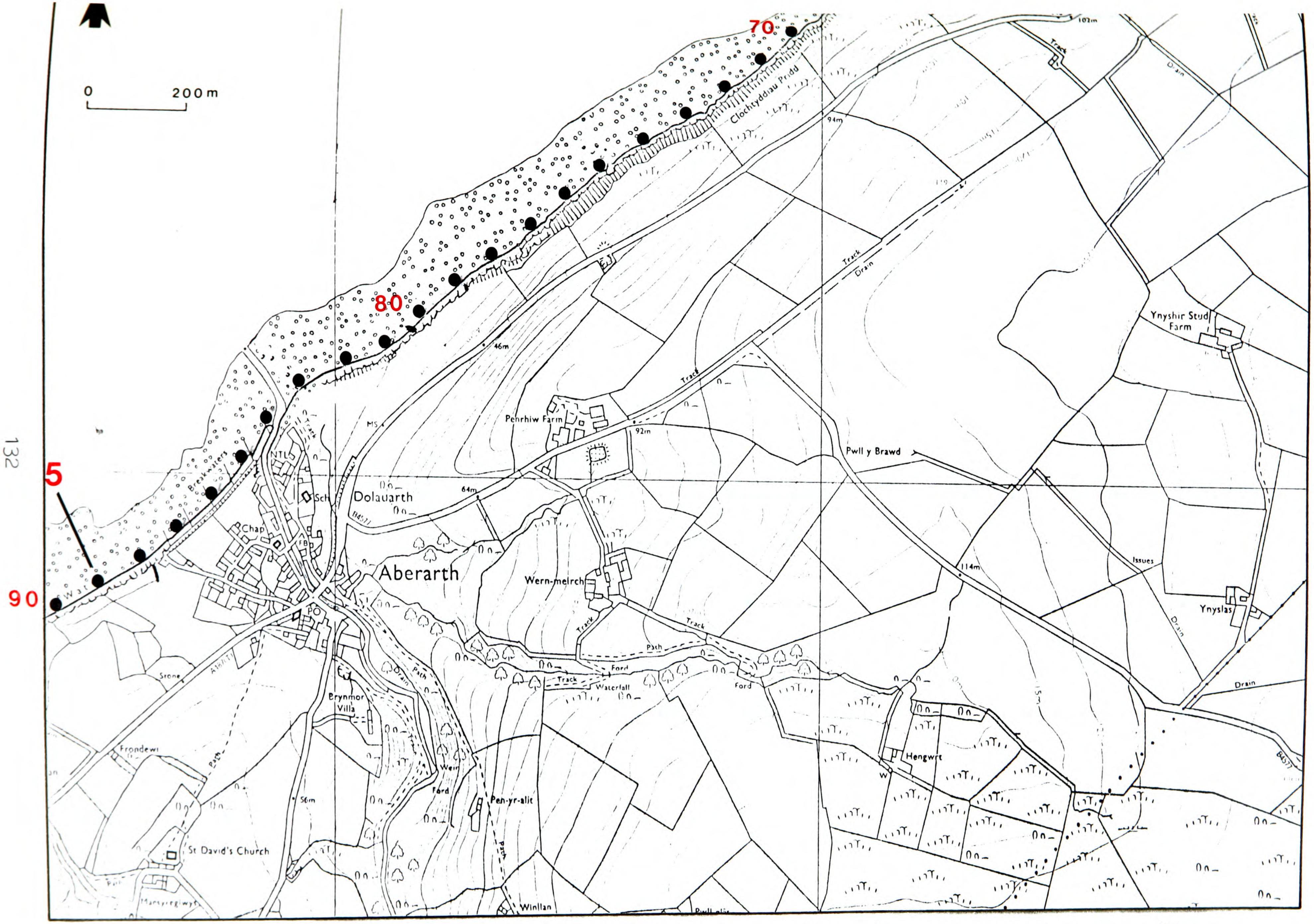


FIG. 6.2d Position of beach profiles in longshore survey (large figure in red indicates specific case-study site)

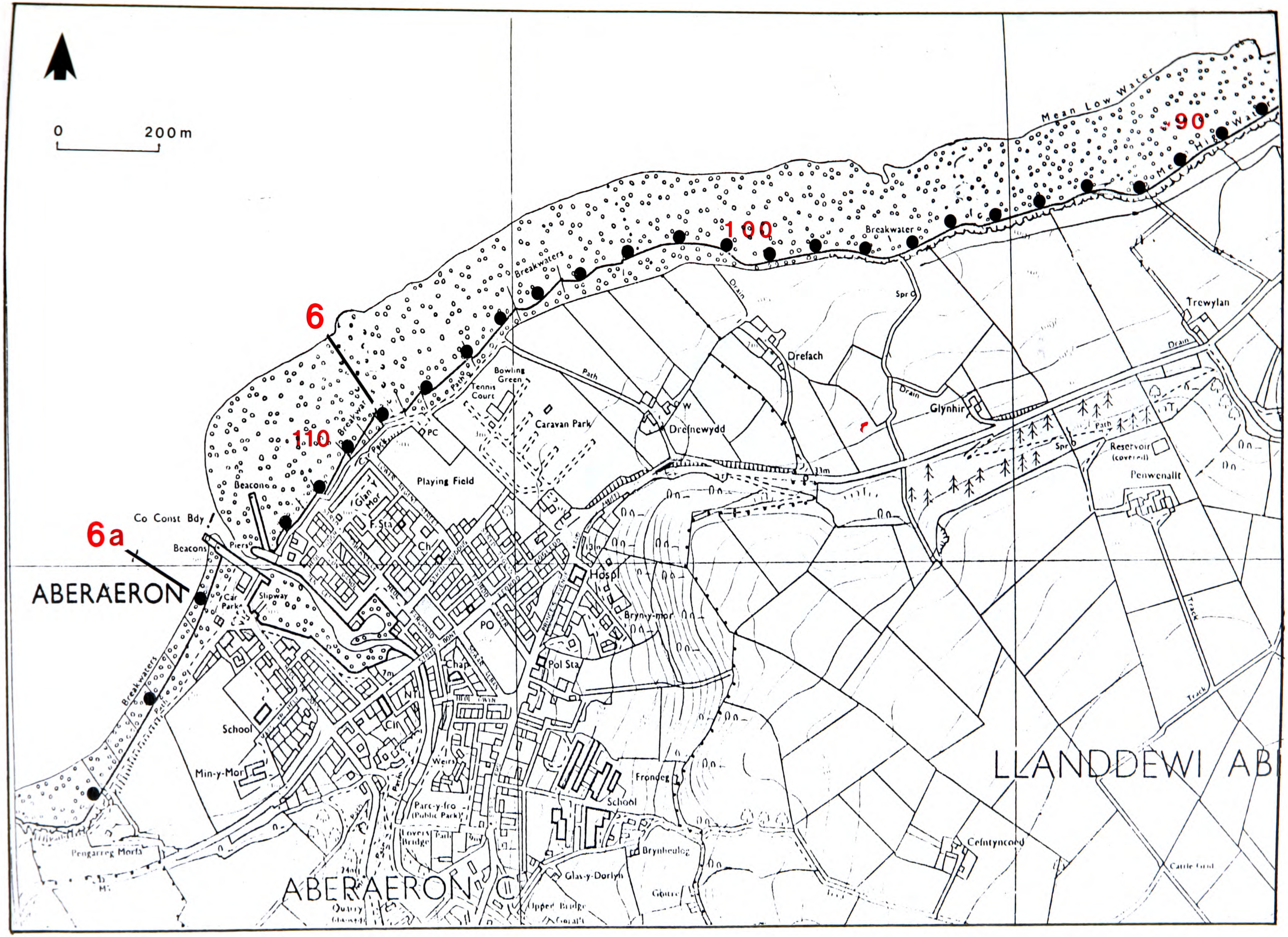


FIG. 6.2e Position of beach profiles in longshore survey (large figures in red indicates specific case-study sites)

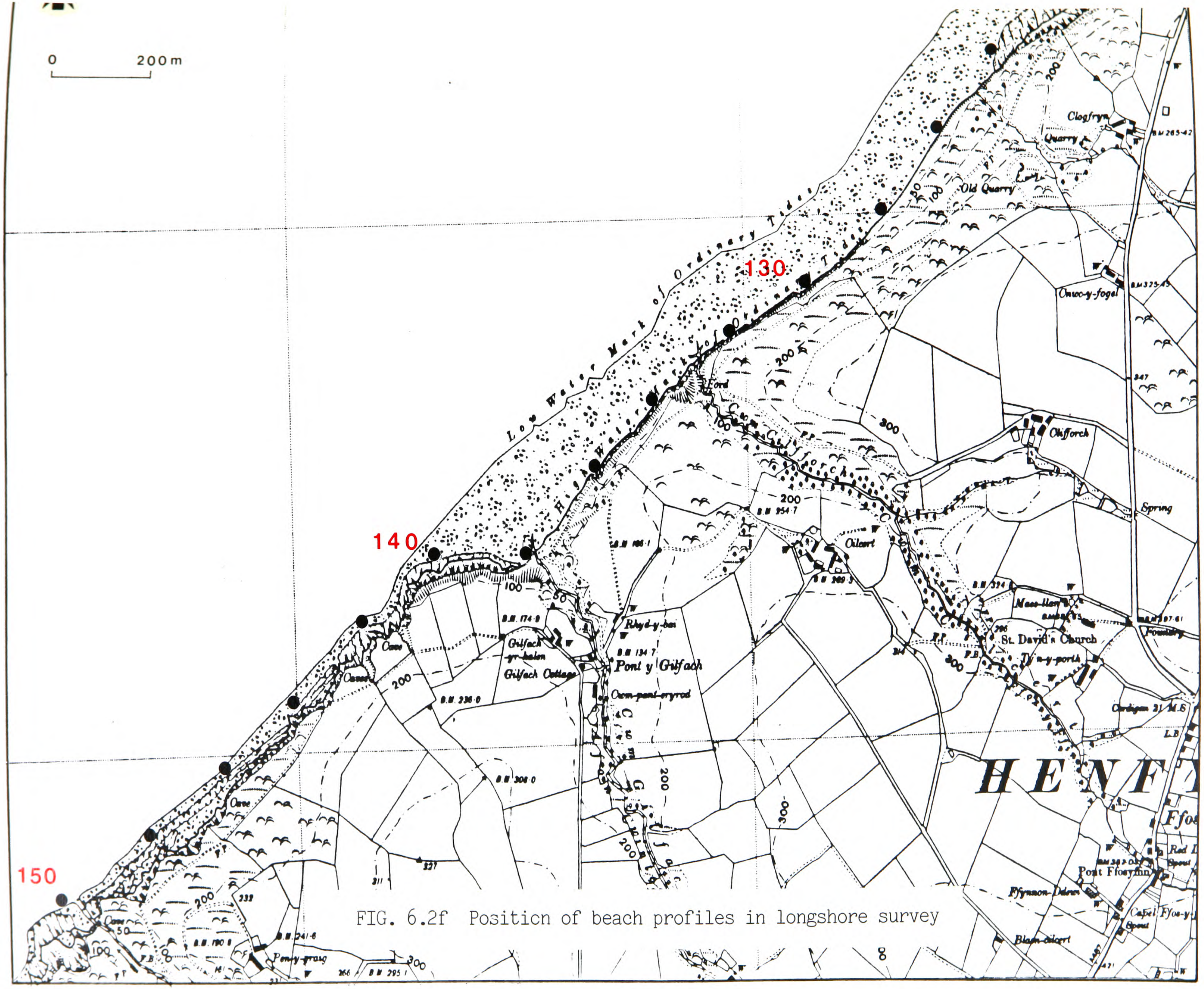


FIG. 6.2f Position of beach profiles in longshore survey

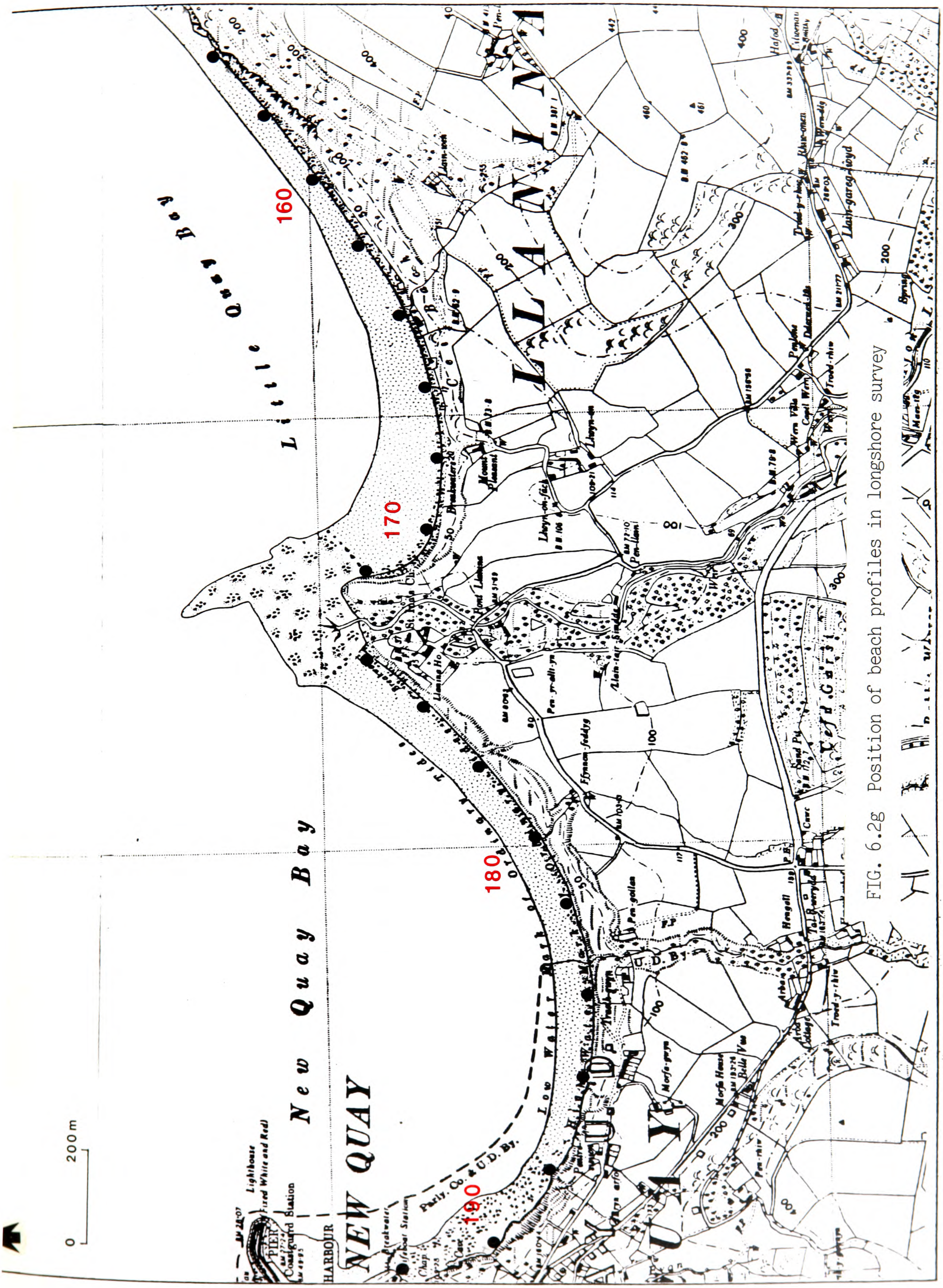


FIG. 6.2g Position of beach profiles in longshore survey

every 100 metres along the coastline between Llanrhystud in the north (chng.0 + 00) and Aberaeron (chng. 107 + 00) with further stations every 200 metres between Gilfach-yr-halen and New Quay in the south (Fig. 6.2 a-g),

Along the section between Aberaeron and Gilfach, where the beaches are backed by high steep cliffs of the Aberystwyth Grits, dangerous access and narrow beaches only exposed for short periods of time precluded ground surveys. Beach profiles in this area were interpolated from the aerial photographs.

The survey was carried out in summer and autumn of 1984 and completed in the summer of 1985. These periods were considered to represent average conditions. Winter surveying was avoided as it might show extreme seasonal trends in the beaches. Detailed topographic profiles were taken from the established T.B.M's located well above the high water level and extended out to low tide mark. Along each profile,note was taken of nearshore low slope, beach slope, storm ridge where present, top of beach, foot of cliff and top of cliff where practicable.

All beach and lower cliff variables are tabulated in the Appendix. Beach sediment volumes were calculated as per Fig. 6.1. Total beach volume was assumed to be the volume of sediment represented by the profile area measured above zero Ordnance Datum per unit length of beach. For the purpose of this calculation the cross sectional area at each profile was taken as a right-angled triangle with the beach dropping vertically from the foot of the cliff, slope or structure (see Fig. 6.1). This obviously does not take into consideration the slope of the cliff or wave-cut platform but is considered suitable for comparative purposes.

The beach face or upper foreshore volume was calculated from the triangle formed by beach height and volume, the base of the triangle being an extension of the beach terrace through to the back of the beach.

As well as the height or width of the beach in relation to a backshore feature (cliff, slope or structure), the beach volume as depicted by profile area may govern the beach's capability as a defence against coastal erosion.

The considerable mass of data created by the survey was stored on disc and beach profiles plotted for each chainage. A computer programme was written for plotting 3 dimensional perspectives of sections of shoreline. Fig 6.3 shows the section between Aberarth and Aberaeron.

While this ad hoc survey was of practical value in assessing the validity of the theoretical prediction of beach heights established in Chapter 5, such an investigation can only show changes as moment situations and the need for future back-up surveys is recognised if any long-term trends of sediment movement are to be clarified.

6.3.2 Specific case-study sites

As the predictive model depicts long-term conditions of beach morphology, any comparison with the actual beach structure will be false if the beaches measured in the long-shore survey are not typical of average conditions. Selected beaches were therefore surveyed at regular intervals to eliminate any seasonal trends in profile.

During 1983 a number of sites were established at potential erosion points along the coast. The position of each site was estimated from a first approximation of possible low beaches as indicated by potential sediment cell boundaries (Fig 5. 8).

Changes in beach profile have been considered an important aspect of the variability of any coastal environment (Christiansen and Moller, 1980). Profiles were therefore surveyed at bi-monthly intervals and, where practible, after storm events. As samples must come from some comparable point, the mid-tide position was chosen, this point, advocated by Bascom (1951) being deemed sufficient to describe the character of the beach material.

The difficulty of obtaining accurate estimates from any sampling proceedure is acknowledged and in evaluating the grading of the beach material from a single sampling point one has to be content with a subjective and possibly less accurate estimate. Particle size distribution obviously varied with depth and along the line of the profile so that

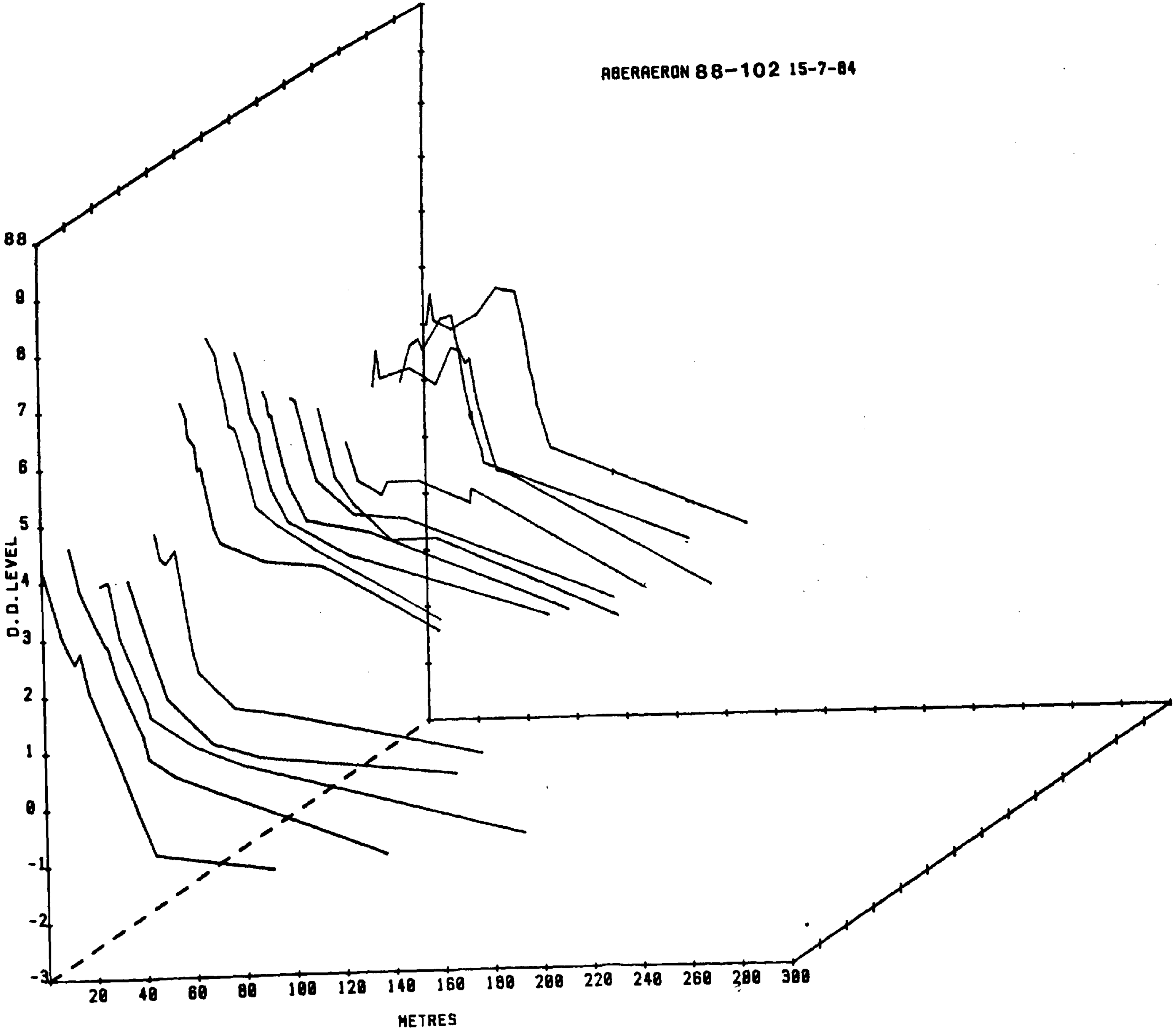


FIG. 6.3 3-dimensional plot of beach profiles between Aberarth and Aberaeron

any deviation would influence the final estimate. With hindsight a better method would have been to collect sediment samples from different positions along the profile (see Krumbein and Slack, 1956 on sampling of beach environments).

Several of the beaches showed pockets of sand covered by a thin veneer of shingle. These conditions are continually changing which further complicates sampling accuracy. Conversations with local residents indicate a general loss of sand from the area in the last two or three decades. This particularly applies to the beaches that front the villages of Aberarth, Llannon and Llanrhystud.

6.4 Offshore/onshore effects on beach profile

"The movement of beach material normal to the coast is mainly responsible for the very considerable changes which occur from time to time on the foreshore" (King, 1972, p345).

A natural beach profile changes almost continuously in shape due to varying boundary conditions e.g. wave height, tide level, onshore winds. Whilst Hanson (1969) provided empirical equations that related changes in beach profile to some 14 controlling process variables, no attempt is made here to interpret the variability of profiles in terms of such variables.

Observations on beach changes along the Ceredigion coast are applied to short term variability at several sites where erosion is problematic. These changes are assessed by the net change in the beach height, the quantity of sediment on the foreshore and the mean slope of the foreshore. For the sake of conciseness, only essential figures are quoted in the text; full results are tabulated in the Appendix.

Figs. 6.4a-h show sweep zones for the period August 1982 - August 1983 for profiles 1-6 and for two separate periods for profiles 1A and 6A. These eight profiles cover the section of coast between Llanrhystud in the north, profile 1 (chng. 1 + 00) and Aberaeron in the south, profile 6A (chng. 114 + 00).

Profiles were established at 200m intervals on New Quay (chng.174-192) and CeiBach (chng.160-172) beaches. The sets of sweep zones for these

FIG. 6.4a Llanrhystud - Profile 1. Sweep zones for the period Aug '82 - Aug '83

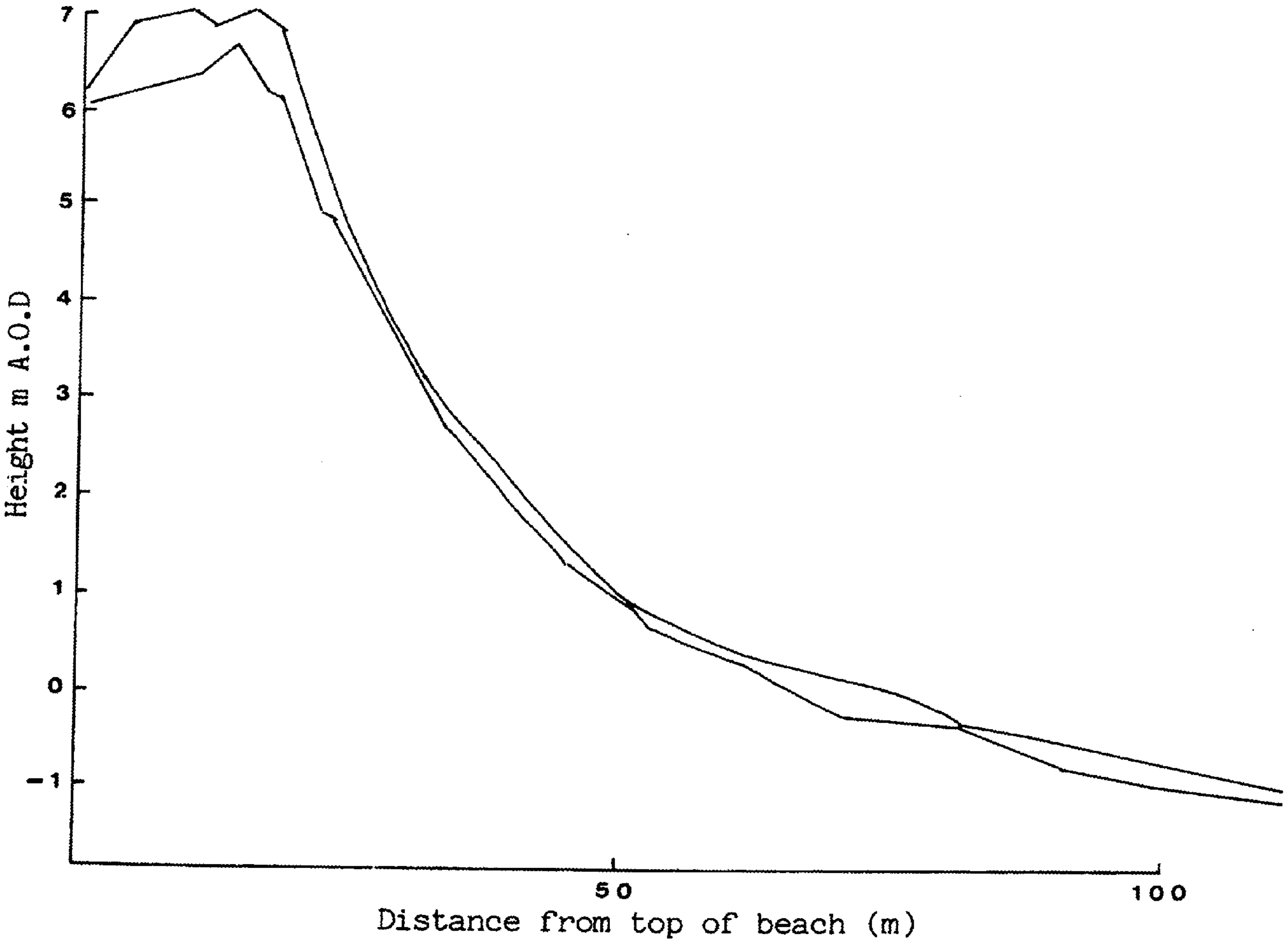


FIG. 6.4b Llanrhystud - Profile 1a. Sweep zones for the period Jan '84 - Nov '84

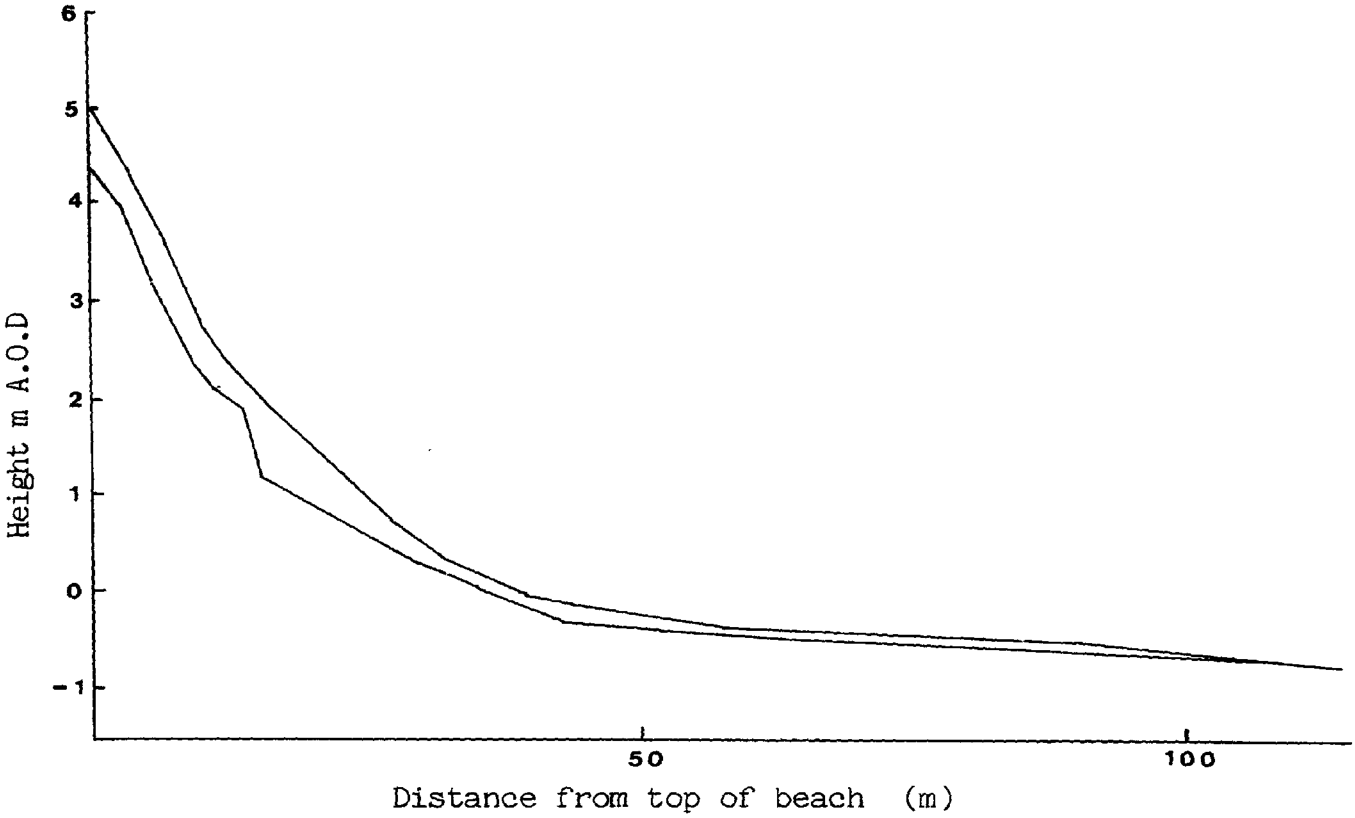


FIG. 6.4c Llansantffraid - Profile 2. Sweep zones for period Aug '82 - Aug '83

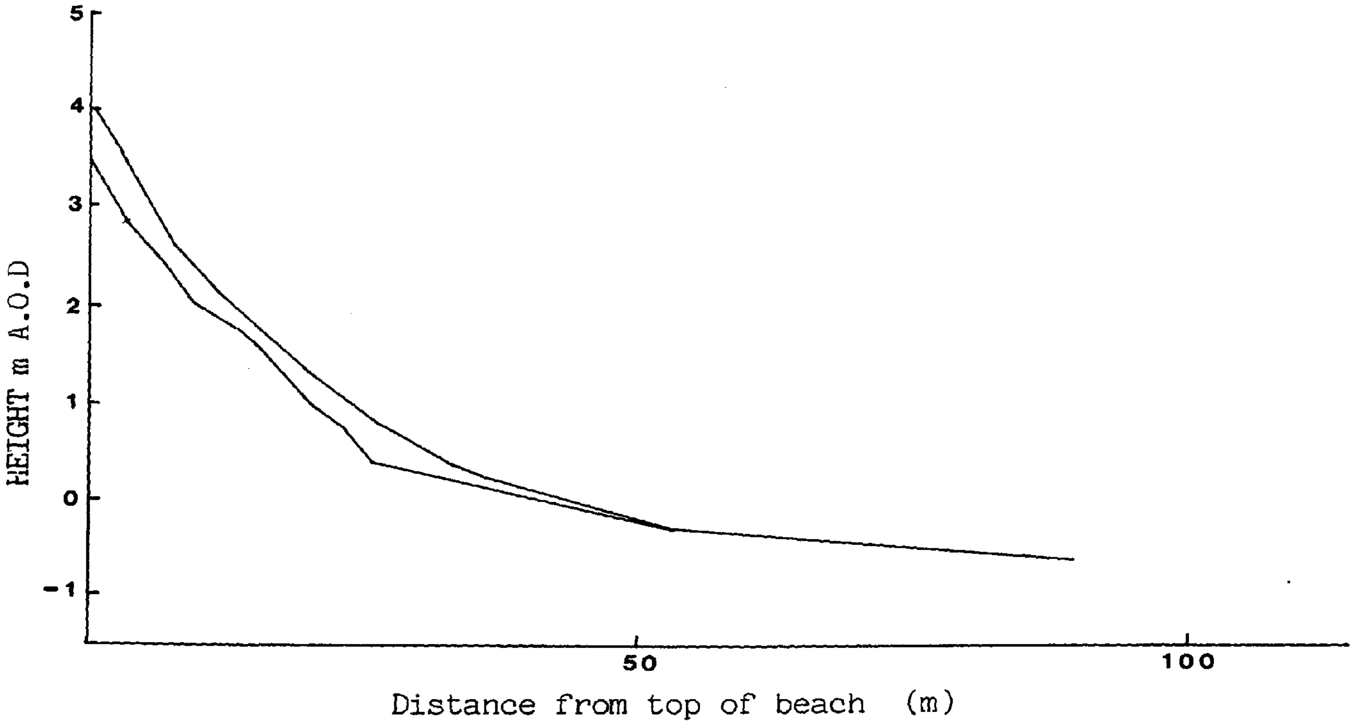


FIG. 6.4d Llanon - Profile 3. Sweep zones for period Aug '82 - Aug '83

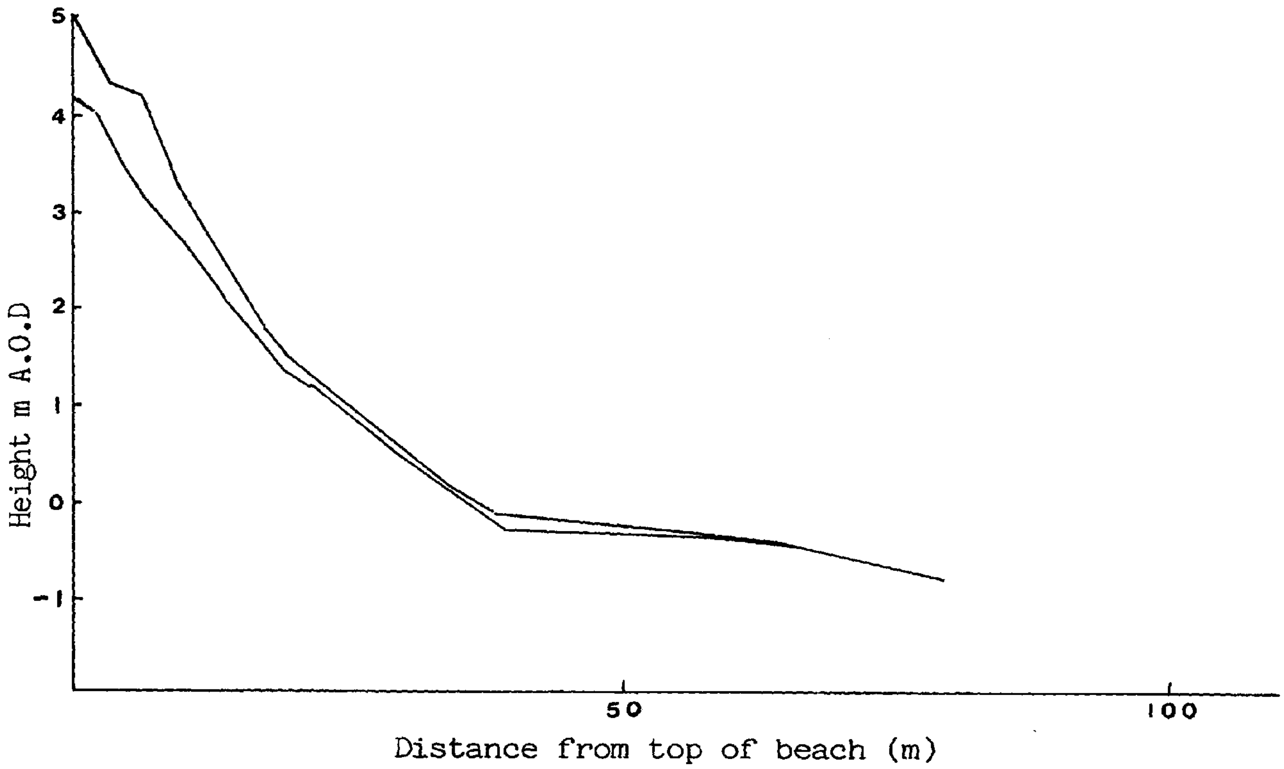


FIG. 6.4e Morfa - Profile 4. Sweep zones for period Aug '82 - Aug '83

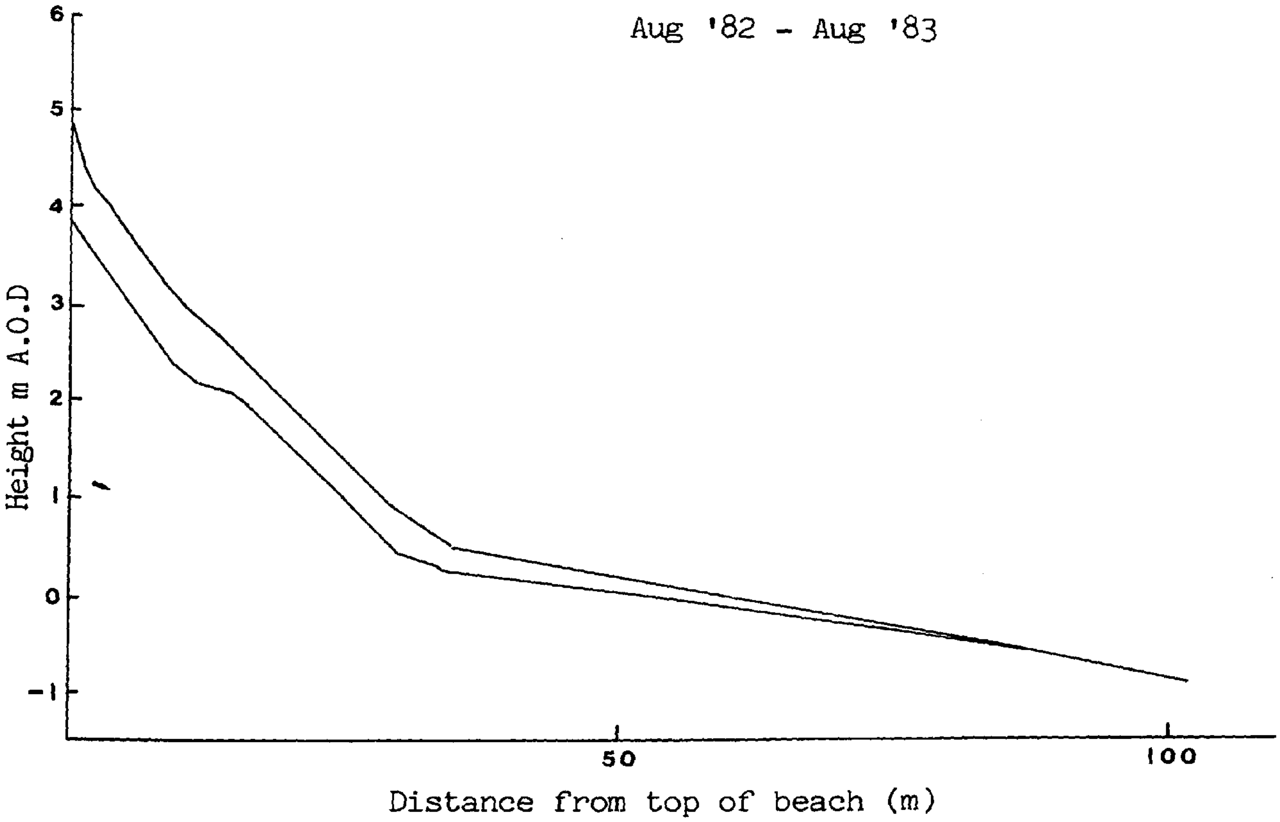


FIG. 6.4f Aberarth - Profile 5. Sweep zones for period Aug '82 - Aug '83

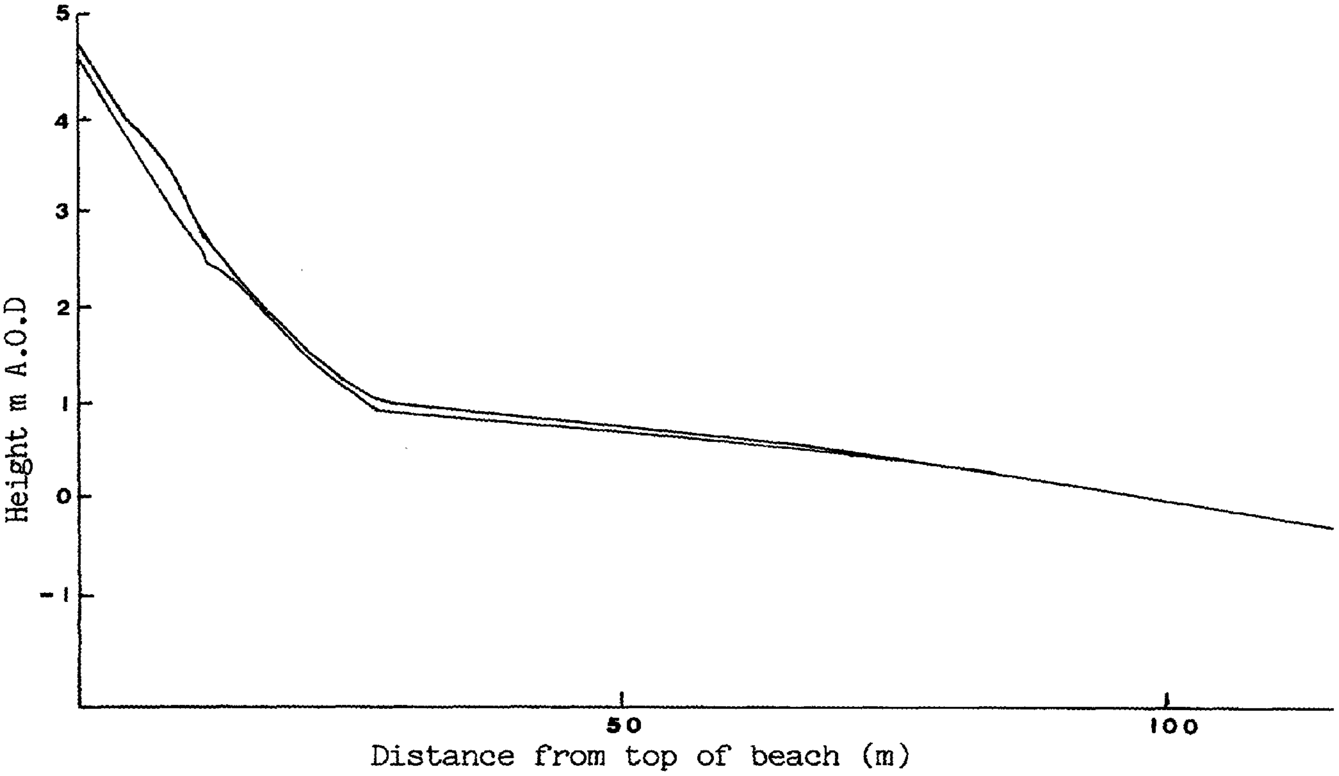


FIG. 6.4g Aberaeron - Profile 6. Sweep zones for period Aug '82 - Aug '83

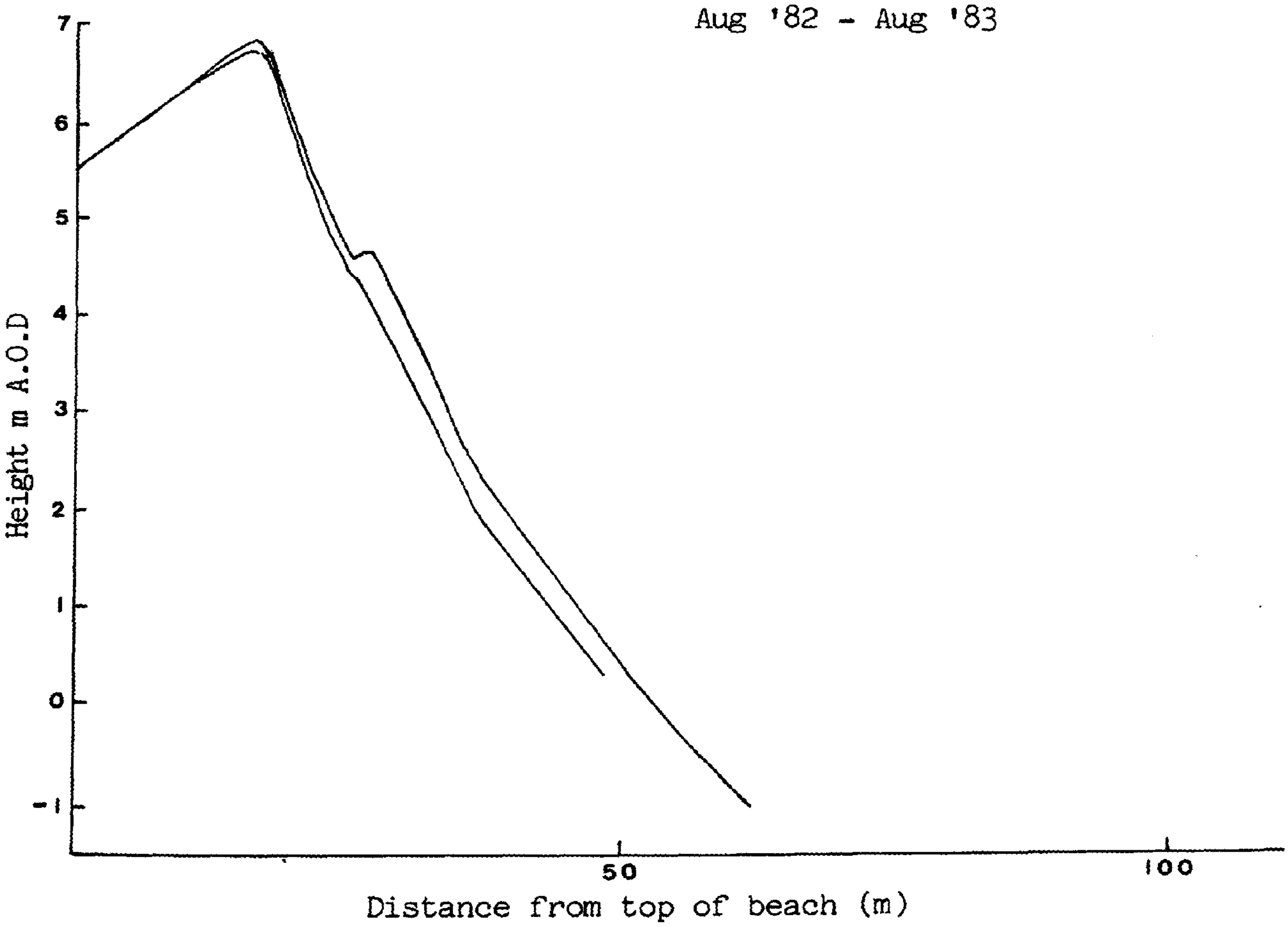


FIG. 6.4h Aberaeron - Profile 6a. Sweep zones for period Oct '83 - Mar '84

profiles for the period December 1982 - January 1984 are shown in Figs 6.5 a-d.

These sweep zones cover the envelope of beach changes during the period they represent. More detailed changes in beach foreshore for individual profiles 1, 3 and 5 are shown on a larger scale in Figs. 6.6 a-c. Particle size distribution curves for mid-tide sediment samples are summarised for each profile in Figs. 6.7 a-h.

6.4.1 (i) Llanrhystud north beach. Profile 1 (chng. 1 + 00).

This shingle beach forms part of a shallow embayment and fronts low-lying cliffs of glacial drift. Profile 1 extends from a concrete slipway at the edge of the adjacent caravan park.

There is evidence of small local falls of material along the cliffline and although this part of the beach is protected to some extent by the shallow headland formed at the mouth of the river Wyre immediately to the south, the coastline is orientated such that it faces nearly due north and is therefore subject to direct attack from the north westerly storm waves.

The beach is narrow and steep, the mean cross-sectional area at the profile being only 90m^2. Beach height increases northwards from the study area and the highest level is observed near the buttress of Carreg-ti-pw. Here there is a significant build-up of shingle where drift has obviously been impeded by the rock cliffs.

Fig 6.6a reveals a gradual accumulation of the beach foreshore through late summer and autumn to give a maximum beach height of 5.5m above O.D in early December. Severe gales on 30.1.83 and 6.2.83, when hourly mean wind of 32.6 and 36.7 knots respectively were recorded at Aberporth for 24 hours, resulted in a scouring of the beach face with a significant lowering of beach level by some 1.5m. Volume loss was measured at 30% of the original effective beach volume, although the loss in terms of overall beach volume, at 16%, is less significant. The subsequent spring and summer profiles indicated a gradual replenishing of beach volumes and the additional survey carried out in July 1985 confirmed no underlying long-term trend of accretion or erosion on the foreshore.

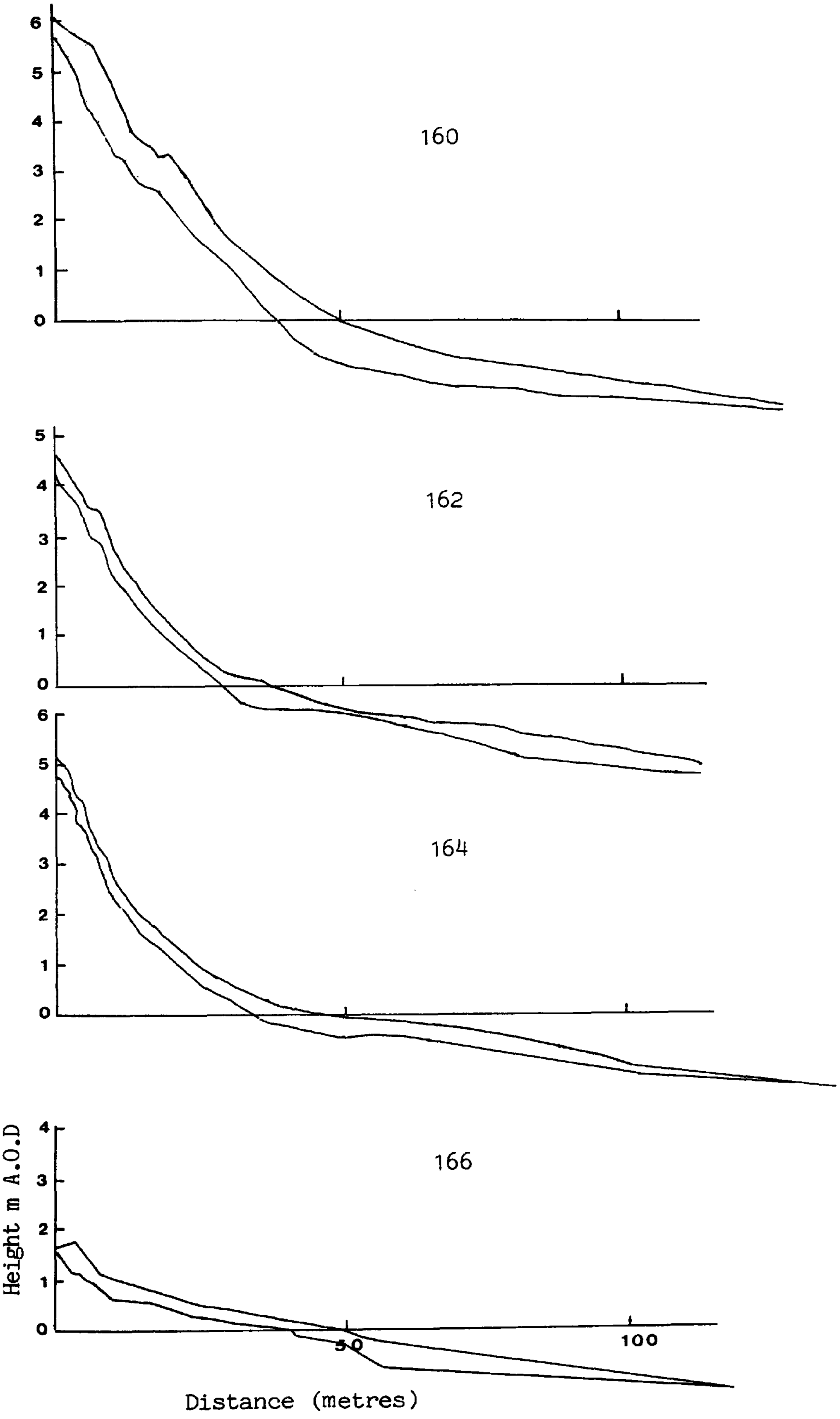


FIG. 6.5a Sweep zones for profiles 160, 162, 164 and 166 for period Dec '82 - Jan '84 (see location map Fig. 6.2g)

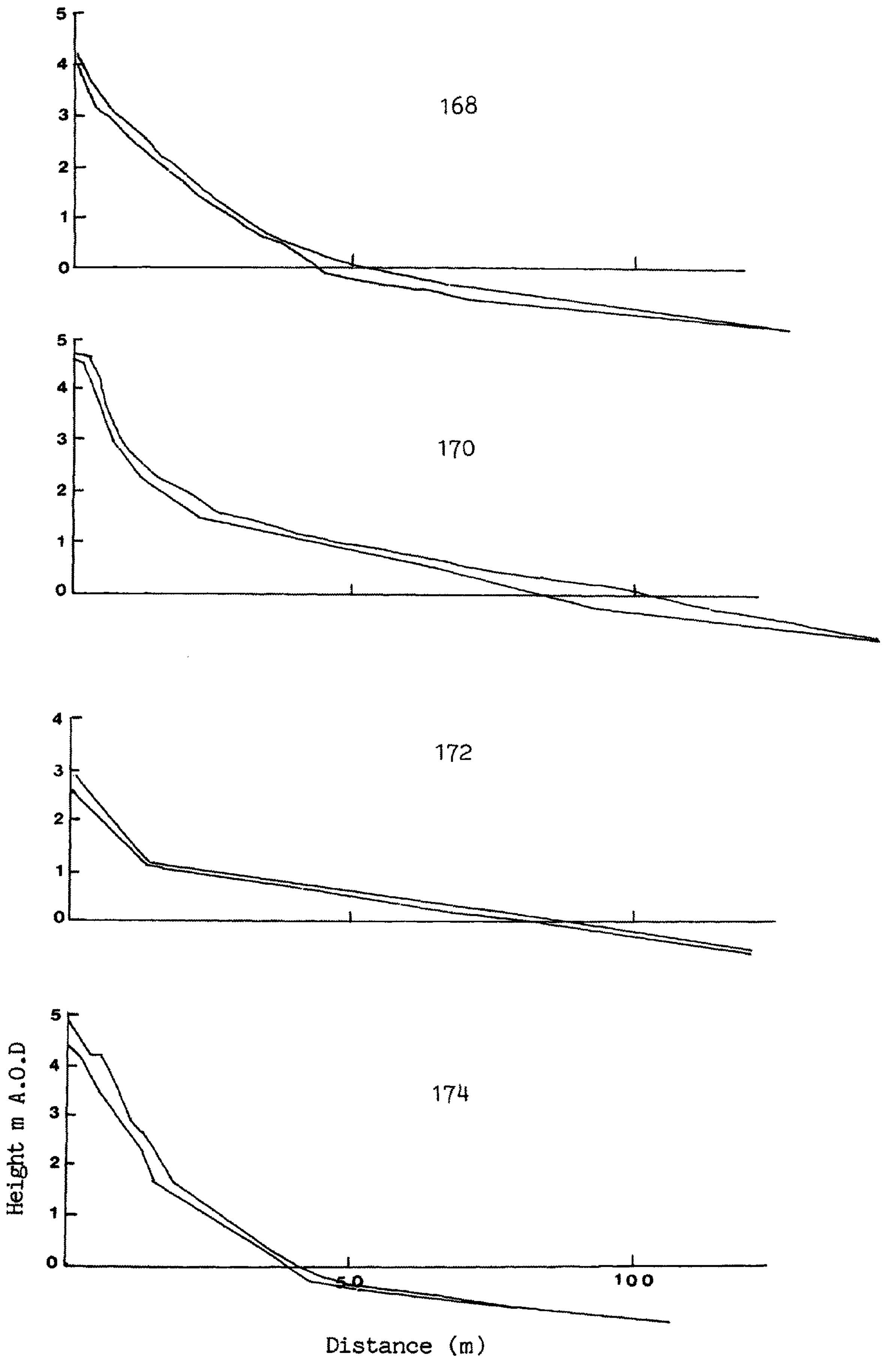


FIG. 6.5b Sweep zones for profiles 168, 170, 172 and 174 for period Dec '82 - Jan '84.(see location map Fig.6.2g)

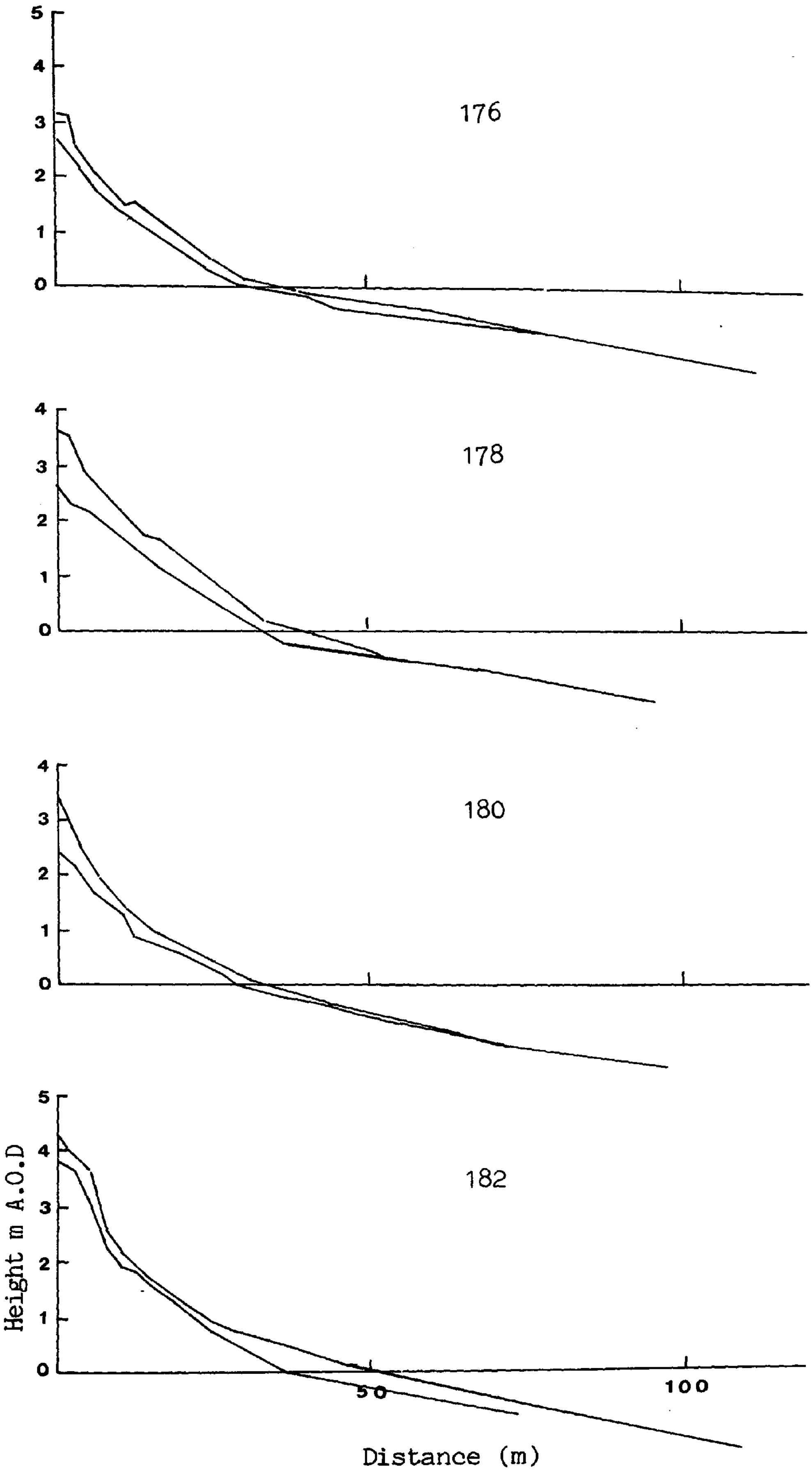


FIG. 6.5c Sweep zones for profiles 176, 178, 180 and 182 for period Dec '82 - Jan '84.(see location map Fig.6.2g)

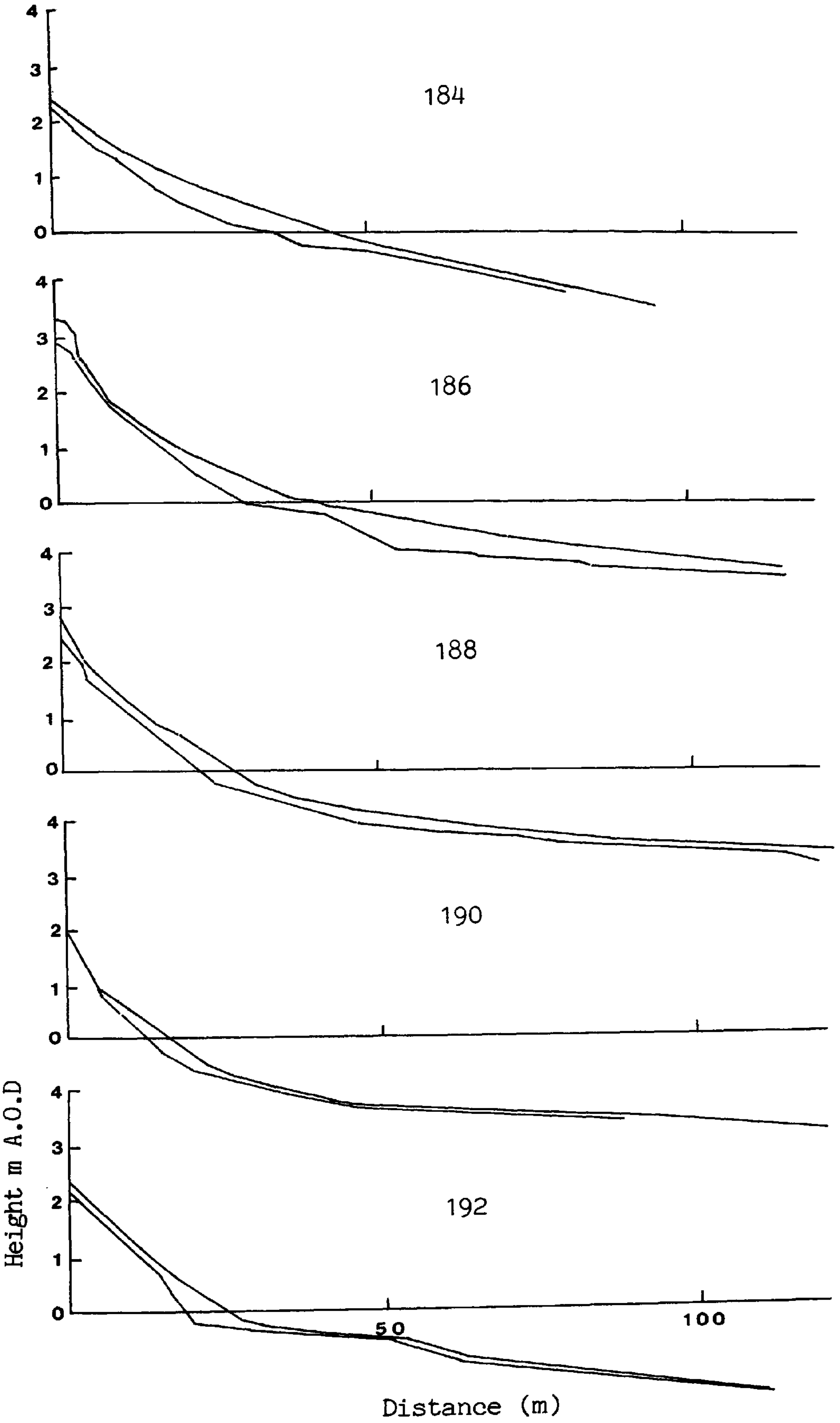


FIG. 6.5d Sweep zones for profiles 184, 186, 188, 190 and 192 for period Dec '82 - Jan '84.(see location map Fig.6.2g)

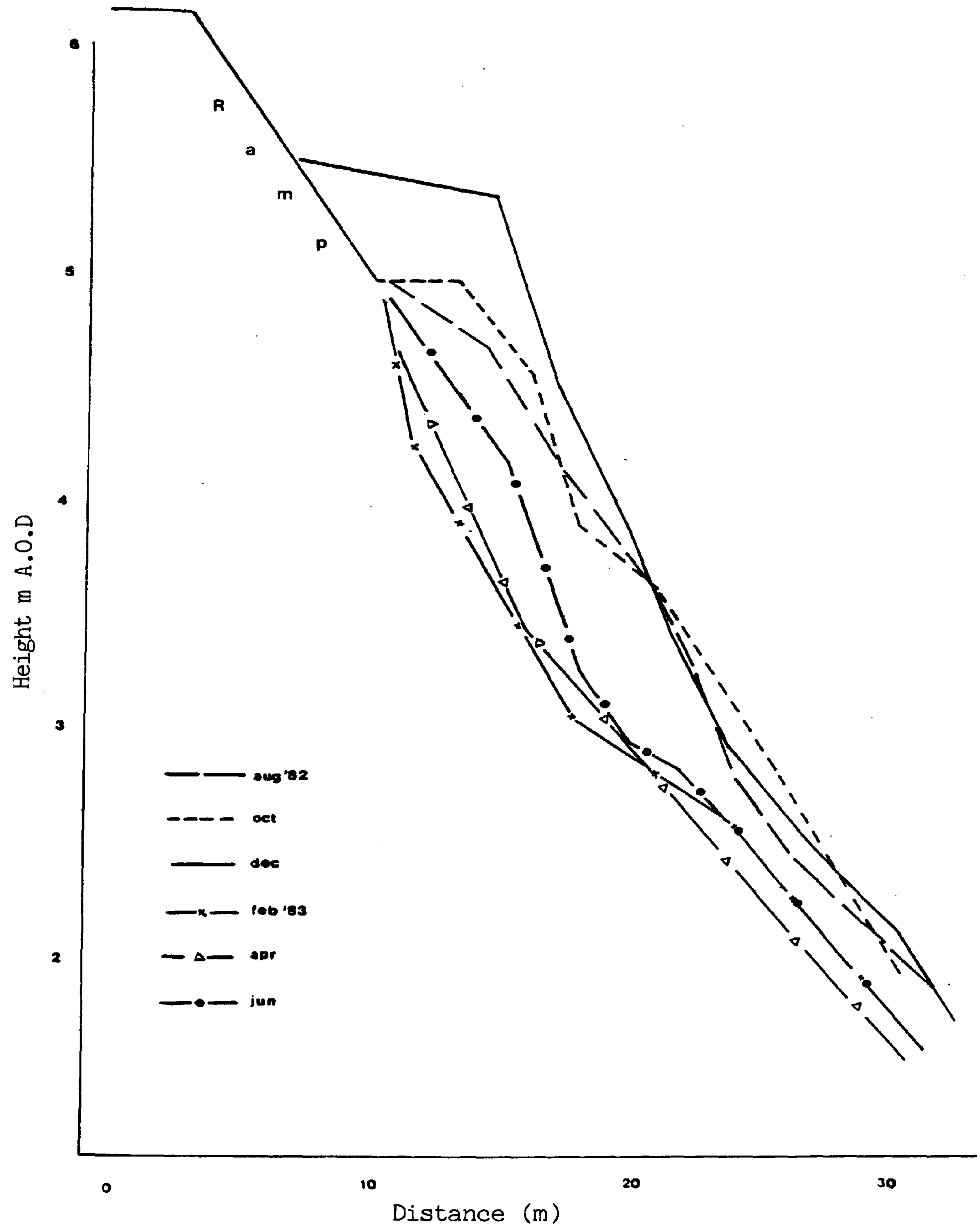


FIG. 6.6a Profile 1,changes in beach foreshore

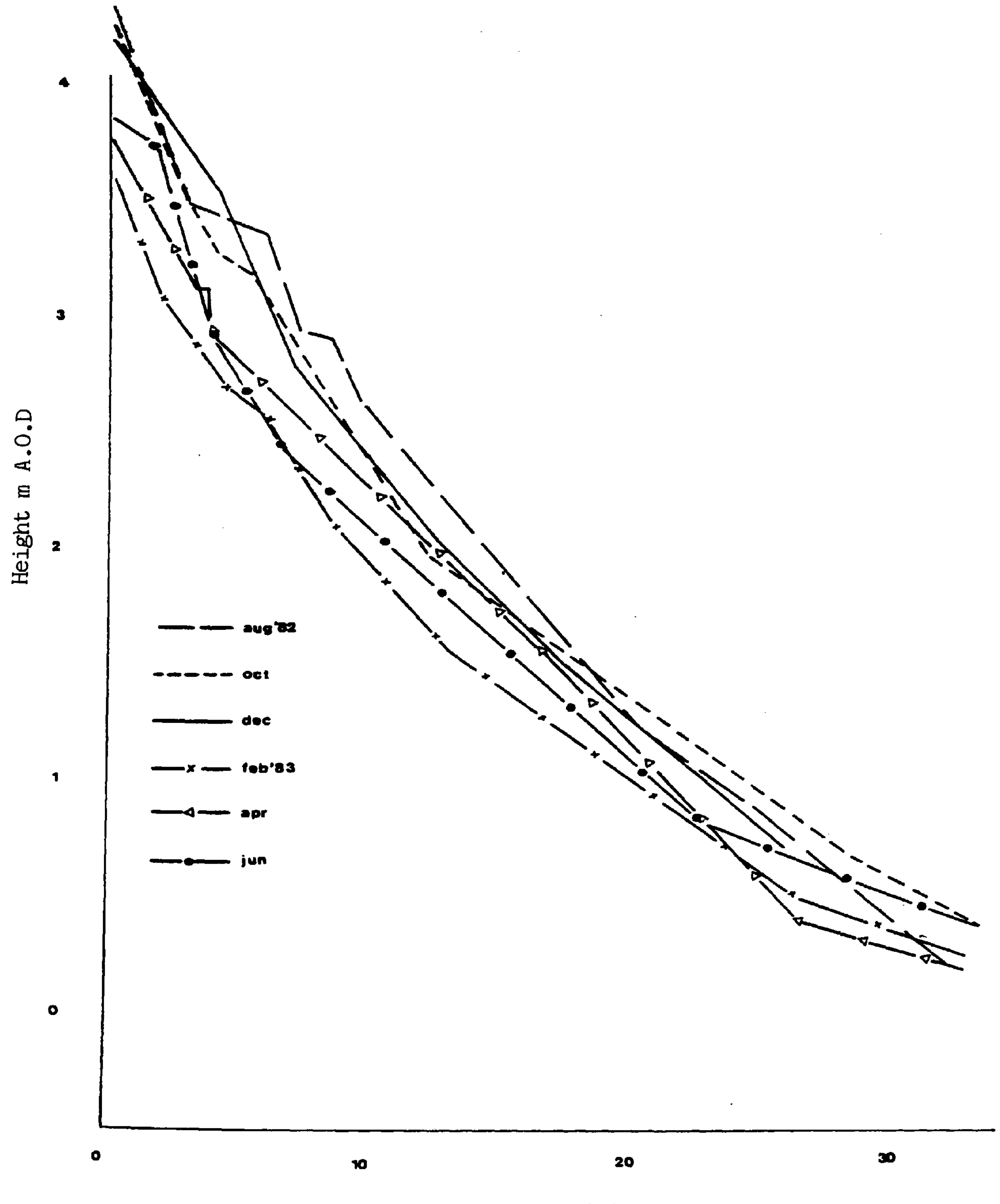


FIG. 6.6b Profile 3, changes in beach foreshore

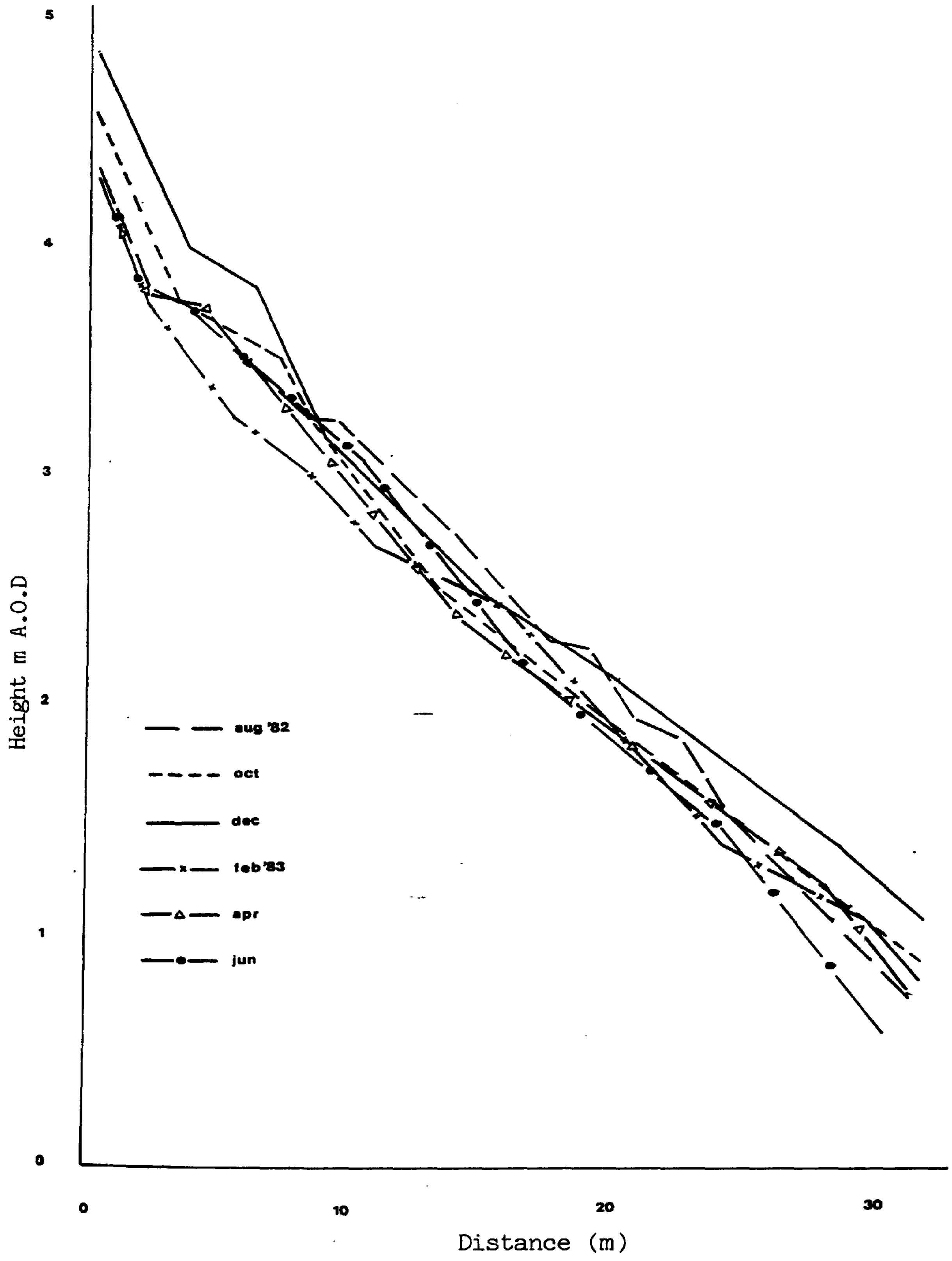


FIG. 6.6c Profile 5, changes in beach foreshore

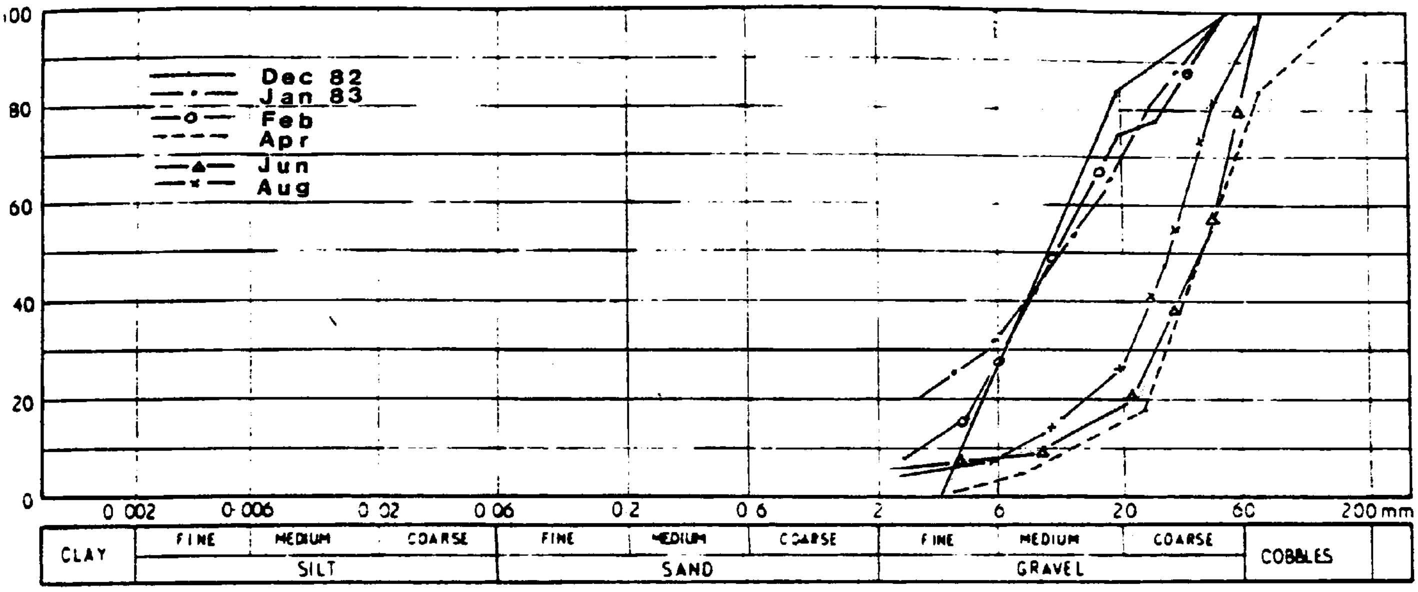


FIG. 6.7a Grading envelope for mid-tide samples. Profile 1

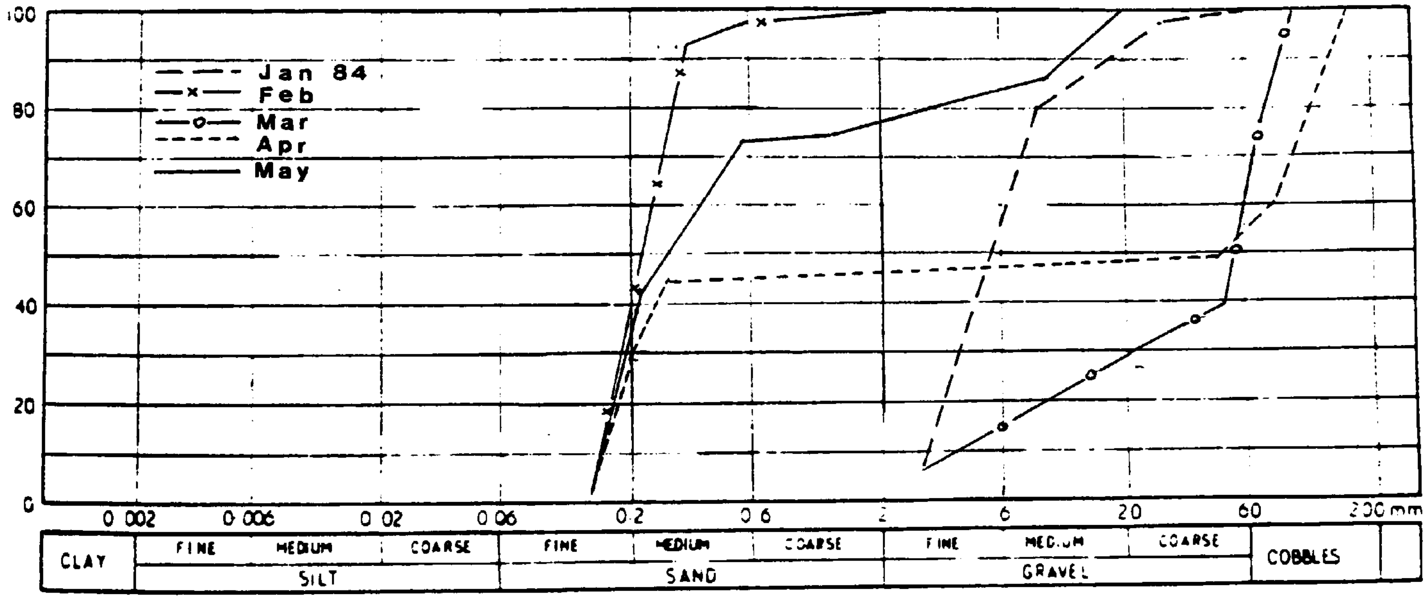


FIG. 6.7b Grading envelope for mid-tide samples. Profile 1a

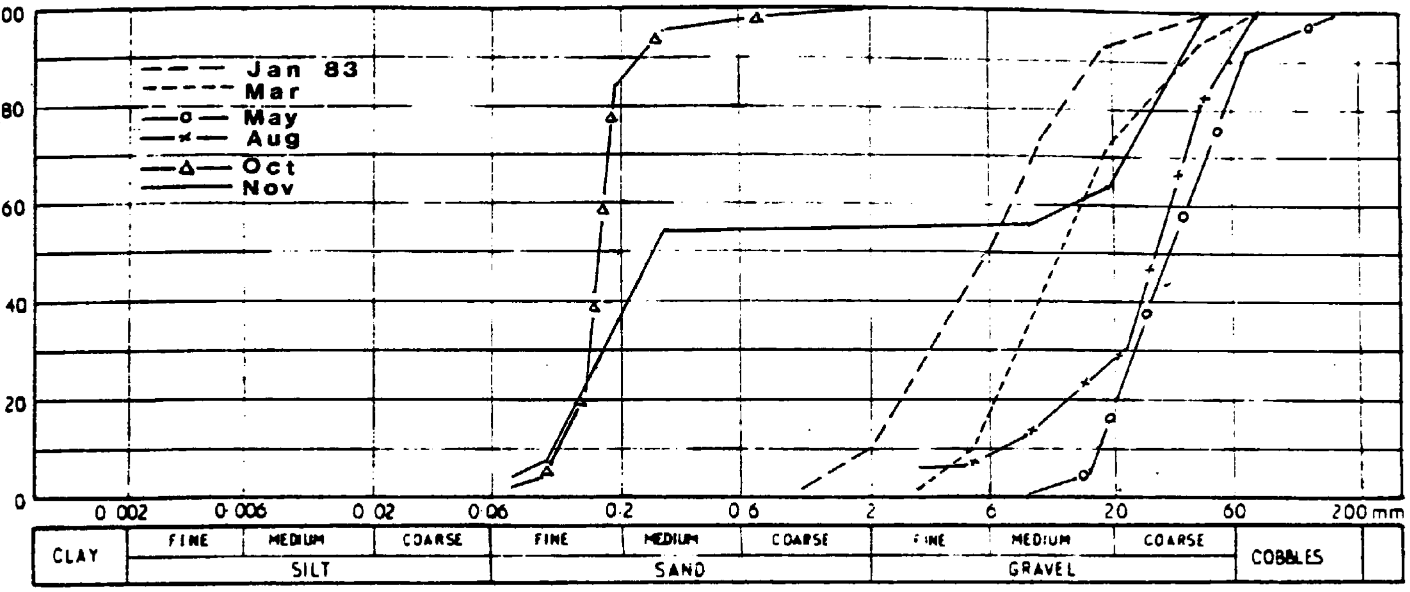


FIG. 6.7c Grading envelope for mid-tide samples. Profile 2

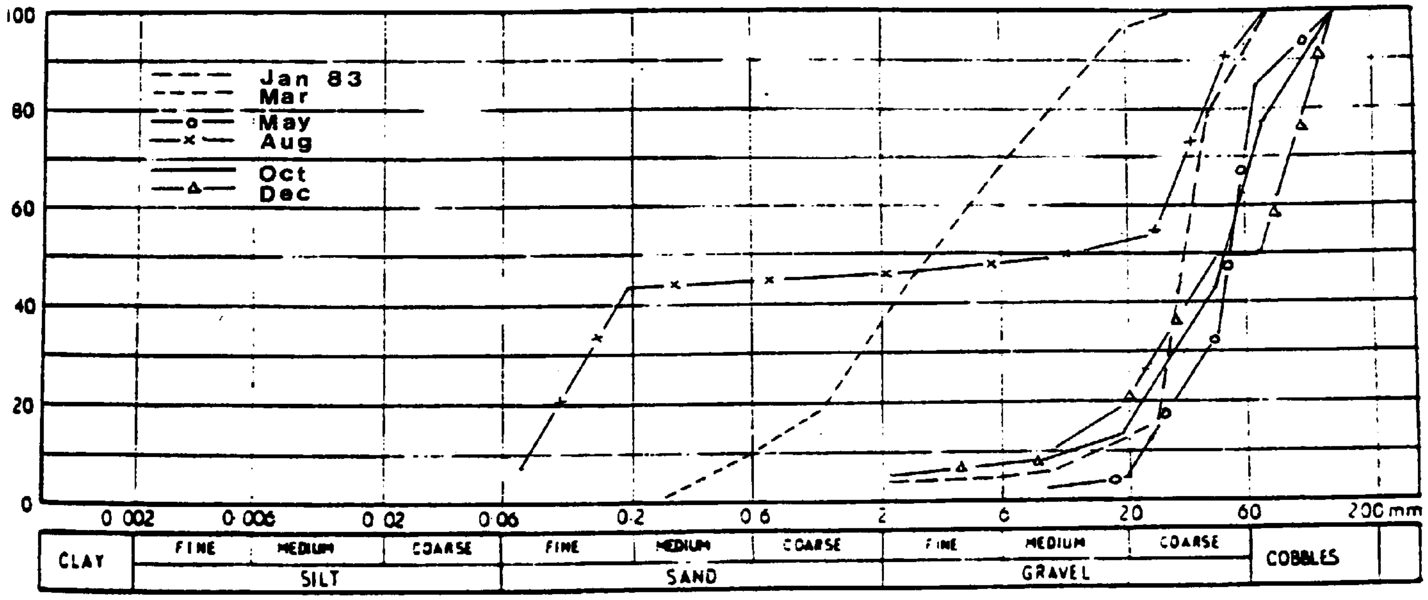


FIG. 6.7d Grading envelope for mid-tide samples. Profile 3

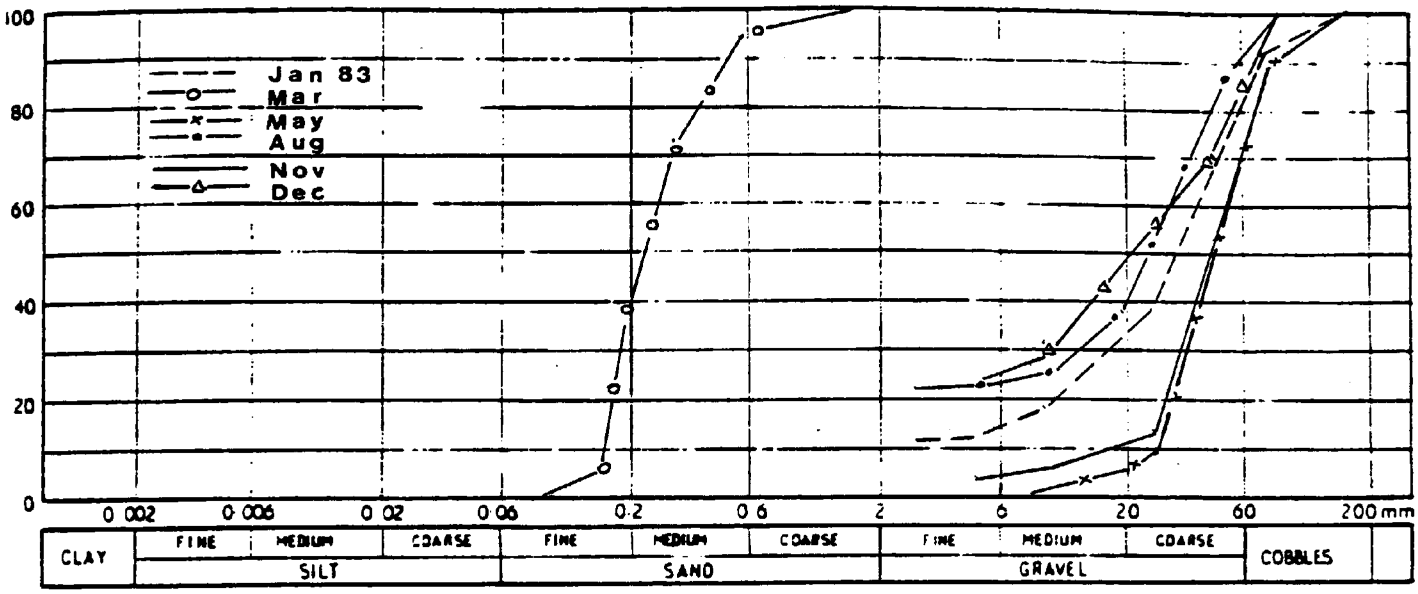


FIG. 6.7e Grading envelope for mid-tide samples. Profile 4

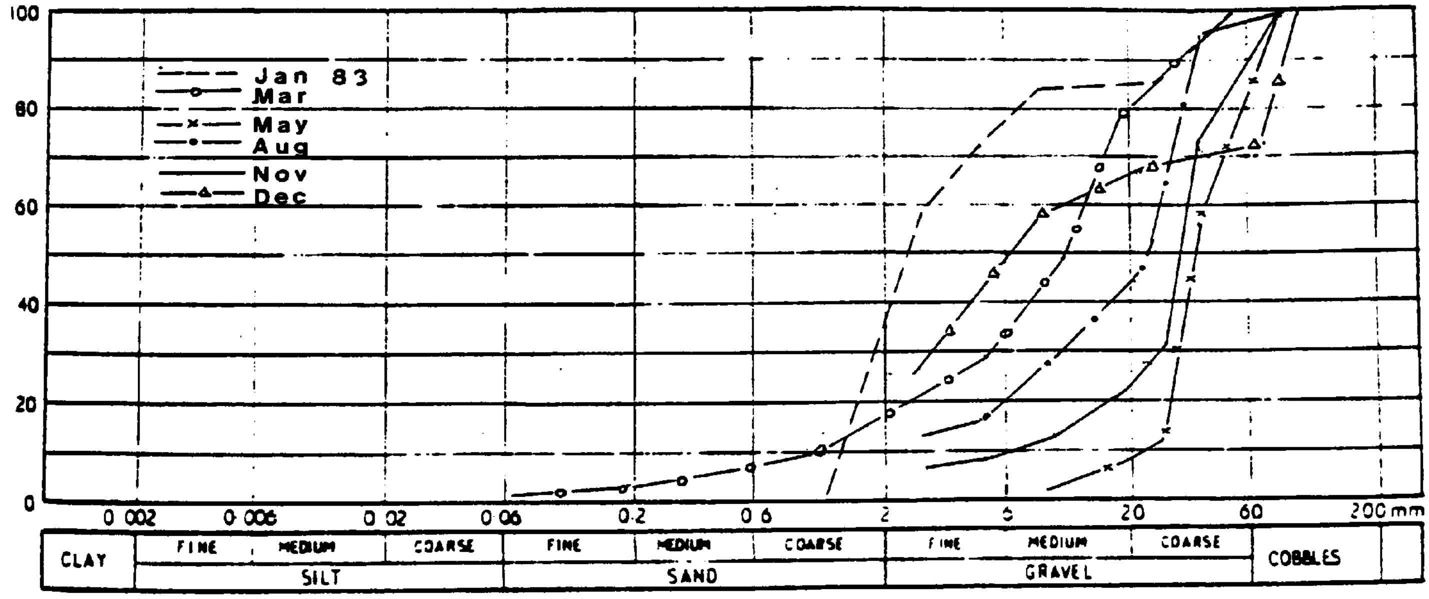


FIG. 6.7f Grading envelope for mid-tide samples. Profile 5

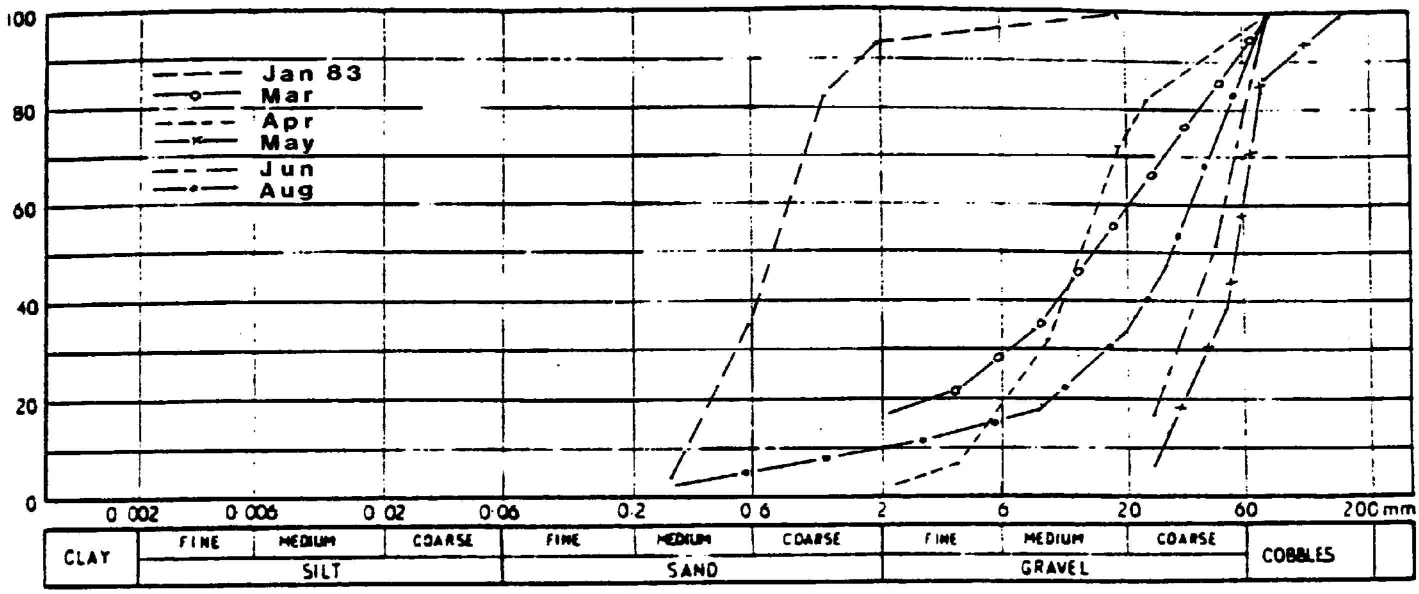


FIG. 6.7g Grading envelope for mid-tide samples. Profile 6

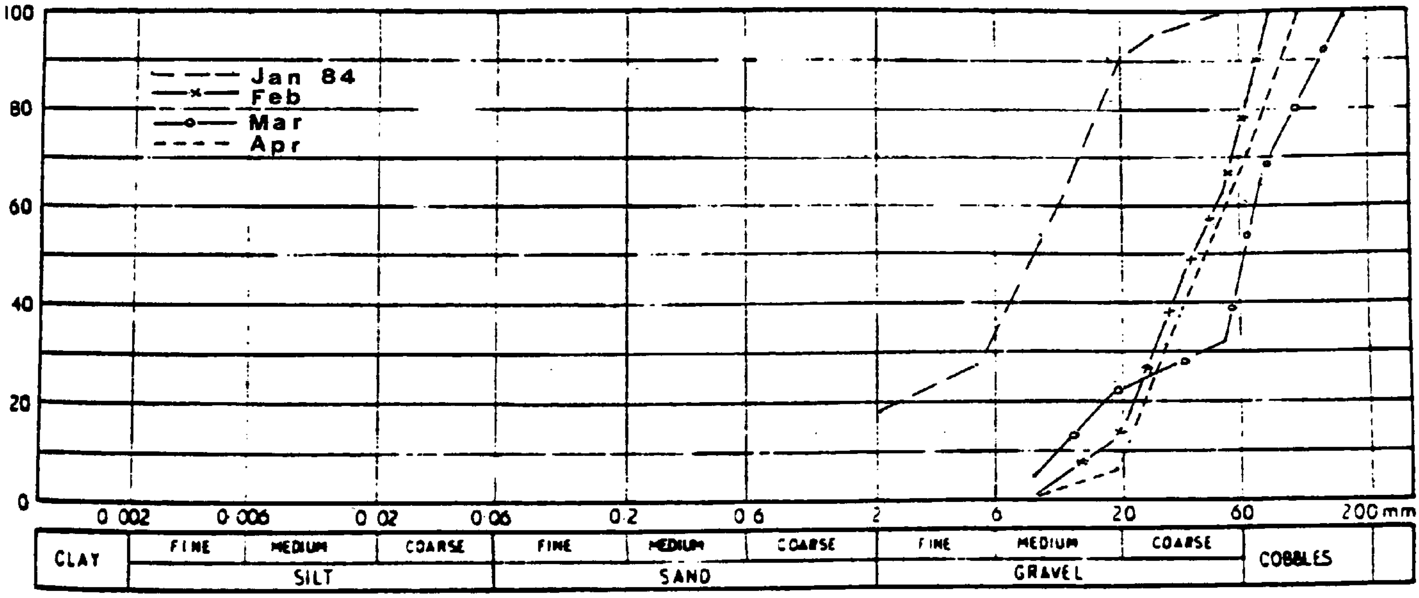


FIG. 6.7h Grading envelope for mid-tide samples. Profile 6a

Sediment samples taken at mid-tide positions (Fig. 6.7a) indicate well graded gravels with little or no sand. The figure suggests a coarsening of beach material during the summer months from a median grain size of 10mm during Dec-Feb to 40mm during Jun- Aug.

6.4.1 (ii) Llanrhystud storm beach. Profile 1A (chng. 12 + 00)

Although this is not a section of the coast that poses immediate concern in terms of land recession, local farmers are concerned about the periodic flooding of adjacent agricultural land where the drift platform in places falls to 4m below the beach crest. The storm beach at its highest point to the north of the bay is orientated in a 030° - 210° direction and again lies normal to the dominant westerly to north westerly storm waves of the Irish Sea.

It is possible that the origins of this storm ridge were related to higher sea levels of a possible Flandrian age (Haynes et al, 1977) although Orford (1978) has taken the view that crest sedimentation has occurred as a result of overtopping of the beach crest by swash activity during winter storms.

Random surveys taken at Profile 1A, positioned half way along the storm beach, indicate no change in beach morphometry during 1984 but a significant overtopping of the ridge during early 1975 (Fig 6.4b). Evidence of this process at +7.0m O.D had been observed by Orford (1977) when overtopping of the shingle bank by run-up transported coarse sediment from the beach face over the crest to the back beach area.

Mid-tide sediment samples taken at this profile (Fig. 6.7b) showed considerable variation in grain size - from cobble and coarse gravel to uniform fine to medium sand. These differences would appear to be a result of intertidal covering and exposure of sediments rather than to seasonal differences. Another explanation for this variation could be put down to the phenomenon of cusp development, frequently observed along this beach, when surveyed profiles can cross alternating positions of cusp centre and horns.

Surveys are likely to be needed for more than a decade to clarify any regular trend for loss or gain of beach material. However, Llanrhystud storm beach is the one section of this coast that can be assessed in terms of longer term fluctuation as comparisons can be made between the present survey and that in 1971 by Orford (1973).

Because the 1971 survey concentrated on relative horizontal and vertical distances between storm ridge and wave-cut platform the overall profiles are more simplistic in that they have been drawn from only 3 points. Also the siting of these profiles along the beach has been plotted from large-scale map features. However, the general shape and position of this series of profiles is considered accurate and when superimposed on the 1984 profiles, valid comparisons can be made.

Fig 6.8 gives a direct comparison of 3 profiles together with an onshore view of the changes in height of various beach features along 800m of beach.

Some variance was noted during the study period (1983-5) in the position of the sand zone that exists between the pebble ridge and the rock platform. This zone is over 100m wide in places and does appear at higher levels in the centre of the bay particularly at profiles 13 and 14 where it is nearly 1m higher. The relative widths and heights of the storm beach has varied little in the 14 year period. The position of the shingle edge has moved seaward by some 10m in this intervening time although the overall level of the sand/shingle interface has remained constant.

The bulging of shingle at the base of the beach face is apparent in the 1984 profiles but the increase in beach volume is difficult to quantify. During 1971 survey beach crest height along Llanrhystud beach, as represented by the seaward edge of the ridge top, showed consistent values around 6.4m above O.D. The rise in level from 6.4 to 7.5m above O.D represents an overall increase in beach volume of only some 3-4%.

There appears to be little or no lateral movement of beach material within the embayment and no evidence to support the northerly drift of sediment suggested by both Steers (1946) and Kidson (1963) for this part of Cardigan Bay. Examination of consecutive profiles shows there is no obvious increase in beach volumes northwards along the beach towards the sub-headland at the mouth of the river Wyre (chng. 4 + 00).

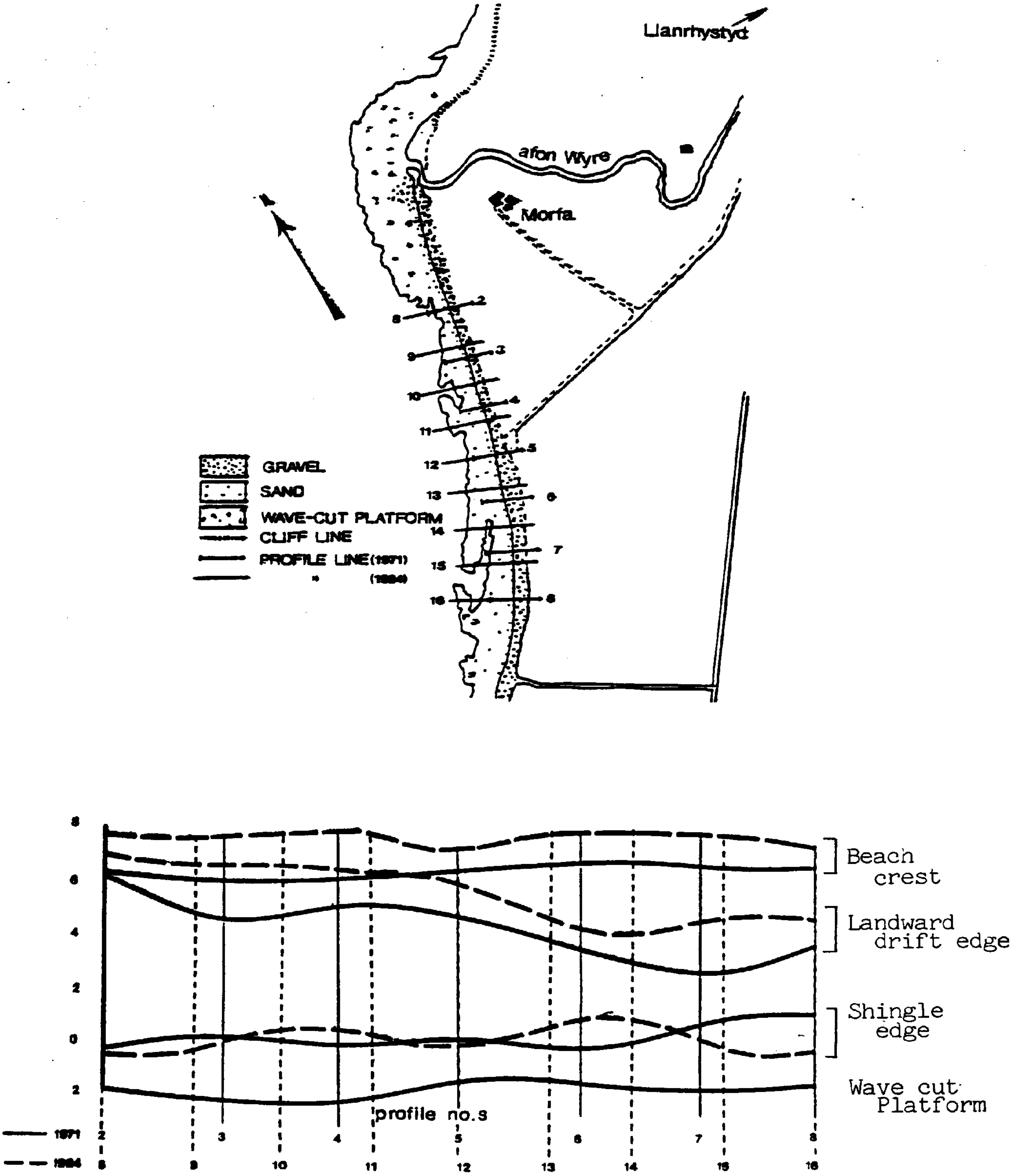


FIG. 6.8 Plan view and longshore profiles of changes in Llanrhystud storm beach 1971 - 84

6.4.2 Llansantffraid beach. Profile 2 (chng. 38 + 00).

What have been defined by the writer as Llansantffraid (Profile 2) and Llanon (Profile 3) beaches are essentially sections of the same beach located in the small embayment formed by the shallow headlands of Llansantffraid to the north and Morfa to the south.

Llansantffraid beach to the north of the bay lies between the mouths of the rivers Peris and Clydan and aligns normal to west-north-west (295°). This section fronts a cliff of till some 3m in height which is presently undergoing erosion, particularly at the southern end where private caravans sited near the cliff edge are constantly under threat. Beach width is narrow and the cross-sectional area at Profile 2 is approximately $80m^2$.

Level surveys and sediment samples indicate a stable beach. Sweep zones drawn in Fig 6.4c show a constant beach level with only the intermediate survey of 12.11.82 showing any deviation from the average profile - a scouring at the foot of the beach face and a loss of beach volume which was recovered by the following month.

Mid-tide samples (Fig 6.7c) show a consistency of gravel-sized sediments, well-graded from 100mm to 2mm with the 1983 October and November samples suggesting the existence of a sand pocket, possibly as a result of the uncovering of the gravel layer.

6.4.3 Llanon beach. Profile 3 (chng. 46 + 00)

South of the river Clydan the cliffs continue at the same height and level for some 300m before being reorientated by some 30°,reducing in level and forming the long sweeping headland of Morfa Mawr. Before the headland beach levels are correspondingly low and fall below 4.0m above O.D.

On a historical note this section of beach was at one time retained by a breakwater (chng. 47 + 30) which gave ships access to the old limekiln. During the 19th century these limekilns provided Ceredigion with agricultural fertiliser and mortar for building. Ships would come close to shore at high tide to discharge limestone overboard which was then collected from the beach at low tide.

At the now derelict breakwater a fall in beach level from south to north is discernible and measured cross-sectional volumes decrease by up to 40%. Whilst the breakwater may at one time have given beach and cliff some stability it is worth noting that the site of the old limekiln is now under threat.

Sweep zones (Fig. 6.4d) again show a gradual build up of beach volumes during late autumn and erosion of the beach face during January storms. Beach profile has been maintained with the maximum range of movement at the cliff base being only 0.8m. Grading curves (Fig. 6.7d) show a medium to coarse gravel with some cobbles.

6.4.4 Morfa Beach. Profile 4 (chng. 57 + 00)

This is a small embayment at the mouth of the river Morfa. North of the river the shingle beach fronts cliff of till some 4m in height where erosion is prevalent . South of the river, where the beach is backed by steep slopes of glacial material banked against the country rock, the rate of slope retreat is not known but the well-grassed slopes suggest stability.

From the position of the beach immediately north of a 1.8km long section of high sea cliffs it is apparent that drift sediment is impeded by the rocky shoreline. Monitoring of a rockfall in the Aberystwyth Grits at chng. 61 + 00 suggest that the time lag before any sediment from the cliffs reach adjacent beaches is considerable. Finer material may well be lost offshore which accounts for the dominance of large boulders in the area.

The beach profile is stable with seasonal change minimal (fig.6.4e). Beach grading is also constant (Fig. 6.7e) indicating gravels well-graded from 150mm down with some sand.

6.4.5 Aberarth beach. Profile 5 (chng. 89 + 00)

This beach fronts the village of Aberarth where substantial alterations to revetment works in the early 1970's has ensured stability. This section of beach is retained by numerous groynes and backed by a series of longshore gabions which gives artificially high values of beach height.

East of the groyne system, the 400m section of beach (chng.87 + 50 to 91 + 50) is backed by vertical cliffs of till some 5 metres high. At chng 89 the series of beach profiles (Figs. 6.6c) indicate that shingle is generally accreting at the top of the beach during the summer and autumn months. This upper foreshore zone is susceptible to January storms when material is lost from the beach.

Particle size distribution curves (Fig. 6.7f) show a consistency of grading with all the mid-tide samples in the fine to coarse gravel zone. The average grading has a median grain size of 15mm.

Along this section beach levels at foot of cliff are lower than normal and at chng. 92 + 00, where the coastline is reorientated by some 30°, this lower beach level allied with a change in till facies has contributed to a marked increase in contemporary cliff retreat rates.

6.4.6 (i) Aberaeron north beach. Profile 6 (chng. 109 + 00 app.)

The north beach at Aberaeron fronts a substantial sea wall which has been improved in recent years. The beach is retained by a series of groynes and beach volumes are consistent. (Fig. 6.4g).

Sediment samples vary in grading from coarse sand (January) to coarse gravel (June) but this variation could be as much due to local variability in beach sediments as to seasonal differences (Fig. 6.7g).

6.4.6 (ii) Aberaeron south beach. Profile 6A (chng. 114 + 00)

Lying immediately south of the harbour mouth at Aberaeron this shingle beach displays a simple storm ridge typically found in pocket beaches between two headlands (Carr, 1983).

In Fig. 6.4h a typical swell profile for late autumn is characterised by a temporary berm which has been removed in the January profile. Beach sediment in the main consists of cobbles and coarse gravel (median size 45mm) (Fig. 6.7h).

6.5 Longshore movement along beaches

6.5.1 Shingle beaches at Llanrhystud, Llanon and Aberarth

In August 1982 direct measurements of pebble characteristics were undertaken every 100m along the coastline, the coastline being divided into three main embayments largely defined by shallow headlands although the exact demarcation of these from maps was subjective.

This exercise was an attempt to give some indication of material distribution along the shingle beaches and, as such, was more concerned with sediment movement caused by longshore transport than with the nature of any relationship of individual pebble movements to wave criteria.

Shingle, in this context, is used to describe beach pebbles, generally rounded or sub-rounded, having a long axis of between 4 and 256 mms. In descriptive terms for grain size these include gravel (2-60mm) and cobbles (60-200mm) although the constituents of storm beaches can exceed this size range as, for example, at Llanrhystud.

A group sample of 100 individual pebbles was measured at each profile from within the high-tide zone, this location being considered more representative of the larger-size fraction transported by the higher wave forces prevalent in Cardigan Bay. Caliper readings of the three major axes (a, b and c) were recorded and shape indices based on these axial ratios were calculated as per the sphericity concept proposed by Sneed and Folk (1958).

Carr (1983, p97) has commented that " the criteria for pebble sorting along and across the inter tidal beach vary, with sometimes size and sometimes shape being important, and it is not yet apparent as to how specific wave parameters affect this process".

In most research where pebble measurements have been made it has been the long (a) or intermediate (b) axis which has been taken although studies at Chesil Beach, Dorset (Carr, 1974) and Start Bay, Devon (Gleason et al., 1975) indicate that it is invariably the short (c) axis that gives the best correlation between distance travelled alongshore and a specific pebble axis. However, the various field results obtained from research work point to a more complex situation and grading trends are often reversed.

As sieving is also governed by the intermediate axis it seemed logical to take the 'b' axis as indicator. Group mean values for 'b' axis were calculated and the relation between particle size and position along shore is shown in Figs. 6.9a-c.

At Llanrhystud there is a considerable difference in the mean particle sizes (b = 36 to 68mm) with a coarsening of beach material from S.W to N.E. This trend is again seen at Llansantffraid - Llanon (b = 37 to 58mm) but not as obvious at Aberarth where smaller size material is evident (b = 28 to 48mm) and where the groyne system at the northern end of the beach may influence longshore transport.

Shape factor appears unimportant and may be due to the rather limited range occurring (S & F index 0.46 to 0.52). Carr (1983) has suggested that the comparative unimportance of shape factors at Chesil Beach may also be as a result of higher wave energy on the strength that many other beaches where shape sorting has been described e.g. Cailleux (1948), Humbert (1968), Carr (1974), Gleason et al., (1975) and Carr and Blackley (1975), are in relatively low energy environments.

6.5.2 New Quay and Cei Bach beaches

New Quay and, to a lesser extent, Cei Bach bays exhibit in plan the concept of the classic crenulate shape bay approached by Jennings (1955) and later Davies (1958) and developed by Silvester (1960) using model studies.

The equilibruim shape for the coastline, with oblique swell from the N.W., is that of a half heart, the curved portion at the up coast end (New Quay Head) and the tangent section at the down coast end (Llanina Point).

The northerly or, more exact, north westerly direction of net sediment transport has been indicated by the littoral drift model (chapter 5) and can be deduced from accumulation against groynes at several locations along the coast. Along New Quay and Cei Bach beaches this north easterly drift of sediment appears to be indicated by a coarsening of beach material in the upper foreshore zone.

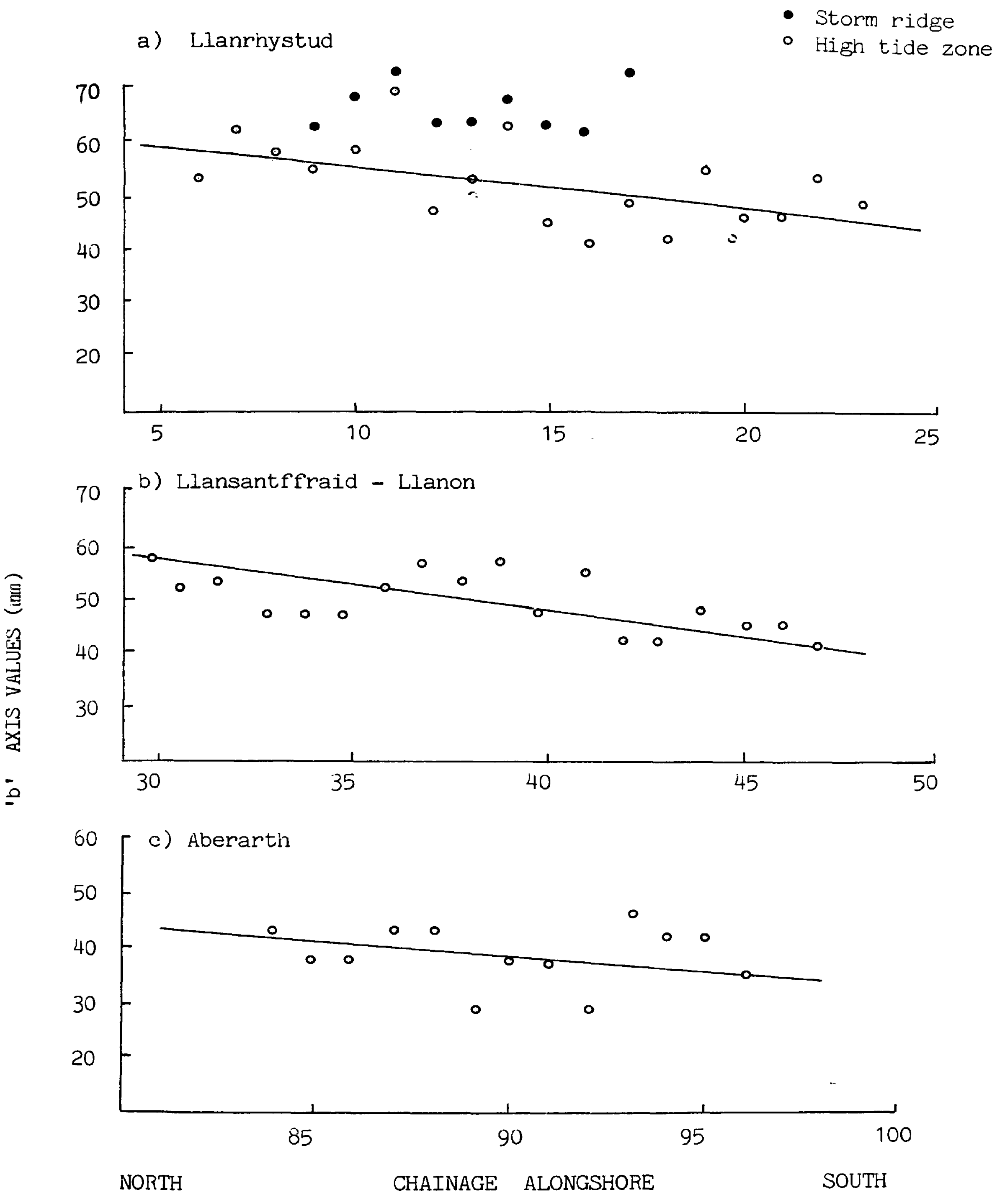


FIG. 6.9 a-c Relationship between pebble sizes and position alongshore

Mid-tide grading is used as a predictor of transport direction and there are numerous examples of both fining and coarsening along transport paths. Along beaches size may either increase, as in the case of East Anglia (Cambers, 1973; Craig-Smith, 1973 and McCave, 1978) and Cape Cod (Schalk, 1938), or decrease as in the case of southern Long Island, New Jersey (MacCarthy, 1931) and Cedar Point on Lake Erie (Pettijohn and Ridge, 1932).

Grain size was determined in samples taken from the mid-tide positions of the beach face (Profiles 160 - 192) at 3-monthly intervals over an 18 month period. Gravel size was removed from the samples so that data represented only the sand fraction although the frequency of occurrence of sizes larger than 2mm was rare.

Information presented in Table 6.1 shows the mean grain size at each profile along the two bays. The figure shows little seasonal variation in grain size and no overall pattern of sediment movement, suggesting perhaps that tidal currents simply work and re-work sediments along the beach.

It is possible to conclude therefore that longshore drift is minimal and that, except for minor periodic cycles of reversed movement of material, these particular bays are approaching equilibrium with little sediment being supplied to, and passing through, each bay.

6.6 Comparison of theoretical and actual longshore beach morphology

The usefulness of the wave refraction model designated in Chapter 5 in identifying zones of erosion and deposition along the Ceredigion coastline was gauged in terms of a comparison between predicted and surveyed beach morphology.

In sections 6.4 and 6.5 seasonal trends in sediment movement have been accounted for and it has been deduced that the beaches are generally stable and that present day conditions are characteristic of the longer term. As the model represents long-term beach structure, comparisons with the field survey are therefore valid.

Fig 6.10 shows a simplified map where data from the model is compared with geomorphic evidence from the field. Actual 'high' and

	MEDIAN GRAIN SIZE (mm)						
PROFILE	JAN '83	MAR '83	JUN '83	SEPT '83	JAN '84	MAR '84	MEAN
160		0.20	0.19		0.19	0.26	0.21
162		0.22	0.19		0.21	0.19	0.20
164		0.21	0.20		0.20	0.20	0.20
166		0.22	0.22		0.20	0.20	0.21
168		0.18	0.20		0.18	0.20	0.19
170		0.27	0.21		0.23	0.25	0.24
172							
174	0.21	0.20	0.18	0.23	0.24	0.24	0.22
176	0.21	0.23	0.25	0.24	0.24	0.26	0.24
178	0.18	0.18	0.22	0.21	0.24	0.23	0.21
180	0.18	0.21	0.20	0.20	0.25	0.25	0.21
182	0.30	0.22	0.21	0.20	0.29	0.20	0.24
184	0.21	0.21	0.26	0.20	0.21	0.25	0.22
186	0.21	0.21	0.20	0.20	0.21	0.21	0.21
188	0.18	0.23	0.21	0.21	0.20	0.23	0.21
190	0.25	0.27	0.27	0.29	0.27	0.25	0.27
192	0.25	0.28	0.28	0.28	0.27	0.22	0.26
MEAN	0.22	0.22	0.22	0.22	0.23	0.23	0.22

TABLE 6.1 Grain-size median variation in mid-tide samples for beach profiles in New Quay and Cei Bach bays

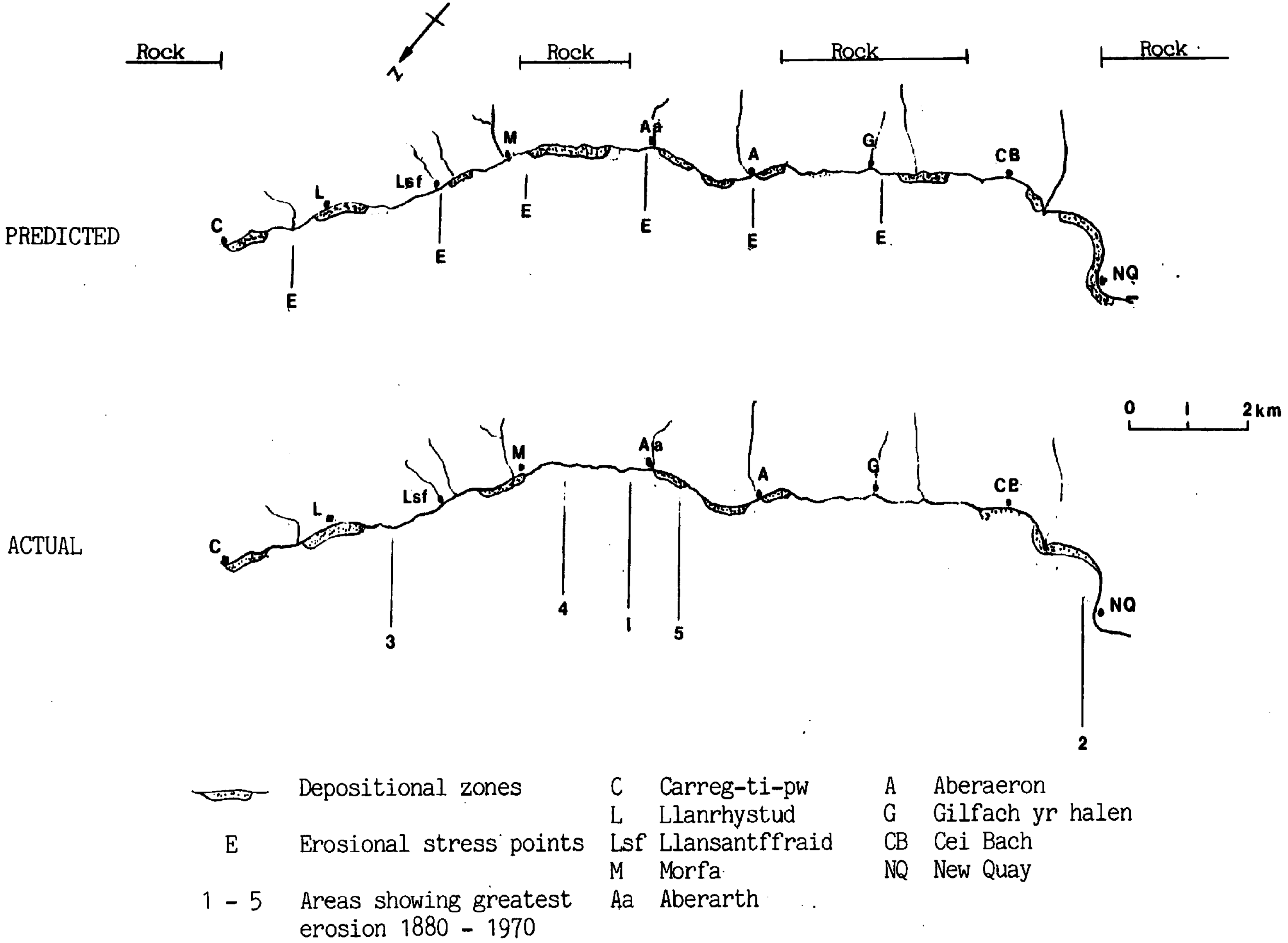


FIG. 6.10 Simplified map of predicted and actual zones of erosion and deposition

'low' beaches have been interpolated from the profile data presented in the Appendix. As sediment cells presented are numbered from south to north, the following discussion will gauge correspondence between predicted and actual zones of erosion and deposition, starting at New Quay in the south and ending at Llanrhystud in the north.

Increasing deposition is identified to the north eastern ends of New Quay and Cei Bach bays though the model predicts a depositional zone to the south-west of both bays. This discrepancy may be explained by one of several reasons:-

(i) wave diffraction induced by New Quay Head
(ii) tidal currents within the two bays
(iii) wave shadow areas due to shallow offshore rocks off the two headlands of New Quay Head and Llanina Point
(iv) presence of engineering structures

As noted in section 6.5, New Quay bay, and Cei Bach bay to a lesser extent, are quite sheltered from winds from south east through south to west but with the winds northward of west a heavy sea swell rolls into both bays.

The complex circulation within New Quay bay is indicated in Fig. 6.11 where tidal currents produced by the ebb and flow of tides alternate in direction in the nearshore zone. Although of limited importance in terms of sediment flow on open coasts, in New Quay and Cei Bach the velocity of tidal currents in a locally restricted zone is related to tidal range and may temporarily exceed 3km/hour.

The natural morphology of headlands such as New Quay Head and Ina Point may impede the longshore drift of sediment but the lack of deposition at the westerly ends of both bays must also be related to the presence of engineering structures.

New Quay beach and harbour are protected by a stone pier extending some 200m eastwards from the mainland. Small piers near the lifeboat station and Ina Point (both recently extended in 1984) give further protection to the westerly sections and further inhibit the north easterly drift of material. What is not known is the degree to which

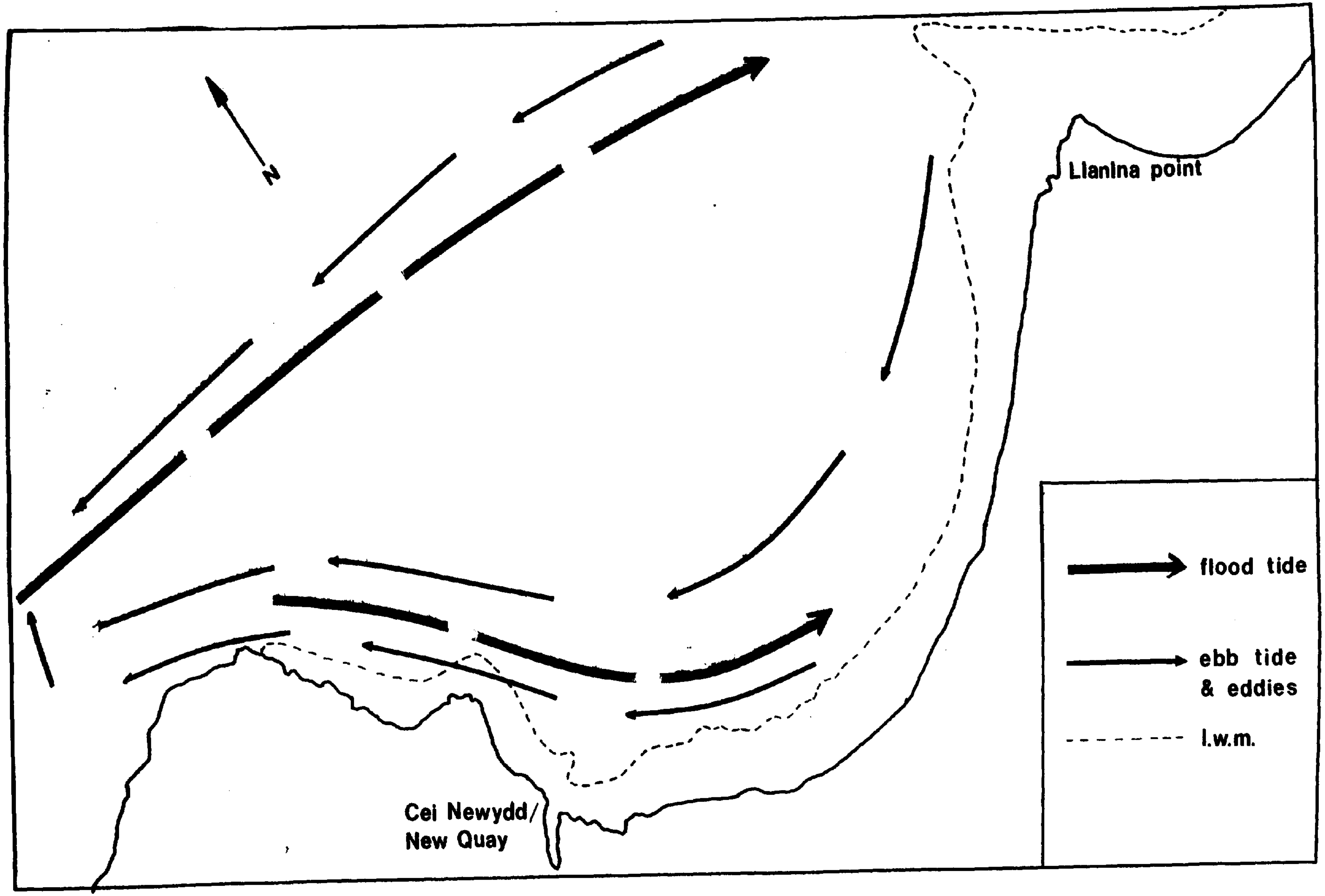


FIG. 6.11 Tidal circulation in New Quay Bay (after Heywood, 1984)

the model littoral drift system is influenced by external impacts such as these engineering structures. The effect of any structure would depend not only on its type and size but also the sediment zone in which the structure occurs and the position of that zone within the integrated system.

At Cei Bach the section of beach immediately after Llanina headland may also be affected by a "wave shadow area" caused by a reef of rocks extending about 0.5 km from Ina Point in a north westerly direction, most of which is exposed at low tides. This would explain the absence of the deposition zone predicted by the model, although profile 168 is locally high within a 400m length of beach, (Fig. 6.10). In the centre of the beach the groyne system and sewer outlet aligned normal to the shore in a zone of easterly transport has not had any noticable effect on sediment movement.

The rock buttress at the north eastern end of Cei Bach bay prevents further sediment drift and beach profiles no's 162 and 160 show a build up of beach material, with the top of beach at 6m above O.D and a narrow storm ridge.

Around the buttress the profiles show a gradual lowering of beach heights to 1m above O.D at profile 148. This higher beach level near Graig - Ddu could be indicative of the longshore sediment protrusion suggested by the model.

Between Cei Bach and Gilfach-yr-halen the model predicts a depositional zone with drift directed to the south. In contrast the area indicates a general deficiency of material, although the complex morphology precludes any definite statement of sediment drift trends. This section of coastline is characterised by caves and jagged-rocks with a narrow rock platform and scarcity of beach sediment.

The predicted low beach at Gilfach-yr-halen is substantiated; a high beach measured at the mouth of the river Gilfach, with a large cross-sectional volume of material relative to the remainder of the beach, can be explained by fluvial deposition.

North along Gilfach beach from the river mouth the gradual reduction in beach volumes is consistent with the erosional zone indicated in the model. Aerial photographs suggest an intermediate sediment bulge along the coast towards Pen-y-Gloyn with an equilibrium point at the headland. The net result of northerly drift within this sediment cell is the high, steep beach immediately south of Aberaeron harbour.

The section of the Aberaeron waterfront is the area of coastline most modified by man's influence, beginning with harbour developments in the early 1800's. Coastal structures north-east of the harbour exist in an area predicted as predominantly one of transport and might be expected to have deleterious effects further east towards Aberarth. At the headland (chng. 102) the beach foreshore is up to 50m wide and consistently between 4 and 5m above O.D. Over a 400m section the beach has been artificially built up with fill material. Old breakwaters in the vicinity of chng. 97 have further impeded the northerly drift of material. At chng. 93 + 00 a sudden reduction in beach volumes coincides with a section of high erosion (Table 3.1, site D).

Between chng. 93 + 88 there is a gradual steepening of the foreshore and the depositional node predicted for chng. 89 + 00 approximately is borne out in the survey by a high beach level of 4.6m above O.D. The model predicted an erosional node near the mouth of the river Arth where erosion had evidently been a serious problem in the past. In the early 1970's revetment works (chng. 87 - 83) have alleviated this problem and have afforded protection to the houses which fringe the cliffline.

Immediately north of the river mouth (chng. 82 - 78) a generally low beach is in agreement with the erosional zone predicted. The undercutting of boulder clay cliffs in this area is problematic.

To the east, at chng. 73 + 00 approximately, the model illustrates a zone of change from erosion to deposition but this depositional zone is not borne out in the longshore survey. The section of the Aberystwyth Grits between Aberarth and Morfa is similar in character to that south of Gilfach-yr-halen. This cliffed section reveals a gently sloping platform which extends from high tide level to beneath low tide level. The inner platform is generally narrow (<3m) and slopes at some 1:12 and is devoid of pebbles and boulders. The outer platform slopes at some 1:80, is covered with large boulders and extends some 100m + to low water mark.

The high and low beaches predicted near Graig Ddu (N) - chngs. 63 and 61 respectively - are not identifiable. The embayment at the mouth of the River Morfa has a relatively high beach (5.0m above O.D) which extends around the flat curve of Morfa headland and which is not predicted by the model.

Neither the depositional zone and high beach predicted at the mouth of the river Clydan (chng. 43 + 00) nor the erosional zone and low beach predicted near the mouth of the river Peris (chng. 36 + 00) is shown in the field survey which indicates a uniform beach between the mouths of the two rivers with little variation in beach height or volume. This embayment is the one section of coast where major inconsistencies occur between predicted and actual deposition which cannot conveniently be explained.

North-easterly drift around Llansantffraid headland leads to the significant depositional zone and high beach along Llanrhystud bay. Around Llanrhystud headland a predicted erosion zone and low beach is identified before the continuing northerly drift of material leads to a high beach near Carreg-ti-pw.

CHAPTER 7.

ENGINEERING PROPERTIES OF CLIFF MATERIALS

7.1 Introduction

Long-term evidence from map sources (Chapter 3) suggests active cliffline retreat along this section of the Cardigan Bay coastline, particularly in sediments of glacial origin. In this chapter, cliff material properties which influence behaviour in terms of erodibility are investigated.

A detailed study of the basic engineering properties of the various geologically distinguishable glacial deposits within the area has been carried out. At different sites samples have been taken to identify and classify the till materials and to ascertain the inherent variability within and between them. Because of their high stone content and high degreee of compaction, they presented special problems in sampling and testing.

Index tests which could provide useful comparison between the facies are discussed and a brief description of the field and laboratory tests, together with their applications and limitations, is given. An estimate of rock strength was obtained along the numerous rock exposures.

This section presents summarised results of standard tests carried out on samples of the main soil and rock types most commonly encountered and attempts to relate (i) the compressive strength of the cliff materials to long-term retreat rates and (ii) the properties of glacial soils to the contemporary retreat rates.

7.2 The Pleistocene history of the Cardigan Bay area

The detrital sediments enveloping the cliffs and hills of the Cardigan Bay coast have been interpreted by most workers as till (Section 3.3) although Watson (1972) maintained that they could be periglacial deposits and has drawn attention to similarities with deposits in N.W. France which are beyond the normally accepted limits of Pleistocene ice advance.

As a means of identifying areas which were ice free during the last glaciation it has been repeatedly proposed that the distribution of periglacial structures and landforms is relevant, (Stephens, 1966; Mitchell, 1962, 1972; Synge, 1964; Stephens and Synge, 1966; Watson 1965, 1972; Watson and Watson, 1967). Bowen (1973a),however, has considered that periglacial structures such as involutions, vertical stones and ice wedges are invalid as a means of time stratigraphic sub-division and that they simply indicate the former presence of permafrost.

Watson (1972) also claimed that pingo remains in Ceredigion demonstrate that ice free conditions existed during the last glaciation; Bowen (1973a)again has questioned whether the features described represent true pingo remains. Usage of other periglacial landforms such as solifluction terraces (Watson, 1968) in identifying ice free areas has been criticised by Potts (1971).

However, it was not the purpose of this study to attempt to recognise or contest the nature of the mode of deposition of these soils, suffice to state that they were probably deposited in the later stages of the Pleistocene glaciation over the bedrock of the Aberystwyth Grits of Silurian Age.

7.3 Till - general characteristics and related terms

The name "till" was originally applied in Scotland to a stiff, hard clay sub-soil, generally imperious and unstratified. Geikie (1863,p185) redefined it as "a stiff clay full of stones varying in size up to boulders produced by abrasion carried on by the ice sheet as it moved over the land."

The definitions of till have varied since then from one author to another but most stress the following characteristics:

1) Glacial origin
2) Presence of a variety of rock and mineral fragments of various sizes, many of them having been transported a considerable distance
3) Poor sorting, in the geological meaning, i.e presence of a wide range of particle sizes, usually with bi-modal or multi-modal

distribution

4) Lack of stratification, although some tills are foliated, or even truly bedded
5) Compactness or close packing, also with certain exceptions

Till can be considered the non-sorted variety of material implied by the generic term glacial drift (Lyell, 1839), in contrast to sorted glacial drift which may include material from high-energy glacial streams (glaciofluvial) or from low-energy glaciolacustrine environments and involve transportation and deposition by agents other than ice.

Other terms which have been used synonymously with till,particularly as descriptive terms, are the English term boulder clay and the French terms moraine and moraine profonde. As till is a clastic sediment not a landform (Harland et al., 1966), the word moraine is not perhaps a good synonym as it confusingly implies a drift land form not necessarily composed of till.

In engineering terms, till is regarded as an "unstriatified glacial deposit of clay, silt, sand, gravel and boulders that covers part of the rock surface in those regions which were glaciated during the ice age" (Terzaghi and Peck, 1967, p7).

In order to emphasize that till is a glacial deposit, the word "glacial" is often added. Goldthwait (1971, p3) however, stresses that "till is the only sediment stemming directly and solely from glacial ice". Hence, according to Flint (1971, p3) " the term (till) is both sedimentalogic and genetic the frequently used term glacial till is redundant". For this reason the short term till has been used generally in this study.

7.4 Classification of tills

Since one of the earliest engineering studies of glacial material was made by Legget (1942), numerous methods have been proposed for the classification of tills, most of which are based on grain size analysis.

Bennel (1957) used the range of water content between the liquid and shrinkable limits of the fine grained fraction in his classification, although this LS difference was later dismissed by McGown (1971). Grain size analysis using only the sand and clay percentages was suggested by Shepps (1958) while Elson (1961) plotted grain size distribution on Rosin and Rammber's "Law of Crushing" paper. Other methods include a statistical technique considering sieve sizes at which certain percentages by weight was passing (Chryssaforpoulos, 1963) and bi-modal particle size distribution (Dreimanis and Vagner, 1969).

McGown (1971) suggested a classification system based on lithology, depositional history, mix proportions of coarse and fine fractions and, more importantly, the identity of the matrix. He noted that the variation in the engineering proportions of the fine soil fraction was greater than that of the coarse fraction, and that this often tended to dominate the engineering behaviour of the till.

An extensive review of the various types of glacial deposits and their engineering properties has been provided by Fookes et al, (1975). According to Boulton (1975) and Boulton and Paul (1976) the properties of any deposit are influenced by genetic processes and McGown and Derbyshire (1977) have since devised a quite elaborate system for the classification of tills. Their classification is based upon the mode of formation, transportation and deposition of glacial material and provides a general basis for the prediction of the engineering properties of tills. However, a glacial deposit can under-go considerable changes after deposition due to weathering, especially in coastal situations where the influence of wave action is important.

Particle size distribution and fabric are evidently among the most significant features as far as the engineering behaviour of a till is concerned. Till fabric comprises structures of primary and secondary origin, any of which may affect its strength and permeability. These include the deposition of clasts and, in particular, the preferred orientation of the long axes (a) of the larger rock fragments.

7.4.1 Till fabric analysis

Till fabric analysis is one of the most commonly used techniques in glacial geology although much of the hypothesis regarding the actual process by which tills acquire these fabrics is speculative. It has commonly been used to find information on the direction of movement of the depositing glacier and the mode of origin of the till, although to infer genesis by till fabric alone seems to be extremely difficult as so many different processes can produce similar results.

The term fabric was defined by Pettijohn (1957,p72) as "the orientation, or lack of it, of the elements of which a rock is composed". Fabric in till was noted a century ago (Elson, 1965) and has been described by Andrews (1971,p321) as "a sample of a 'population' of till stones at an exposure".

In the context of this study, fabric analysis may be useful in assessing the engineering behaviour of the till in terms of resistance to erosion. Field work was used to analyse a limited number of sections in order to observe any variability of till fabric, both within a single exposure and between adjacent exposures. All the fabric information presented alludes to the size and shape of the clasts and to the preferred orientation and dip of their long axes within the matrix.

7.4.2 Field Procedure

Macrofabric analysis was carried out at 10 locations within each of the 3 sites, A, B and D indicated in Figs 3.12 a and 3.12b. Site C at Morfa headland was not considered because of the shallowness of the till face (<1.5m) which in many places was overgrown and obscured by beach material. Sampling at the other 3 sites was limited to the lower 2m of the till i.e the available population. Bias was avoided as far as possible by ensuring that visually there was no meaningful difference in fabric within the whole of the vertical face.

At each location the bearing and plunge of the long axis of ten stones, ranging in size from 20 to 150mm, were measured. A sample size of ten measurements was chosen because it was considered more relevant to take a larger number of samples with less observations per sample, rather than to increase the number of pebbles per sample (Andrews and Smith, 1970).

The orientation of each pebble was determined by excavating around it until all axes were visible. The pebble was then gently removed from the till matrix. A non magnetic 3mm brass rod was inserted in the 'cast' left by the pebble, orientated parallel to the long or 'a' axis. Bearing (or azimuth) and plunge (or dip) were measured with a Suunto compass/clinometer aligned alongside the rod.

The length of axes, the long (a), intermediate (b) and short (c), was measured with sliding calipers and the clast roundness assessed by reference to a standard Krumbein chart.

7.4.3. Till fabric description

7.4.3.1 Size

Mean values of the 'a','b' and 'c' axes for each of the 3 sites are given in Table 7.1. The sampling procedure may have been biased towards a larger pebble size in that (i) an effective lower limit is imposed by the crudeness of field techniques when material is less than 10mm,and (ii) there is a great temptation when sampling a vertical face to select the larger pebbles that are projecting out of the face.

Nevertheless, comparison between sites should not suffer and in terms of pebble size the exposures are not readily differentiated although the Aberarth site shows a marginally greater median size for the 'a' axis.

7.4.3.2 Roundness

The same pebbles (10 per sample) used for size and shape measurements were compared to Krumbein's (1941, Fig 7.1) roundness scale (0.1 = very angular, 0.9 = well rounded).

The mean values for the individual sections grouped well with the gross mean roundness for Llansantffraid being 0.56, Llanon 0.49 and Aberarth 0.54.

Roundness data showed that 72% of the pebbles measured were sub-rounded (0.4 - 0.6 index) 20% rounded (0.7 - 0.9) and only 8% angular

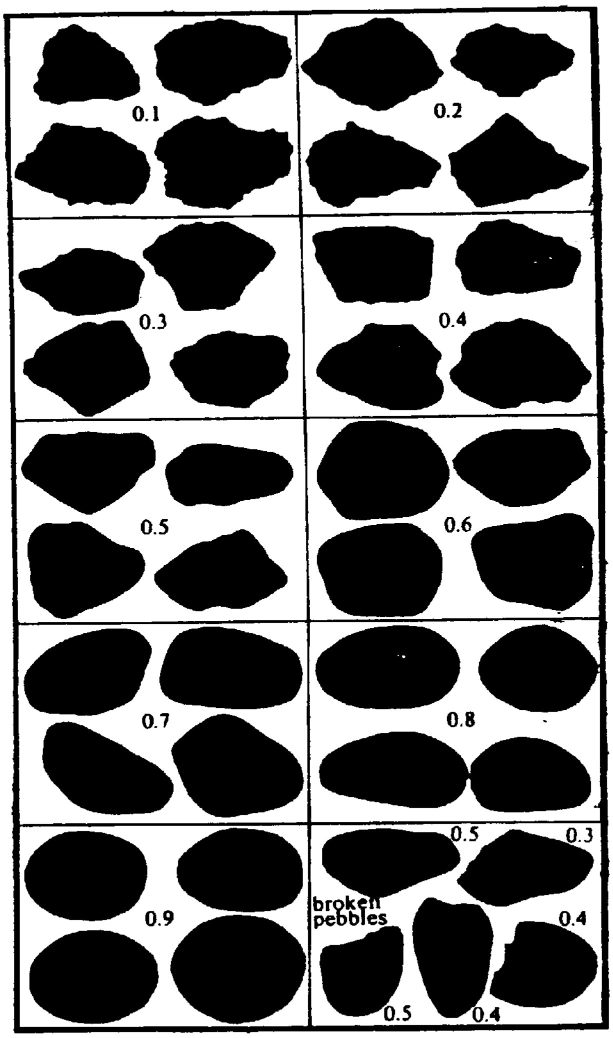


FIG. 7.1 Images for the visual assessment of pebble roundness (based upon Krumbein 1941)

SITE LOCATION (Figs. 3.12a & 3.12b)	AXIAL LENGTH mm			ZINGG SHAPE INDEX			KRUMBEIN ROUNDNESS
	a	b	c	$^{b}/_{a}$	$^{c}/_{b}$	Shape	
Llansantffraid (A)	57.2	40.5	25.5	0.71	0.63	Disc	0.56
Llanon (B)	60.0	37.9	0.63	0.63	0.64	Blade	0.49
Aberarth (D)	70.1	41.6	24.3	0.59	0.58	Blade	0.54

TABLE 7.1. Mean axial lengths, shape and roundness indices for till clasts

(0.1 - 0.3). This suggests that the drifts are locally derived, as pebbles are rapidly rounded during transportation and roundness value of 0.5 can be attained within a few miles of their source (Drake, 1968).

7.4.3.3 Shape

Shape, the relationship between the axial lengths, can be assessed by calculation of one of any number of shape indices e.g Zingg (1935) or Sneed and Folk (1958).

The average shape of each ten pebbles was plotted as a point on a Zingg diagram in Fig 7.2, which delimits four broad groupings,namely oblate, spherical, bladed and rod shaped. From this figure it is seen that the different till units show a consistency of particle shape, confined mainly to discs and blades with few spheres. The Aberarth till tend to show a predominance of blades.

7.4.3.4 Orientation and dip

Fabric data from the different exposures are shown as two dimensional diagrams in Fig 7.3. Each diagram represents a 10-stone sample from which the bearings of long axes of stones are grouped in 20-degree class intervals. Polar equidistant diagrams in Fig 7.3 a-c indicate both bearing and plunge of individual pebbles.

From these figures, it is seen that the long axis of elongated stones in these deposits lie predominantly parallel to the slope of the land and at right angles to the existing coastline. This suggests that drift material was laid down by local ice moving broadly east to west, the assumption being that clasts will be orientated in a direction which corresponds to an equilibruim condition of the applied force field, be it gravity, river or glacier.

Pebbles from the Llansantffraid site have their axes orientated E - W dipping 0-20 degrees down from the horizontal in an easterly or up glacier direction. The till diagram for Llanon shows a similar preferred W.N.W - E.S.E orientation although the dips are well distributed with only 32% dipping 0-20 degrees. At Aberarth the

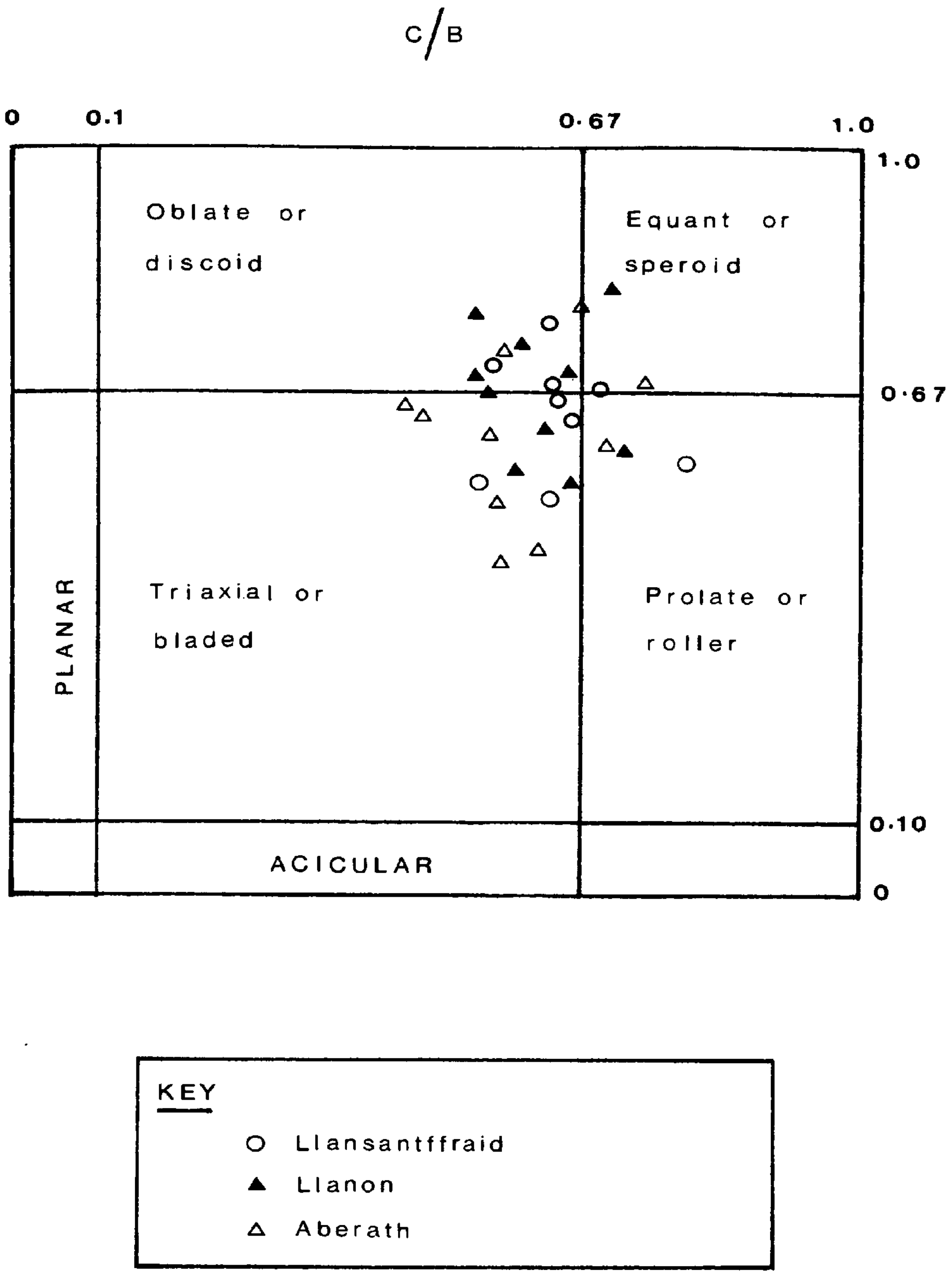
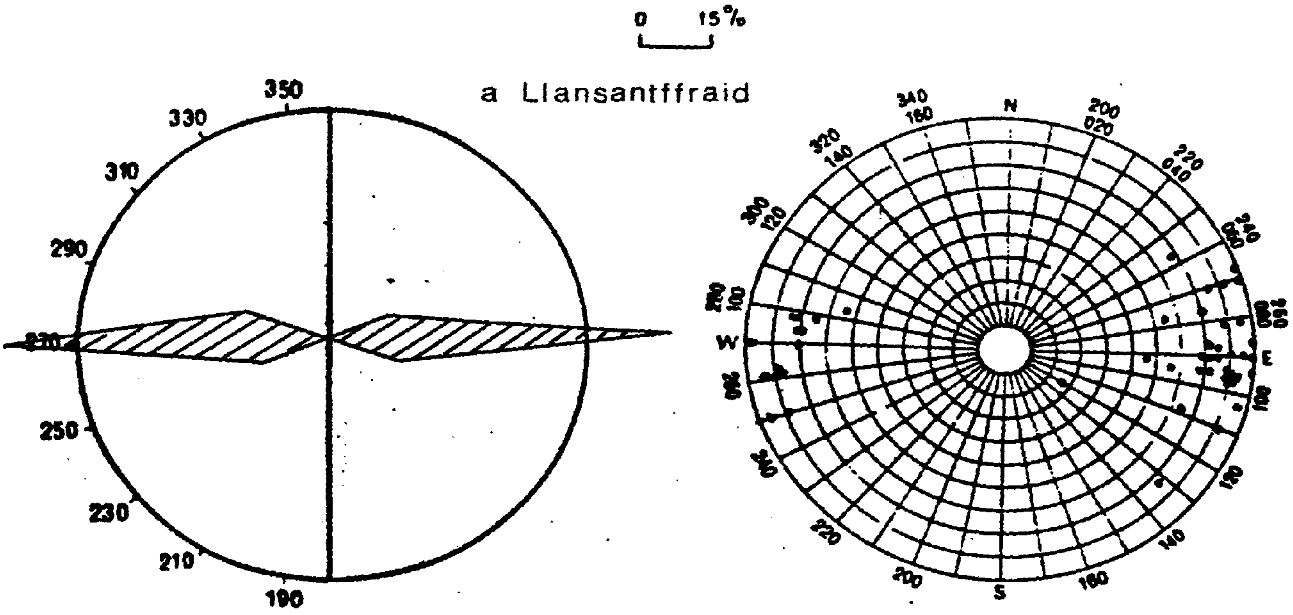
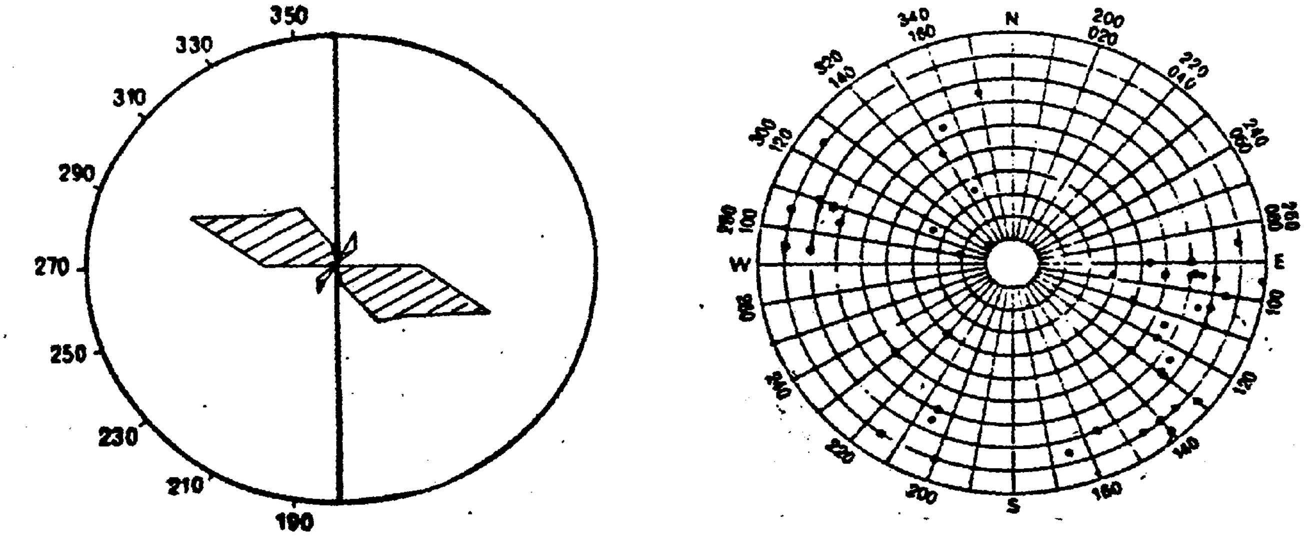


FIG. 7.2. Zingg diagram of till pebble shapes. Each point represents the mean value of 10 pebbles from each site.
Classification of particle shape is based upon Zingg (1935) with additions of Brewer (1964).

a Llansantffraid



b Llanon



c Aberarth

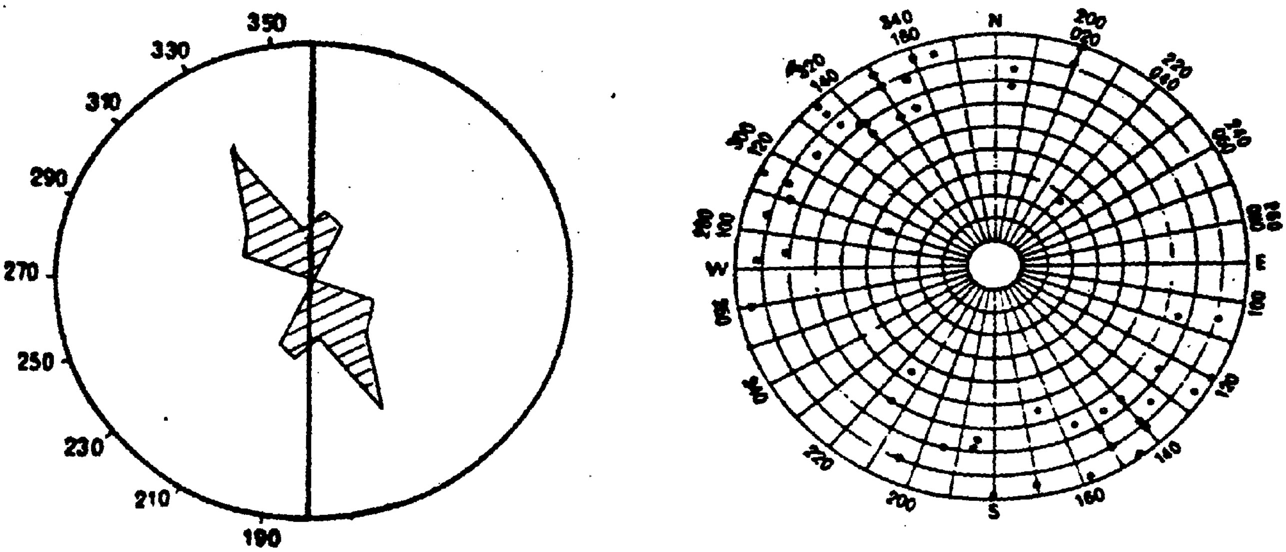


Fig 7.3 Till fabric data

orientation is essentially N.W - S.E with dips again predominantly 0-20 degrees. This up-glacier plunge found in most till fabrics has been explained by numerous theories which fall into one of three main groups - ice shear, slope or till shear theory (Evenson, 1971).

Although clast measurement orientation may help identify flow direction it does not differentiate between tills and does not necessarily explain the mass behaviour of the sediments,particularly in terms of resistance to erosion.

Perhaps a more relevant parameter and one closely allied to bulk fabric, is that of packing. The concept of packing can be looked on as the spatial density of particles in the aggregate and, in simple terms, can be described as the way in which particles fit together. In engineering terms it has a significant influence on the behaviour of granular soils, particularly in terms of shear strength and drainage characteristics. It is a function of size and grading, orientation and form and is impossible to measure in its own right. Bulk density and grading perhaps give the best indication of packing and will be considered in the following section.

7.5 Engineering characteristics of till materials

Part of the objective of this investigation was to obtain the fullest possible picture of the soils and rocks present within the study area, their distribution and their properties. From a cursory examination of the cliff facies it became evident that different testing and different modes of sampling would have to be applied.

At the outset testing and sampling available was governed by several considerations, namely

(i) manpower requirements
(ii) access limitations
(iii) need for ancillary plant
(iv) minimum amount of disturbance

One of the main problems of this part of the research was to decide what parameters were important in describing the resistance of the cliff and material to erosion and what were relevant tests in identifying and quantifying these parameters.

7.5.1 Field testing

In-situ tests arguably provide results which bear more relationships to the actual performance of soils in the natural state and are therefore more accurate in assessing their geotechnical behaviour.

However, standard test equipment will not conveniently deal with samples containing stones much in excess of medium gravel size (20mm) and it is probable that the excluded coarser fraction would have a significant effect on any strength results.

Furthermore, in-situ testing tends to be expensive, labour intensive and time consuming and therefore beyond the scope of this investigation. Simpler techniques were available and these are considered in the following section.

7.5.2 Techniques to assess degress of erodibility

No simple tests have been developed to give a reliable indication as to whether a sediment is susceptible to erosion or not although the erodibility of clays in particular has received attention in the USA during the last two decades (Sherard et al., 1976).

Tests are either simple laboratory tests based on visual assessment – pinhole test, crumb test and the SCS dispersion test, or chemical tests which involve the determination of the effective amount of sodium cations present in the pore water of the clay, the presence of sodium and the relationship of the concentration of sodium cations to other metallic cations being considered the prime factor responsible for a clay being dispersive.

In this instance erosion takes place because individual clay particles of dispersive soils are capable of going into suspension in practically still water. In a coastal environment a flow of water of considerable velocity is required to cause erosion of most ordinary clays.

7.5.2.1 Pressure gun

To simulate wave erosion on the cliffs a form of hand-held pressure gun was considered by which one could compare the relative effect of a high pressure jet of water on the different sediments (Bradley,1982, pers.comm.). This would constitute a simple and quick index test by which the operator could either

(i) directly measure the indentation in the cliff face as a result of a specified pressure of water acting over a specified length of time, or

(ii) indirectly measure the amount of material collected in a wash tray at the base of the cliff. Although different forms of sediment traps have been used extensively in the erosion of slopes (Goudie, 1981), the technique is fraught with difficulties, not least of which is the problem of physically collecting all the eroded material.

Enquiries within the building and construction industry revealed no suitable hand held gun on the market. The only viable jetting pump was a diesel powered one delivering 136 Bar at 16 litres per minute driven by a 6 H.P engine (Plate 7.1).

Preliminary trials were encouraging. Although highly manouverable and lightweight in industrial terms the manufacturer's claim of 2000 p.s.i pressure delivered through a high pressure water jetting gun assumed a suction hose length of only 4m. Along the majority of beaches this would not be sufficient, thus necessitating a separate water supply.

This fact, together with the need for additional manpower and high hire costs, eventually precluded its use in the testing programme.

7.5.3 Field index tests for determining material strength

Hand instruments were used to obtain some measure of classification and consistency within the cliff materials and also to give an indication of the material's inherent strength and resistance to erosion. It must be stressed that this was often very approximate and was no real substitute for proper laboratory testing. However, as only comparative strength values were required, these index tests were justified.

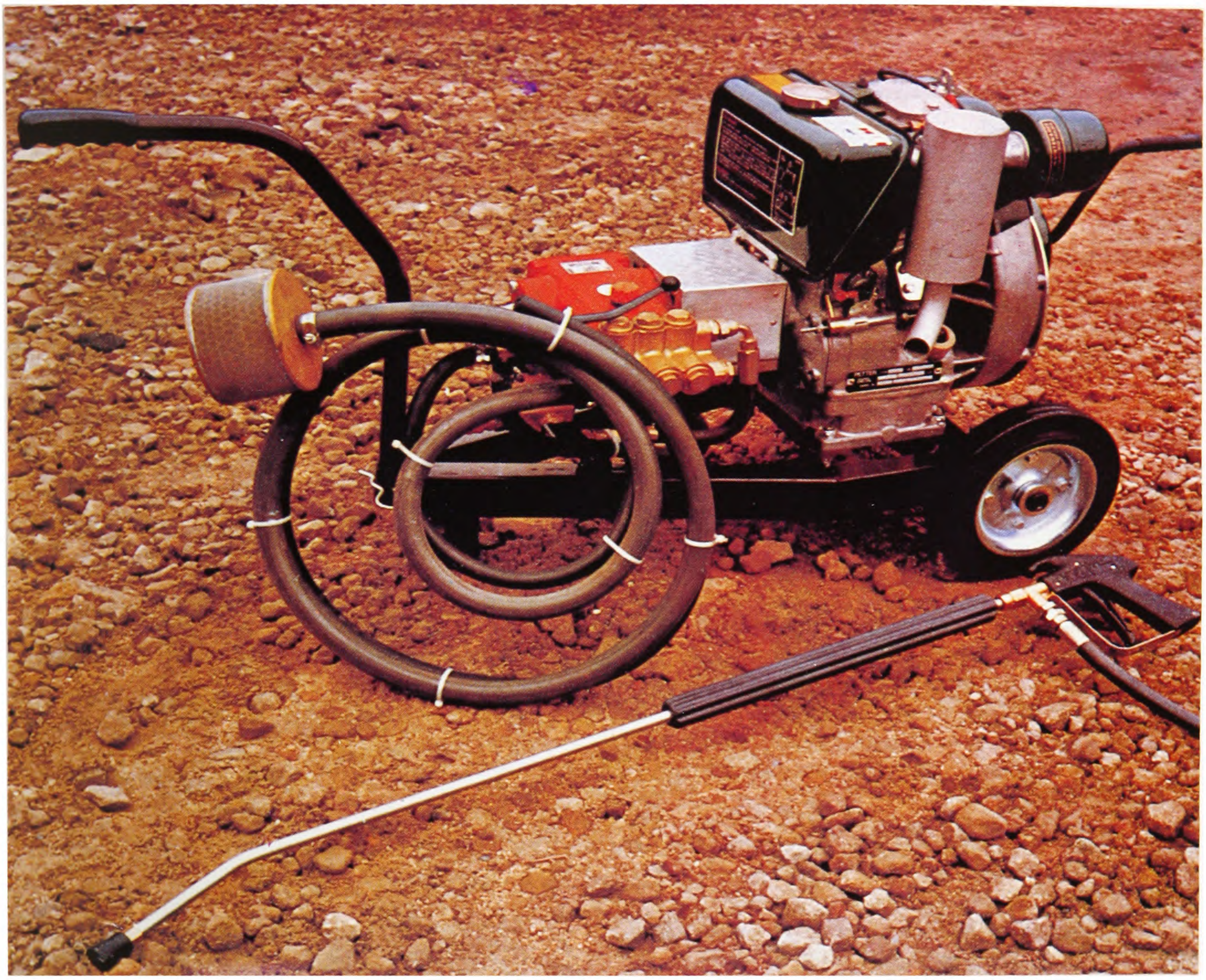


PLATE 7.1 Neolith high pressure water jetting pump

7.5.3.1 Pocket penetrometer

Plate 7.2 shows a typical pocket penetrometer which was most useful since it gave a direct measure of compressive strength and did not rely on empirical rules for its interpretation.

This instrument was used on the sections of boulder clay and other cohesive soils containing little or no sand and gravel. These included the steep banks of boulder clay at Aberarth (section 3.4.2) and the low cliff sections of clay at New Quay bay (section 3.4.5) together with the bluish grey boulder clay exposed in cliff sections at the western end of the bay.

For purely cohesive soils the undrained shearing strength is equal to one half the unconfined compressive strength of undisturbed samples of the clay (Terzaghi and Peck, 1957,p346). The shearing strength can also be determined directly by means of laboratory testing (section 7.6.4) for use in slope-stability calculations (section 9.6).

It was used by pushing the spring loaded plunger into an undisturbed surface as far as the cut graduation line and the maximum reading read off a sliding indicator on a marked scale. At each location numerous readings were taken on a grid basis and averaged (Table 7.2). The dense packing and concentration of clasts made it impossible to use this instrument on any of the till exposures.

7.5.3.2 Schmidt rebound hammer

The intact rock strength was determined by direct measurement of the unconfined uniaxial compressive strength with a Schmidt hammer (Plate 7.3).

The Schmidt Concrete Test hammer was originally developed for the non-destructive testing of the quality of concrete and other building materials in any finished structure or prefabricated sections. It has since been used by geomorphologists and engineers to assess rock material strength (Day and Goudie, 1977).

In essence, it measures the rebound hardness of the rock which is directly related to the compressive strength. In testing, a plunger

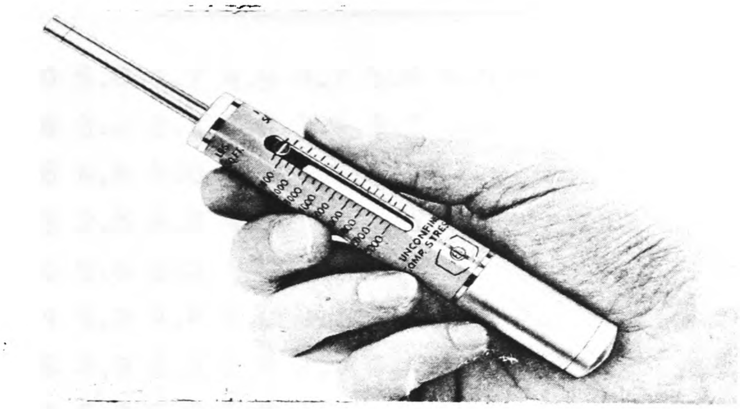


PLATE 7.2 Pocket soils penetrometer

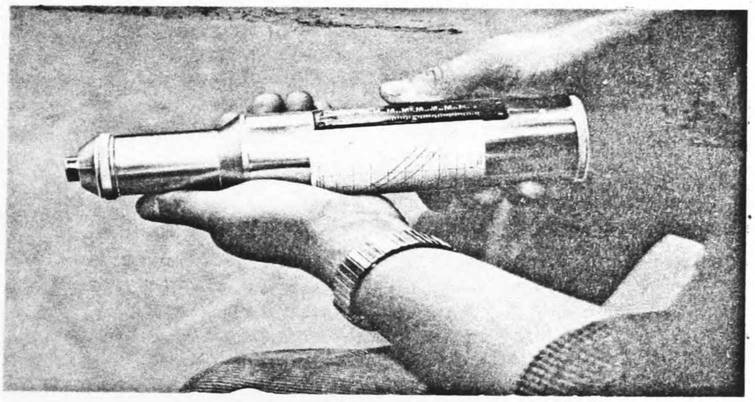


PLATE 7.3 Schmidt test hammer

CHNG.	PENETROMETER READINGS										MEAN	UNCON COMP STRENGTH Kn/m^2
174	4.6	5.0	5.0	4.7	4.9	4.7	5.0	4.6	4.4	5.0	4.79	190
176	3.4	3.6	3.2	2.3	2.8	3.4	3.3	3.0	3.2	2.7	3.10	120
178	4.8	3.8	4.4	4.0	4.2						4.24	170
180	3.8	3.5	2.8	4.8	4.2						3.82	150
182	5.0	5.0	5.0	5.0							5.00	200
184	4.3	4.4	5.0	4.4	5.0	4.1	3.3	4.4	2.6	2.6	4.06	160
186	4.4	3.5	2.9	2.9	2.8	2.4	1.4	1.5	2.2	4.2	2.82	110
188	5.0	5.0	5.0	5.0	5.0						5.0+	200

TABLE 7.2 Soil penetrometer readings on clays in New Quay

is pressed against the surface to be examined, whereupon by means of a spring a percussion weight strikes against the plunger. After the strike the weight rebounds a certain distance which is shown by a pointer on a scale. This reading represents the rebound measured as a percentage of the forward movement of the percussion weight.

The conversion of rebound readings to unconfined uniaxial compressive strength has been criticised by Neville (1973,p501) who advised that this relationship should be determined experimentally for each material considered. Singer and Yaaton (1974) however established the following linear regression between the rebound number R and the compressive strength δ

$$\log (\delta/9.81 \times 10^4) = 0.0387 R + 0.826.$$

Jones (1981) found that, with appropriate precautions, the Schmidt hammer test gave excellent correlation with the unconfined compression test results for N sized cores taken parallel to the bedding plane in both limestone and shale.

Schmidt hammer rebound values were determined at 30 different locations, a minimum ten number of impacts being made at any one site. These ten values were taken from within an area a metre square. Following the method recommended by Selby (1980) the upper and lower twenty percent of impact readings were ignored and the remaining values averaged. Barton and Choubey (1977) have recommended that the highest five of ten measured values taken within a metre square are averaged.

Fig 7.4, based on the work of Deere and Miller (1966) was used to correct for hammer impact angle and to convert impact reading to uniaxial compressive strength for the type 'L' hammer used.

Readings were taken from alternating beds of greywacke and mudstone within 2-3m of M.H.W.M of ordinary tides.

The rocks in this zone will obviously be subject to wetting and weathering which may reduce the rebound value (Barton and Choubey,1977). Consequently the adoption of Schmidt hammer values as an estimate of rock strength is likely to result in an underestimation of shear strength as related to dry unweathered surfaces.

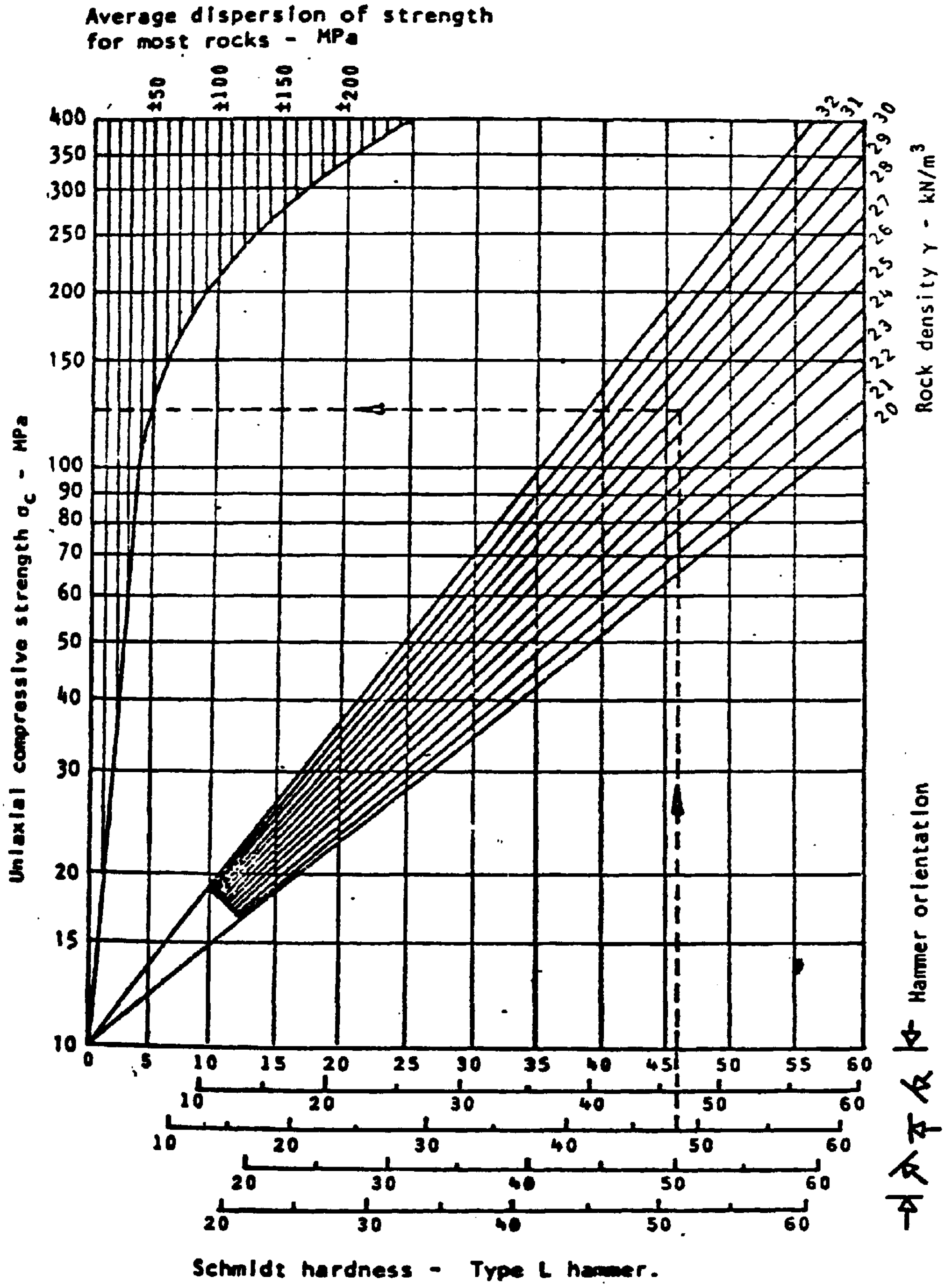


FIG. 7.4 **Relationship between Schmidt hardness and the uniaxial compressive strength of rock, after Deere and Miller**

1 MPa = 1 MN/m² = 10.2 kg/cm² = 145 lb/in²
1 kN/m³ = 102 kg/m³ = 6.37 lb/ft³.

It should be stated that for purely comparative purposes within a particular rock facies it is unnecessary to convert rebound values to compressive strength. However, when it is required to make meaningful comparisons between rock strength and strength in other soils which have been determined by some other field index test then this conversion becomes relevant.

The Schmidt hammer rebound values determined for the rock section north of Aberarth and that between Aberaeron and Cei Bach are tabulated in Table 7.3.

7.5.4 Laboratory testing

7.5.4.1 Representative sampling

The most important requirement for any test sample is that it be fully representative of the material from which it is taken. Rowe (1971) defined a representative sample as that representing a material content fabric arrangement and stress state in a soil. It follows that unless a test specimen includes all of these factors it cannot be considered representative of the original material in situ.

7.5.4.2 Sample disturbance

It is a well known fact that sample disturbance occurs to some degree or other during any site investigation. The causes of sample disturbance can be attributed to the efficiency of sampling technique and to the release of in situ stresses within the soil.

The effect of sample disturbance is to alter the characteristics of the soil by destroying the soil fabric and structure which is generally reflected in a reduction in the undrained strength (Jorden, 1975).

The tills of the Cardigan Bay area are commonly very dense and often contain clasts of 150mm size and greater. It was recognised that the presence of these large stones would lead to sample disturbance and the question of obtaining undisturbed samples of any size from these soils was therefore never considered.

CHAINAGE	ROCK TYPE	HAMMER READINGS						MEAN	U.C.S MPa
62	G	44	41	46	48	40		43.8	
	M	18	24	16	19	25		20.4	
64	G	51	41	42	49	42		45.0	
	M	22	19	27	26	26		24.0	
66	G	49	47	46	48	50		48.0	
	M	18	17	23	23	25		21.2	
68	G	41	52	47	47	43		47.5	
	M	18	20	22	19	19		19.6	
70	G	42	42	45	40	51		44.0	
	M	24	20	19	24	24		22.2	
72	G	46	49	53	50	48		49.2	
	M	24	27	20	20	19		22.0	
74	G	37	52	50	53	46		47.5	
	M	26	28	30	26	20		26.0	
							G	46.4	118
							M	22.2	23
140	G	47	46	46	38	49		45.2	
	M	21	21	23	23	22		22.0	
142	G	50	52	43	47	49		48.2	
	M	17	19	28	22	25		22.2	
144	G	53	52	40	51	47		48.6	
	M	18	25	24	26	20		22.6	
146	G	40	39	38	52	50		43.8	
	M	30	22	23	20	22		23.4	
148	G	46	47	46	48	40		45.4	
	M	22	26	25	30	18		24.4	
150	G	42	42	44	44	49		44.2	
	M	20	19	20	23	21		20.6	
							G	45.9	112
							M	22.5	24

TABLE 7.3 Schmidt hammer readings

7.5.4.3 Till disturbed samples

Visual examination of coastal till sections showed that weathering affected the surface material, generally reducing the fraction of fines, and samples of visibly weathered material were not taken.

At specific sites scrape samples, consisting of bulk disturbed samples representative of the overall deposit, were collected. These samples were cut from a channel approximately 0.3m wide and 150mm deep down the face, the channel itself being excavated some 150mm into the cliff face so that only fresh material was sampled. The channel extended from the foot of cliff exposed at top of beach to a height up the face estimated to be within the range of ordinary spring tides.

The number of samples taken was limited by the large quantity of material required for sieve analysis. B.S 1377:1975,in Section 1.5.4.2 (5) recommends minimum quantities for representative results to be obtained. Since the tills in general contained a substantial proportion (i.e more than 10% of the total sample) greater than 75mm the minimum mass taken for sieving was 70kg.

The material was excavated on to plastic sheeting and pieces larger than 150mm set aside. This oversize fraction was weighed separately and recorded with the laboratory grading on each sample. Each sample was then sub-divided in the laboratory by cone and quartering. This process was repeated as many times as necessary until a small enough representative sample was obtained.

7.5.4.4 Boulder clay undisturbed samples

Undisturbed samples were collected for laboratory testing at two locations, Aberarth and New Quay. Care was taken to ensure that the samples obtained from each site were representative of the deposit. Structural disturbance (section 7.5.4.2) was kept to a minimum by careful excavation and removal by hand of sufficiently large blocks (approx. 0.5m cube).

Experience has shown that the change in condition is such clays due to stress release is not significant and that the influence on the test results, for all practical purposes, is minimal. Changes in moisture content were prevented by careful protection and packing.

7.6 Laboratory Testing

The problems associated with establishing,in engineering classification terms, the inherent variations within till materials are well documented (Midland Soil Mechanics, 1975).

Differences in gradings and natural moisture contents have been shown by Fookes et al (1975) to be sufficient to affect engineering decisions along sections of the Taff Vale Trunk Road in South Wales. Information on various road schemes in Cumbria and Cleveland has led Cocksedge and Hight (1975) to suggest the main differences affecting the engineering properties of glacial tills were related to variations in both the amount of coarse material present (gravel, cobbles and boulders) and the amount of the fines fraction and its associated plasticity characteristics.

The shear strength of cohesionless, or near cohesionless material is determined by the contact forces and friction between the individual particles and varies with the grading and degree of compaction or density of the deposit.

As a basis for classification therefore, the laboratory testing programme included particle size analysis, bulk density,plasticity and shear box tests.

7.6.1 Bulk density and moisture content

For practical reasons, bulk density was extremely difficult to determine under in situ conditions, especially for large samples which would be representative. Estimations of bulk density were achieved in the laboratory using the modified AASHO test. Although primarily used for controlling soil as engineering "fill" material, it is believed that this test represented in the laboratory the natural state of compaction achieved in the field (McGown, 1971).

In comparing laboratory density against field density the following qualifications have to be made:

(i) laboratory tests were carried out on samples at their respective natural moisture contents, the assumption being made that these values were similar throughout the various exposures. This moisture content did not necessarily represent the optimum moisture content at which the maximum dry density was achieved under that compactive effort.

(ii) the results of laboratory compaction tests on the matrix could only be compared directly with the density on site for the total material if the effect of stone content was taken into consideration.

In theory the presence of stones would give the total material a higher density as the stones have a greater density than the matrix material they displace. The resulting field density of the whole material was calculated from the equation below (Madison, 1944)

$$\rho_D = \frac{G_S}{(1-F)\rho_{md} + FG_S} \cdot \rho_{md}$$

where ρD is the theoretical dry density to be expected in situ, derived from the dry density ρ_{md} of the matrix material measured in the laboratory. G_s is the specific gravity of soil particles.

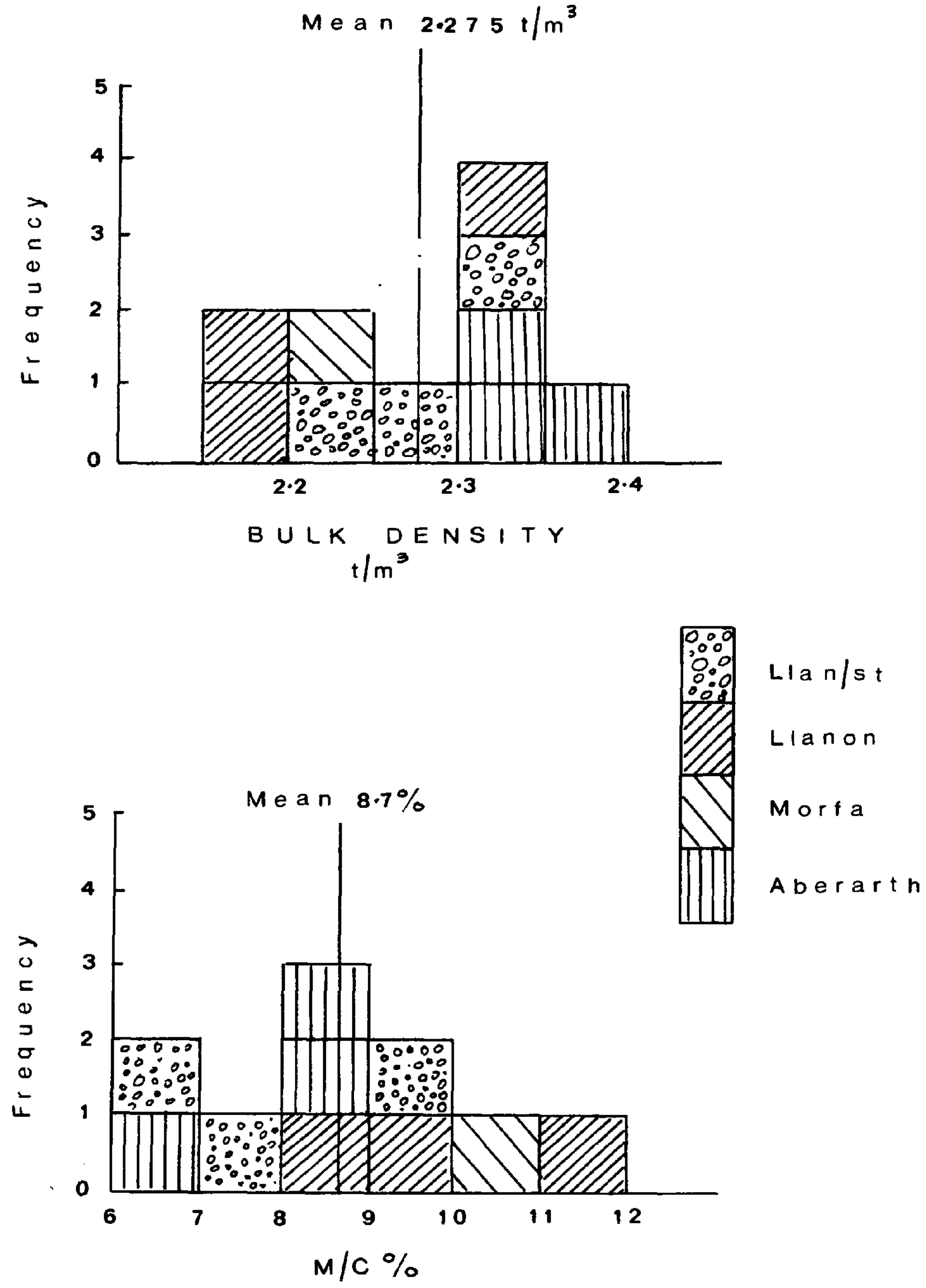
The overall moisture content of the total material was given by

$$w = Fw_m + (I-F)\ w_s$$

where w_m = moisture content of matrix and

w_s = moisture content (absorbed moisture) of stones. F is the ratio of the matrix material to the whole.

Particles larger than 20mm were removed before test, weighed and recorded. Material passing the 20mm sieve was compacted in a Proctor mould using a compactive effort equivalent to that applied in the B.S "Heavy" Compaction Test (B.S 1377:1975, Test 13). The moisture content of this fraction was determined and used for comparative purposes. Figs 7.5a and 7.5b show respectively bulk density and moisture content results obtained from 10 samples of till from various sections.



FIGS. 7.5a and 7.5b Histograms of bulk densities & moisture contents of tills

7.6.2 Particle size distribution

Analysis of grain size distribution in bulk samples of till was carried out using a combination of wet sieving (B.S 1377:1975,Test 7A) and sedimentation (B.S 1377:1975, Test 7D) procedures.

Because samples contained particles of coarse gravel and cobble size, a sufficiently large sample of 10kg or more was necessary after sub-dividing (section 7.5.4.3). After drying and weighing the material was washed, a portion at a time, through a large diameter 20mm sieve nested in a 63m sieve. An additional intermediate 3.35mm sieve was also included to protect the 63m sieve from overloading.

Material passing the 63m sieve was collected when required for a sedimentation analysis, otherwise it was allowed to run to waste. Retained material was oven dried and sieved through the complete range of sieves from 75mm downwards.

For the sedimentation test, the quantity of dried material passing the 63mm sieve was sub-divided to a convenient 50g approximate sample and pre-treated with a standard dispersant solution of sodium hexa-metaphosphate to remove organic and possible calcareous matter. Using a specially calibrated hydrometer the density of the soil was measured in a suspension in water at various intervals of time. From these measurements the distribution of particle sizes in the silt range (60mm - 2mm) were assessed.

The grading curve from the sedimentation test was added to the sieving curve after the appropriate proportional adjustment had been made. Figs 7.6a-d show grading curves for samples from each section of till while Fig 7.7 shows the mean grading curve for each section together with the limits of the grading curves for all samples. Fig 7.8 presents summarised results in the form of a multiple histogram. Grading curves for individual tests were examined and each of the four fractions of boulder plus cobble, gravel, sand and silt plus clay (% by weight) were read off and plotted on separate histograms Fig 7.9 gives a comparison of the gradings of the deposits investigated with the boulder and cobbles fraction (>60mm)omitted.

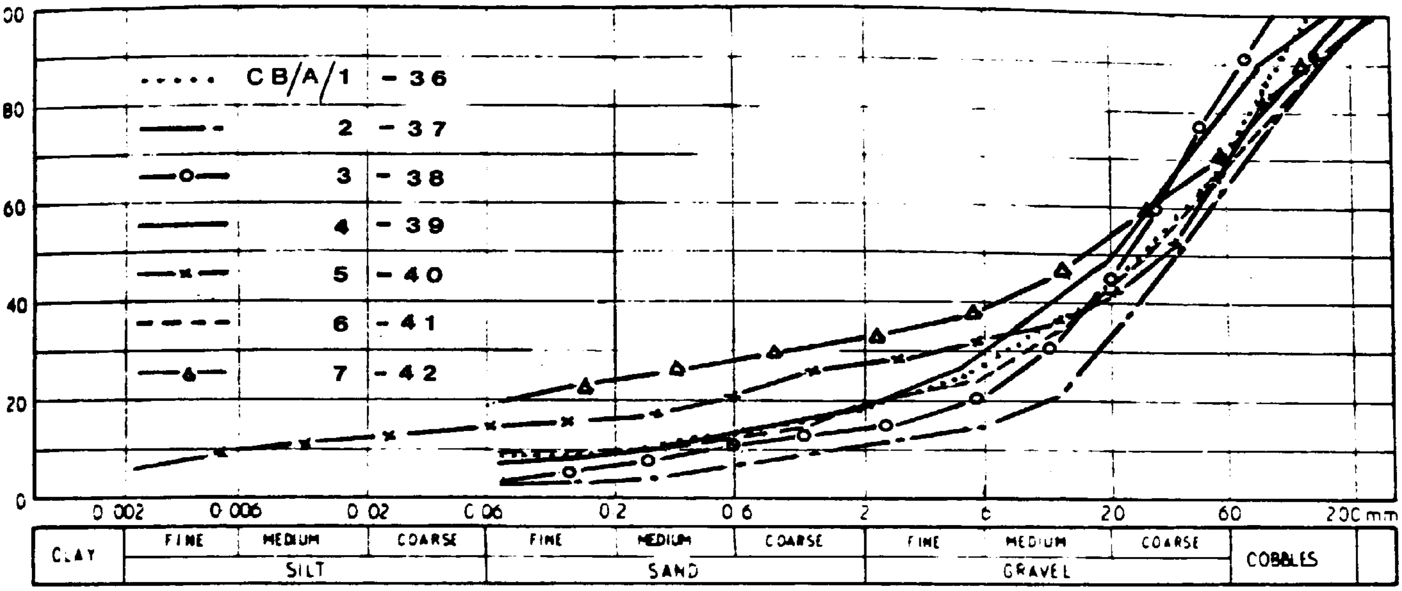


FIG. 7.6a Grading curves for samples of till from site A

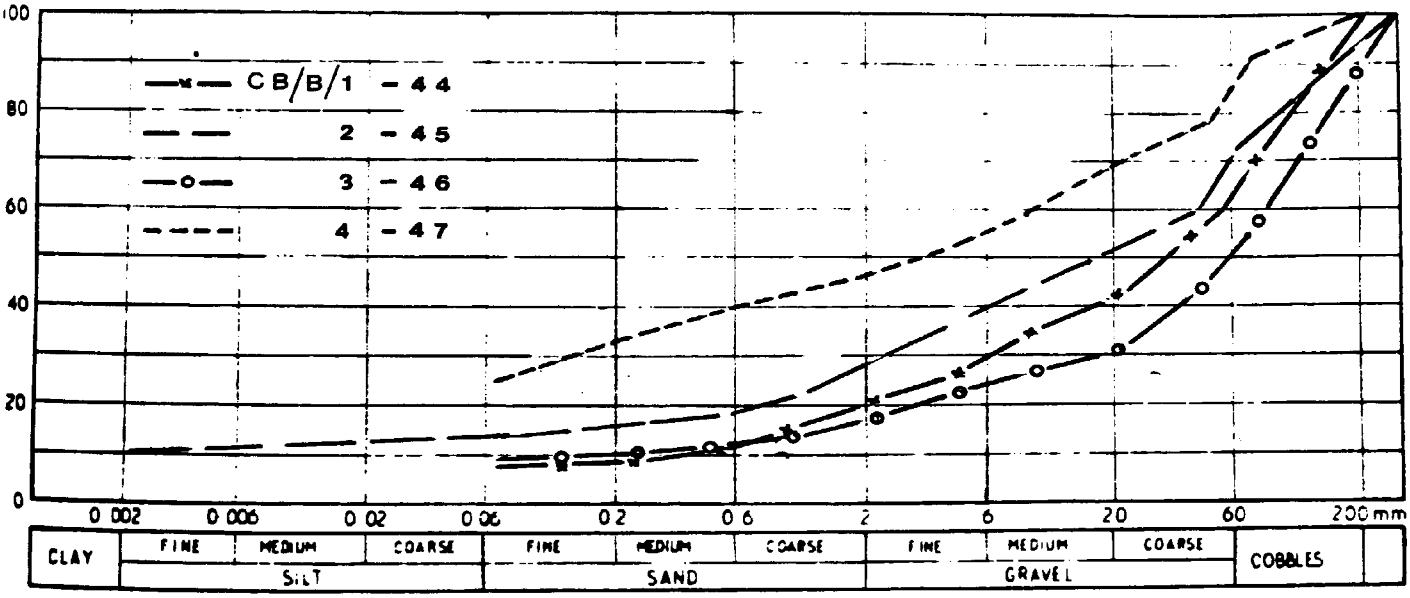


FIG. 7.6b Grading curves for sample of till from site B

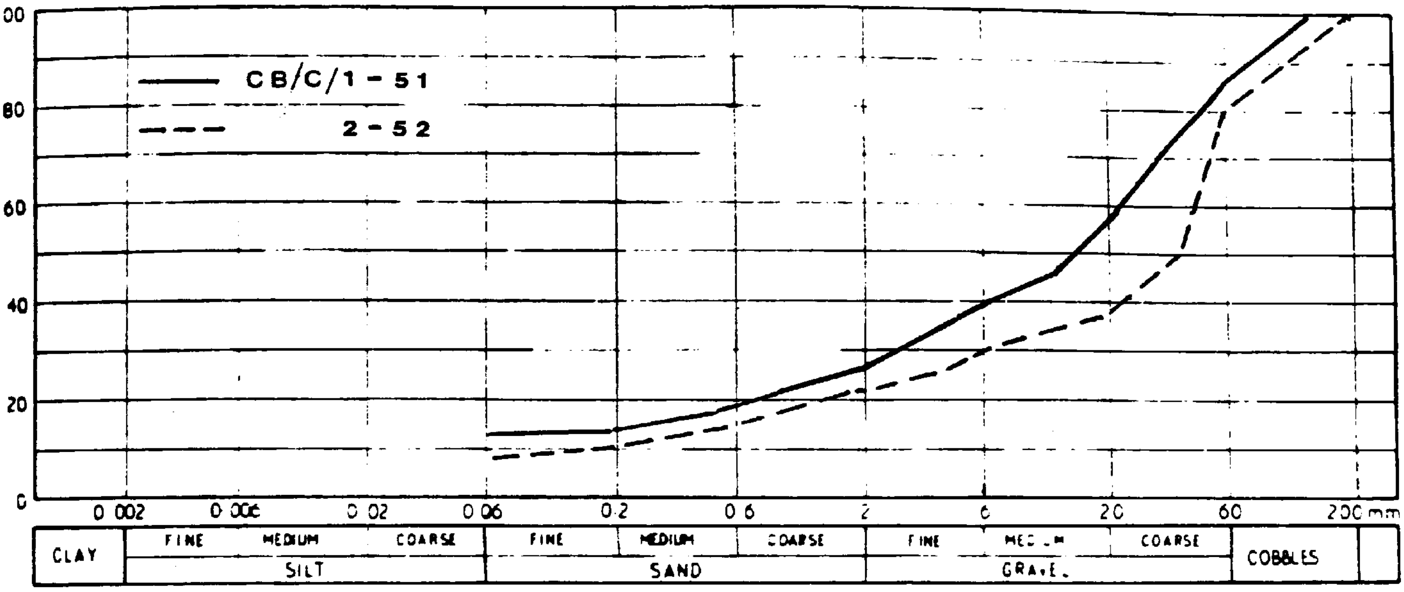


FIG 7.6c Grading curves for samples of till from site C

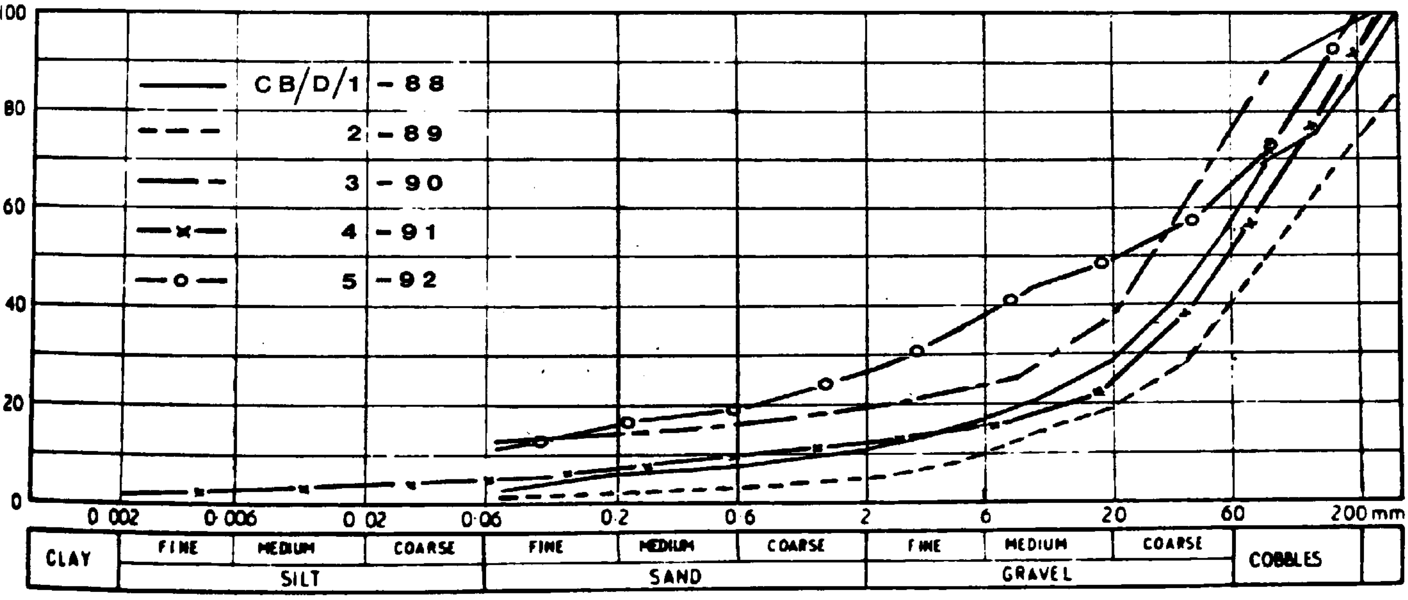


FIG. 7.6d Grading curves for samples of till from site D

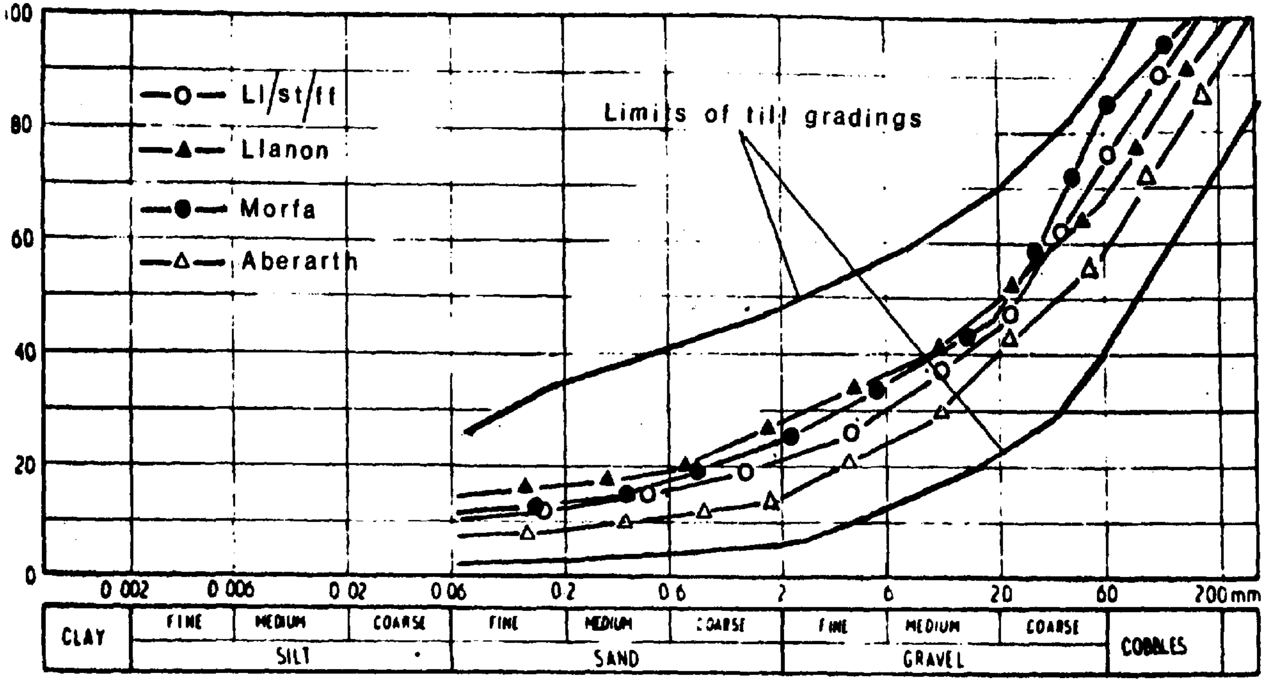


FIG. 7.7 Grading envelope for tills showing average grading curves for each site

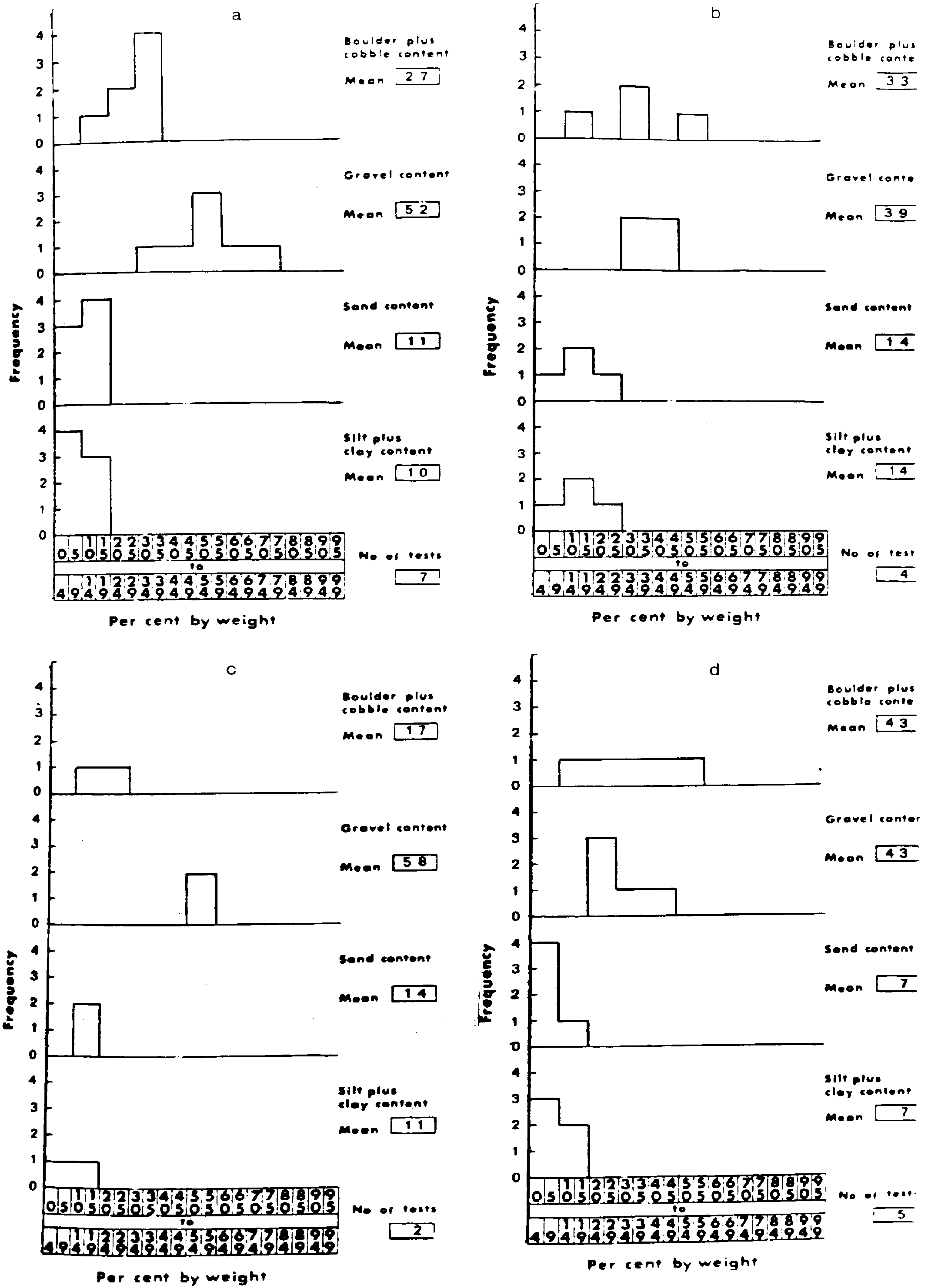


FIG. 7.8 Multiple histogram for till samples from sites A - D

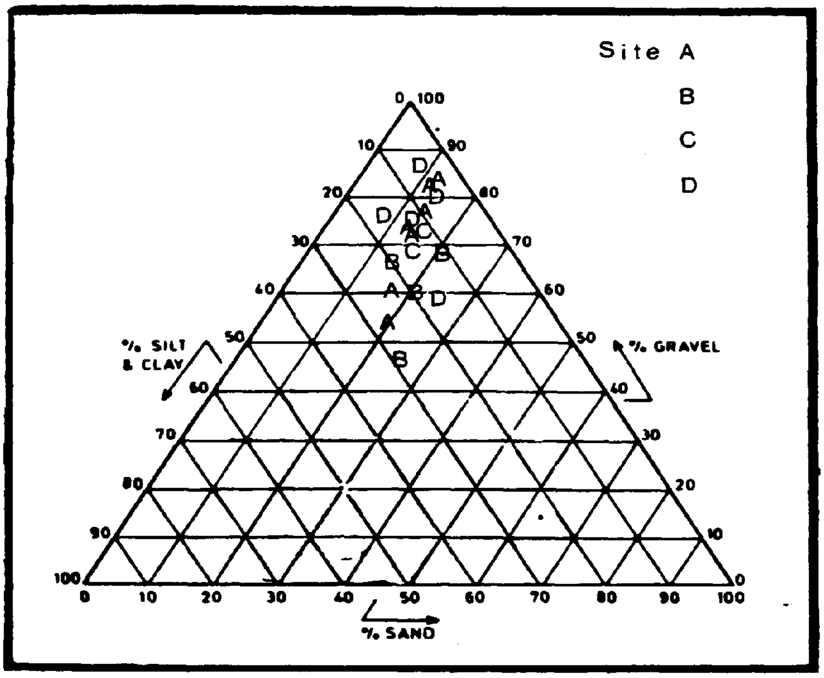


FIG. 7.9 Comparison of till gradings (less-than-60mm fraction)

7.6.3 Atterberg limits

These simple tests, originally devised by Atterberg (1911) for the classification of fine-grained soils in the particle size range 0.002 to 2mm, have acquired a practical significance since they give a consistent guide to the important engineering properties of shear strength and compressibility in clay soils.

The tests have remained, in principle, the same since Casagrande (1932) proposed to define the various limits by reference to the moisture content of the soil under certain conditions.

Both liquid and plastic limits are rather arbitrarily defined, hence the importance of adhering to the standard procedure described in B.S 1377:1975 (Tests 2b and 3 respectively).

For clay samples, wherever possible, the test was carried out on the natural soil with coarse particles removed by hand. For till samples, a portion of the air-dried soil passing the 425mm sieve was mixed thoroughly with de-ionised water prior to test.

The results of these tests have been plotted on a Casagrande classification chart in Fig 7.10.

7.6.4 Shear strength

As stated, it was not possible to carry out any in-situ shear strength tests so that limited laboratory evaluation had to be relied on. The grading curves show a limited amount of fines but do not illustrate the packing of the stones within the matrix.

In testing the fines element from the matrix, using a standard direct shear machine, it was believed that the differences in cohesive strength within the till material could be examined.

Though Schultze (1957) has pointed out that it is unrealistic to separate out finer material and then test it, Whalley (1975) has argued that sensitivity in most cases is caused by the failure of the finest material. Since in this case a maximum value for cohesion was desired the approach seems valid.

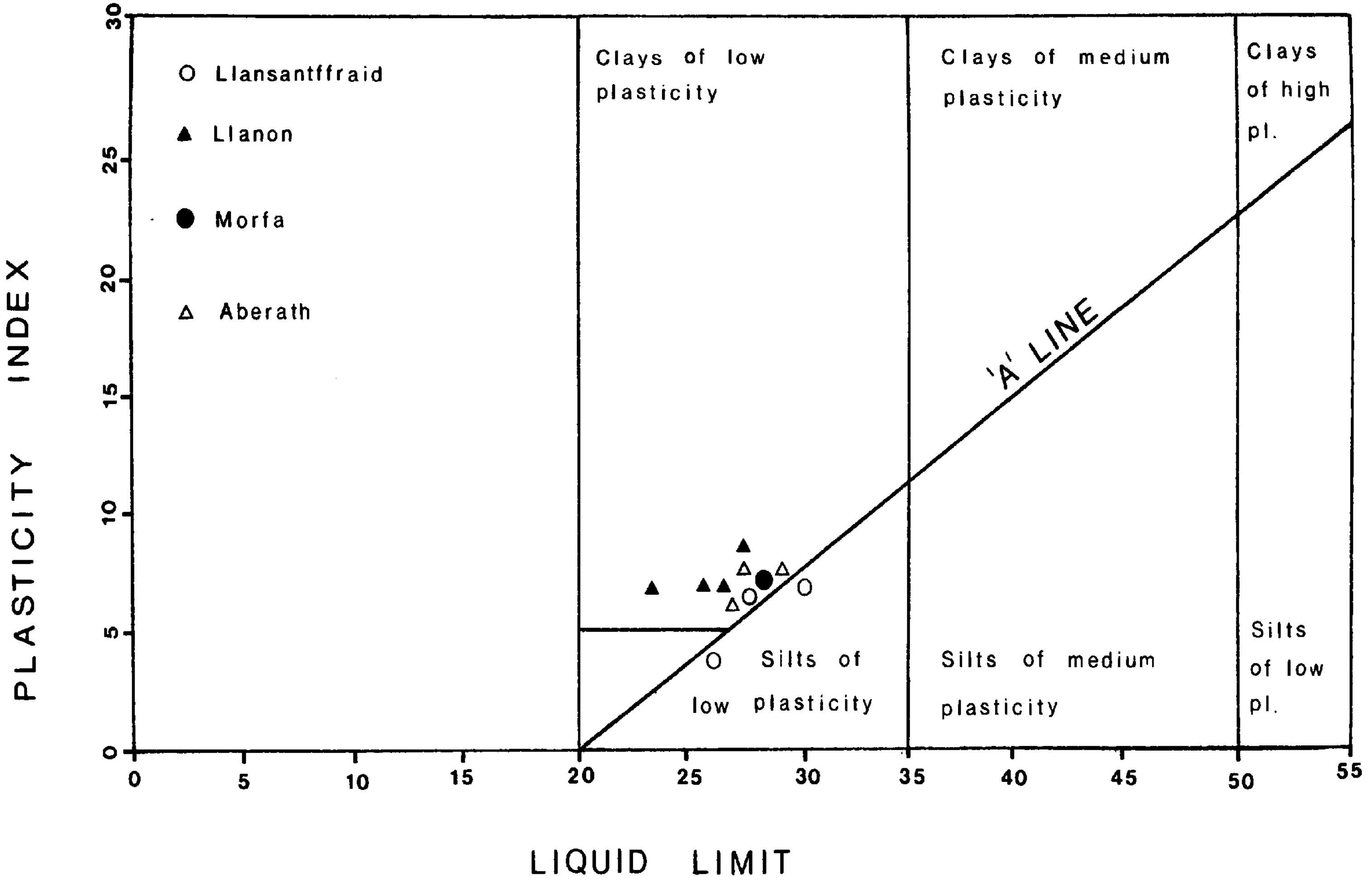


FIG. 7.10 Casagrande classification chart showing plasticity characteristics of tills.

Reversible shear box tests were therefore performed on the matrix of specific till samples, the assumption being made that in long-term failure it is the residual strength of the matrix that is important in any stability assessment.

7.6.4.1 Apparatus

The apparatus used was the standard one-speed controlled displacement 60mm Bishop type shear box, modified to enable multiple reversal tests to be performed (Plate 7.4). The diagrammatic layout of the shear box can be seen in Fig 7.11. Constant rate of strain was applied through a screw jack by motor & 25 speed gearbox (A in Plate 7.4). The shear force being applied to the soil by the screw jack via the lower half of the box is shown by the proving ring (B) which is in contact with the upper half of the box. Normal stresses were applied to the sample from a yoke (C) carrying weights under the shear box stand. To obtain high normal stresses a 5:1 level loading device (D) was used.

The essential modifications to the system used (Rouse, 1966) permits the shear box, through the swan neck yoke arrangement, to place the proving ring under tension as well as compression.

Experimental data was gathered at regular scan intervals (0.2hour) by a Troxler 3800 Service Data Acquisition system (Plate 7.5) which is a modular instrument for recording data from measurement transducers. The transducers (Plate 7.6) convert the mechancial measurement from the gauges into a proportional electrical signal. This electrical signal is conditioned by a Signal Conditioning Module (SCM) to provide an output that is more easily related to the measurement. A multiplexor selects the outputs of the SCM one at a time for display on a Digital Panel Meter (DPM) in a numerical form. A digital printer receives the data from the DPM and prints it, together with the time, on paper tape to provide a permanent record for future programming.

7.6.4.2 Sample preparation and test procedure

Test samples were prepared in the usual manner for slow drained

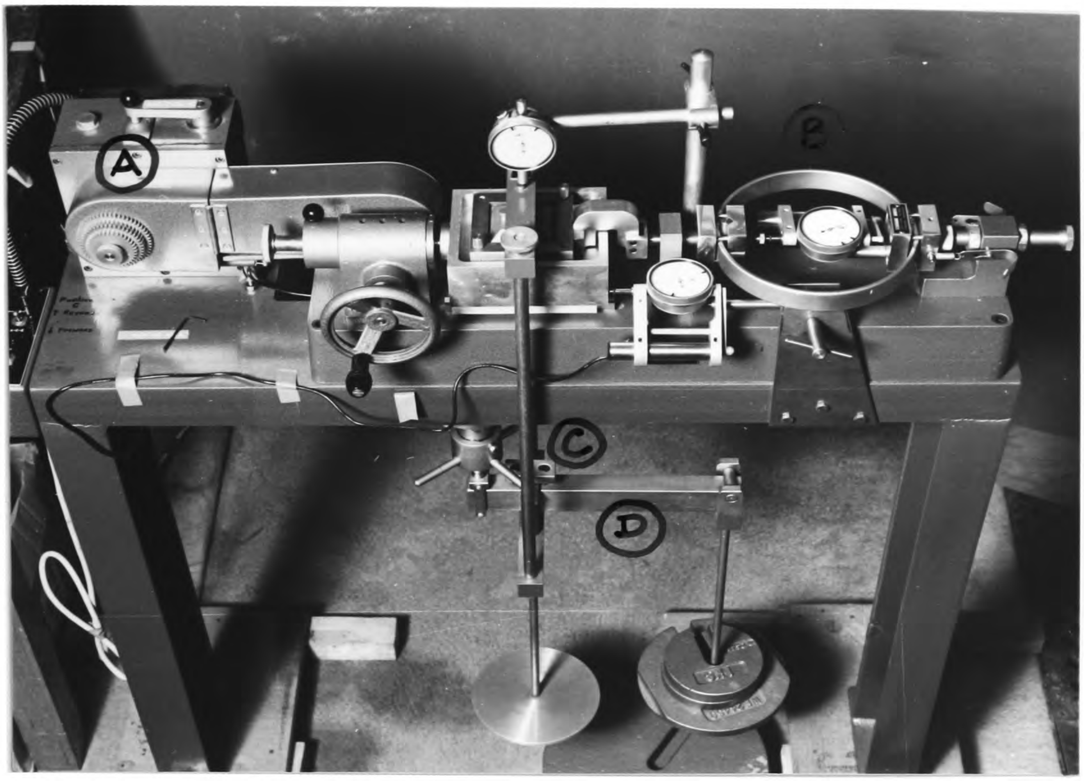


PLATE 7.4 Reversal direct shear apparatus

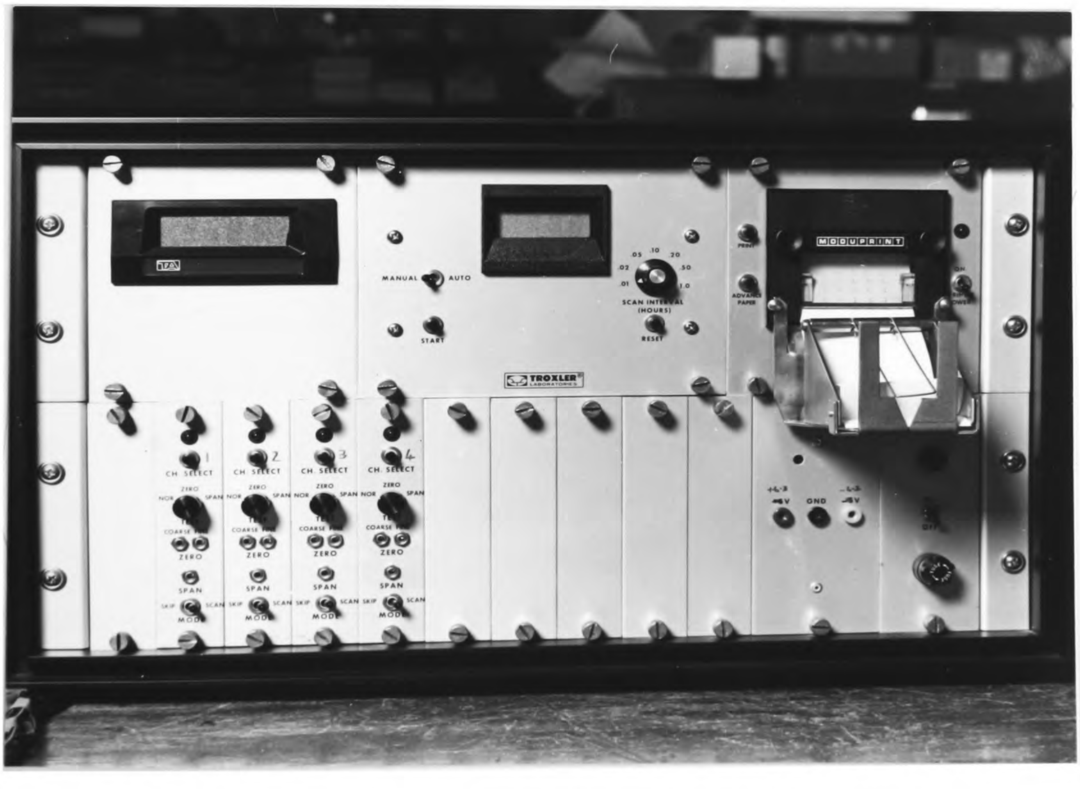


PLATE 7.5 TROXLER 3800 data acquisition system

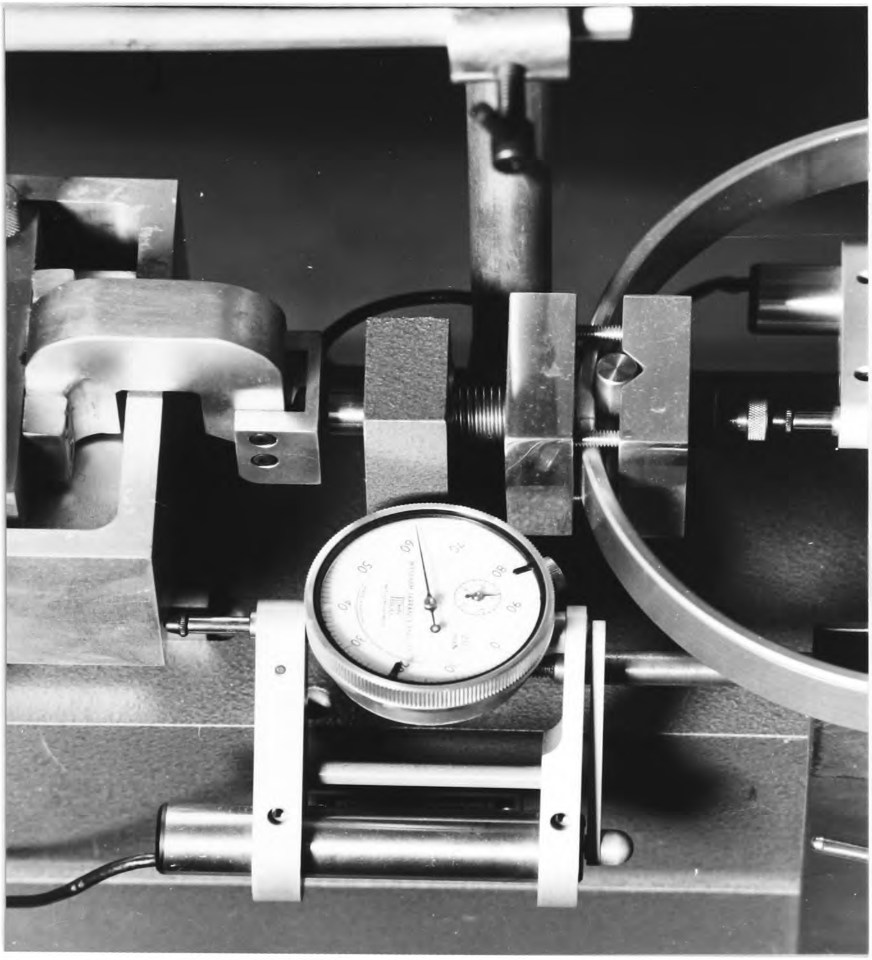


PLATE 7.6 Sangamo linear transducer

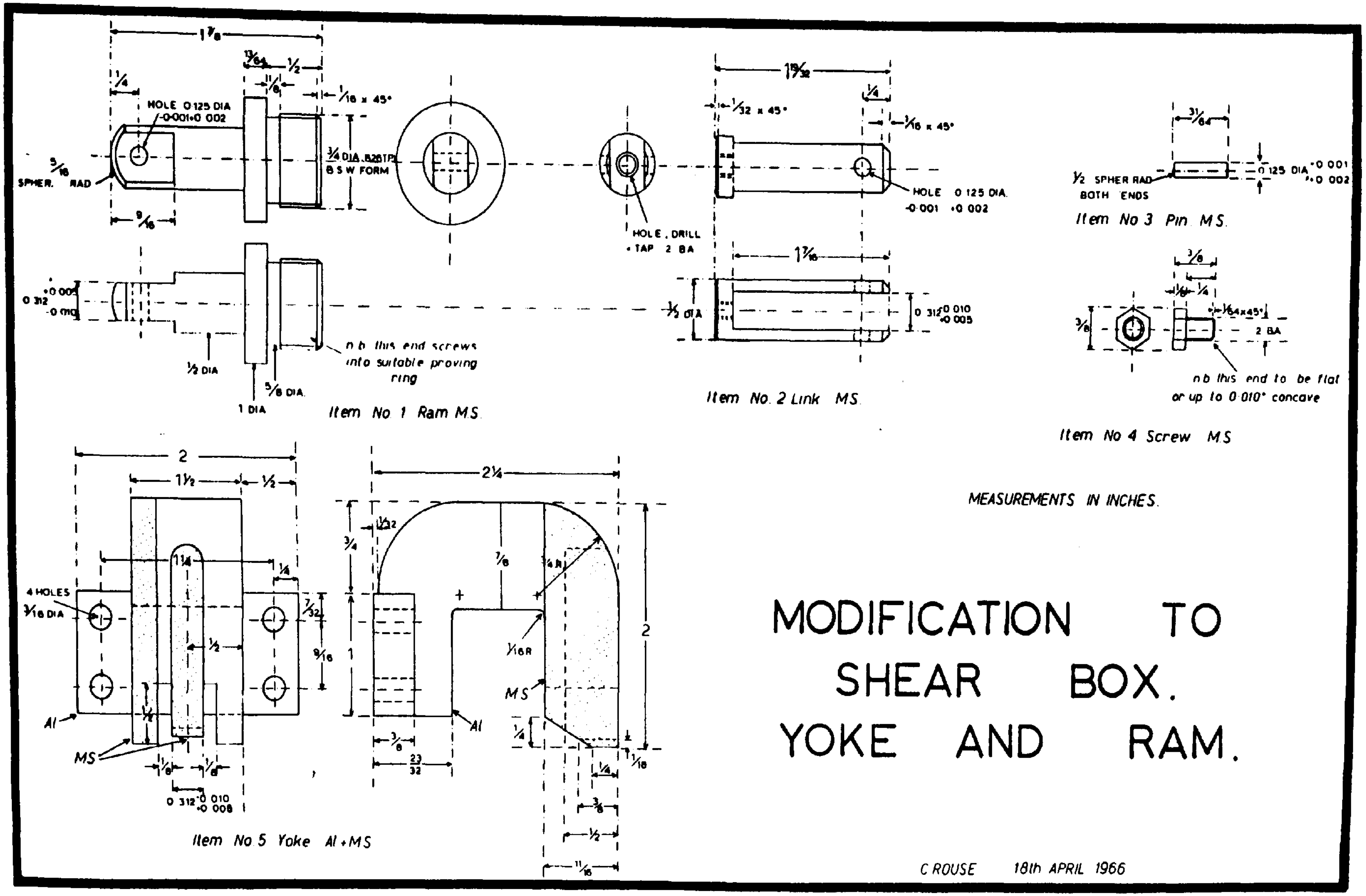


FIG. 7.11 Modification to shear box for reversal use

tests on normally consolidated material (Head, 1982,p548). Material passing the 3.35mm sieve was air dried and re-constituted to its approximate liquid limit. Clay samples were prepared in their natural state to fit the shear box.

For the consolidation test a multi-stage technique was used where the load was applied in incremental stages allowing partial consolidation at each stage. Consolidation was carried out at the same normal pressure as shearing so that the tests were slow, drained tests on normally consolidated samples. Permutation of weights enabled convenient resulting normal stresses of 41.8, 74.5, 134.6 and 229.8KN/m^2 to be used. The consolidation curve was drawn on a ‘t’ graph and the time to 95% consolidation (t_{95}) derived.

The residual shear strength was measured by extending the standard shearbox test well beyond the point at which the maximum (peak) strength occurred. Displacement was continued to the limit of travel of the shearbox which was then returned to the starting position so that the specimen could be re-sheared. This process was repeated several times until a constant value of shear resistance (residual strength) was reached.

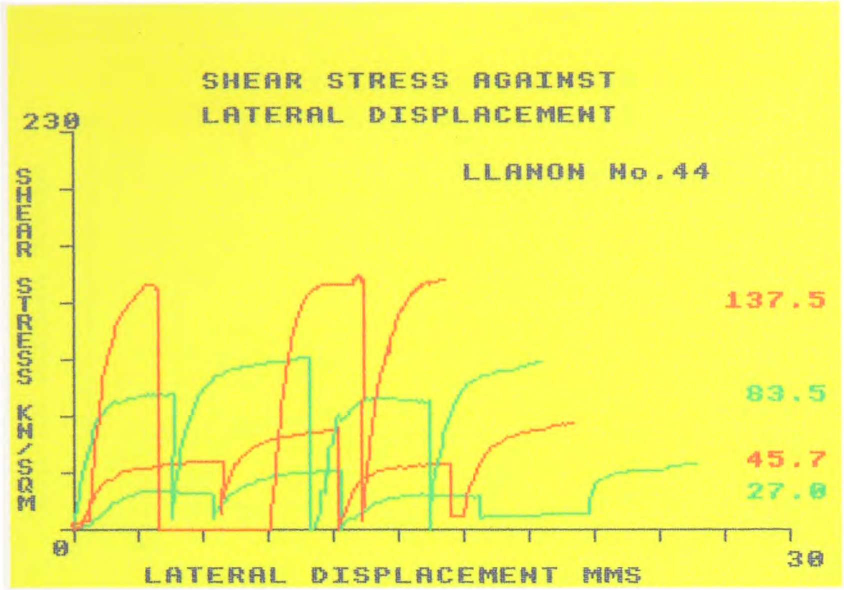
The test programme involved consolidation on the first day followed by shearing for a total length of four days in the sequence 1st Forward 24hrs, 1st Reverse 24hrs, 2nd Forward 24hrs, 2nd Reverse 24hrs.

Incremental consolidation and shearing was repeated for 3 other normal pressures thus necessitating a total test time of 20 plus working days for each sample. Although this 24 hour test was eminently suitable for automatic recording requiring once daily supervision,the time element did curtail the number of tests possible.

The test data was processed by computer programme (Rouse, 1982). Results for shear box tests on till materials are shown in Figs. 7.12a-d.

7.7 Analysis of results of basic engineering tests

The limited number of test results from the site investigation does not permit a detailed examination to be carried out on a statistical basis. However, it is considered that the test results



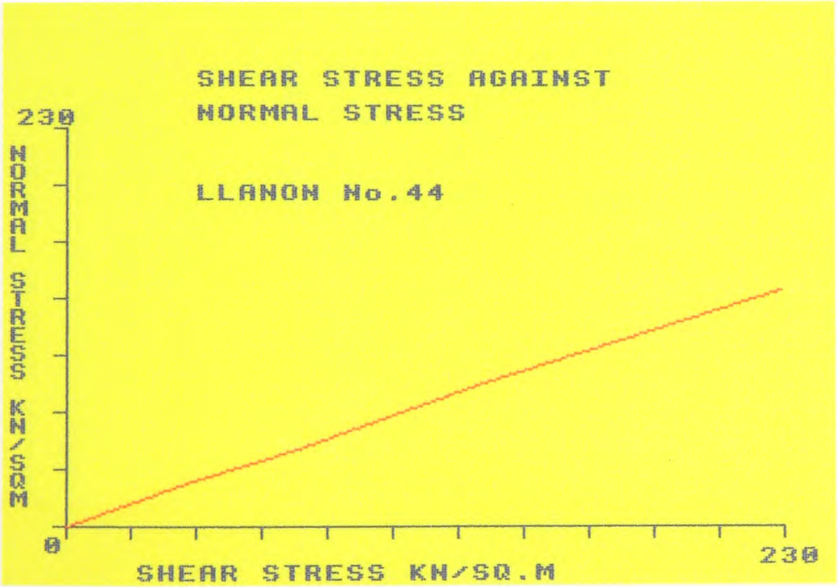


FIG. 7.12a Shear strength parameters for till chng. 44 + 00

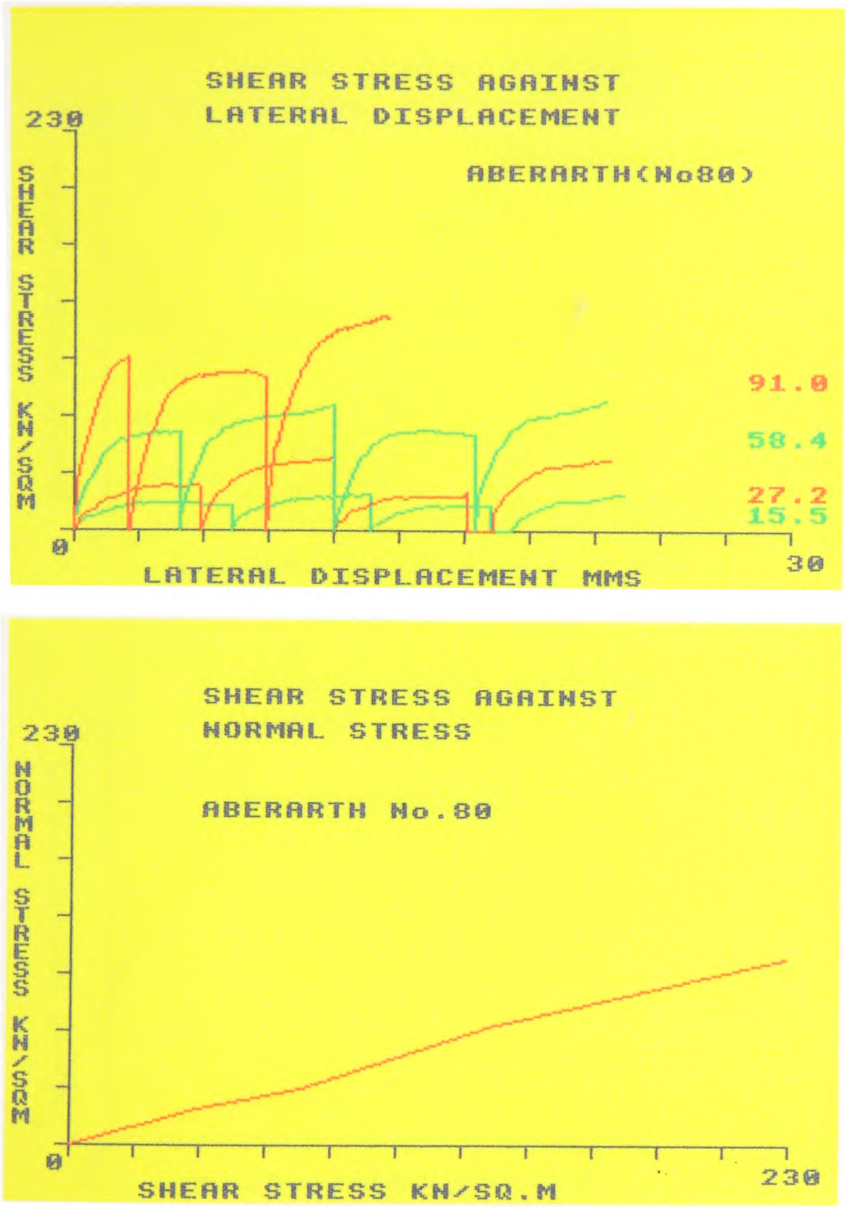


FIG. 7.12b Shear strength parameters for till, chng. 80 + 00

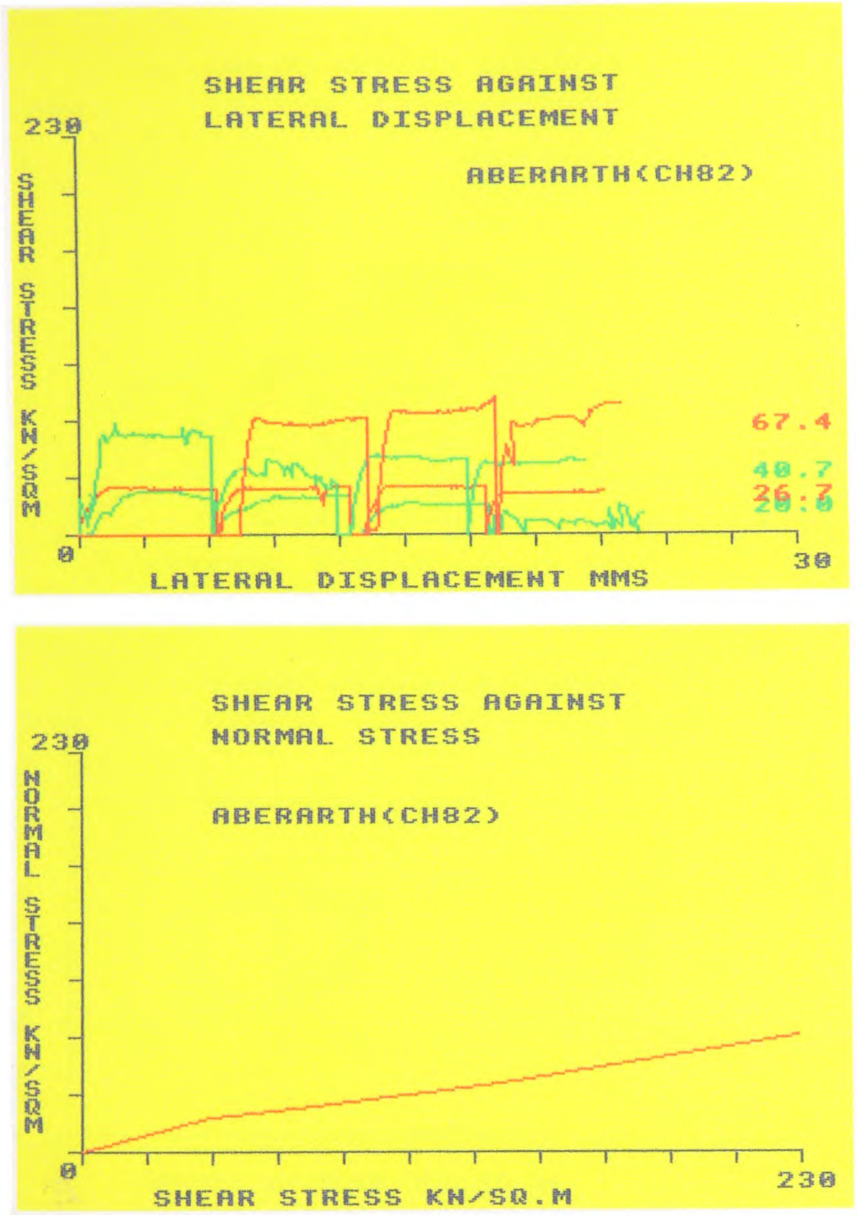


FIG. 7.12c Shear strength parameters for till, chng. 82 + 00

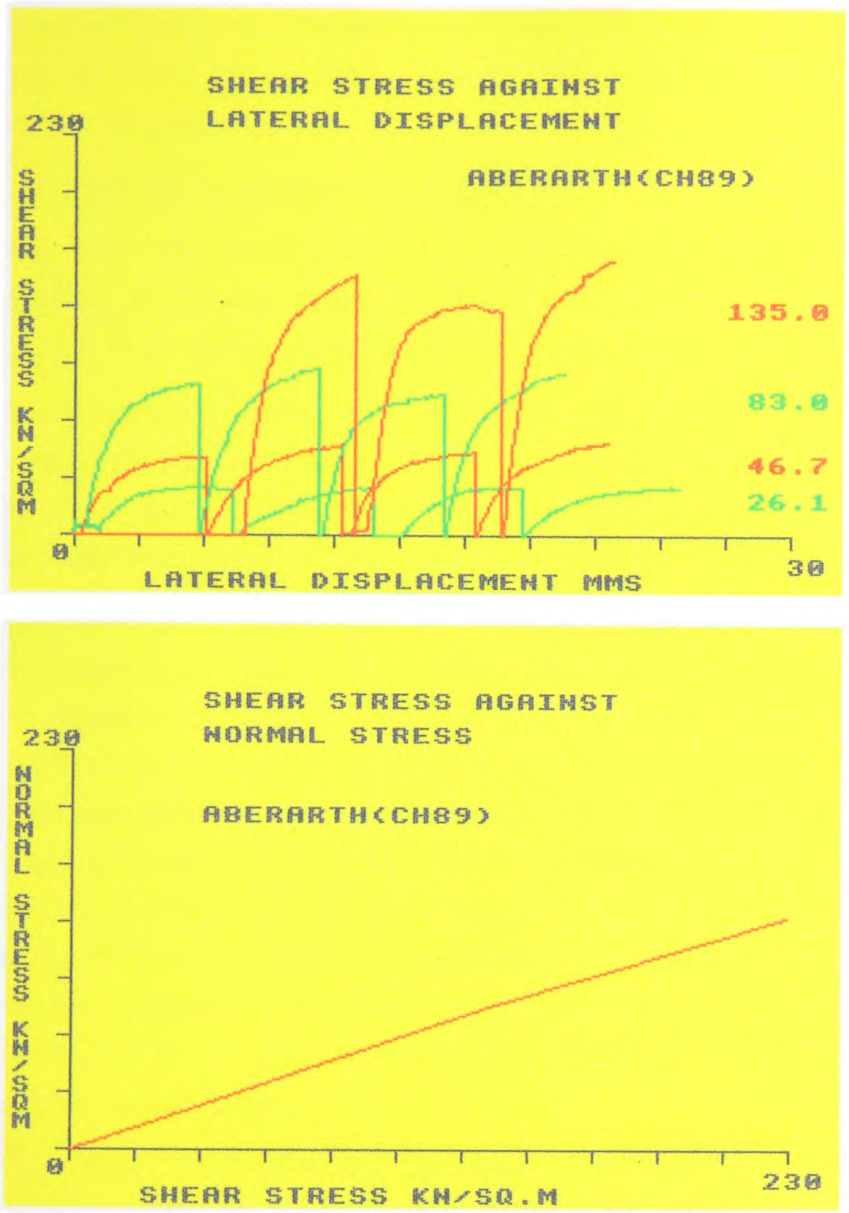


FIG. 7.12d Shear strength parameters for till, chng. 89 + 00

obtained were representative of the different sections examined and to enable a comparison to be made of the variation of soil properties along the coastline. Comparisons here are limited to the main sections of till previously discussed, results being presented for four basic properties.

7.7.1 Particle size distribution

The average particle size distribution for the four sections (designated sites in Figs. 3.12a and 3.12b) are shown in Fig. 7.7, the curves for each individual section being shown in Figs. 7.6a-d.

One property which all the samples have in common was in being exceptionally well-graded. Practically all samples contained material ranging from boulder size (>200mm) down to clay size (<2mm) and in none of the sampling sites were the larger clasts absent.

The cumulative grading curves and frequency histogram (Fig. 7.8) all indicate that the till shows some variance within each section but the distributions do not deviate grossly from normal distributions. This fact is borne out in Fig. 7.9 which indicates the close grouping of the minus 60mm fraction for all the till samples. The main differences which may or may not affect the engineering properties are therefore related to variations in the respective amounts of coarse (gravel, cobbles and boulders) and fine material present. Essential differences in grading between and within the till exposures can be evaluated from Plates 7.7 - 7.18, which show profile and close-up of cliff face at several chainages.

From Fig. 7.8 it will be seen that there is a wide scatter in the overall results for boulder and cobbles content (10-70%). The boulder and cobbles content is significantly higher (43%) for site D samples (Plates 7.15-7.18) as is the fraction of total coarse material (86%). There is a marked change in facies towards the southern end of this section, borne out by sample no. CD/D/5 which shows a fines content of 26% compared to 12% for the remainder.

Samples from sites A and D have fewer total fines (18 and 14% respectively) than those from sites B and D (28 and 26%

PLATE 7.7 Site A Llansantffraid - till face at chng. 37 + 00

PLATE 7.8 Chng. 37 + 00, close-up of till material

(50mm tape measure for scale)

PLATE 7.9 Site A Llansantffraid - till face at chng. 39 + 00

PLATE 7.10 Chng.39 + 00, close-up of till material
(50mm tape measure for scale)

PLATE 7.11 Site B Llanon - till face at chng. 47 + 00

PLATE 7.12 Chng. 47 + 00, close-up of till material

(50mm tape measure for scale)

PLATE 7.13 Site C Morfa - till face at chng. 52 + 00

PLATE 7.14 Chng. 52 + 00, close-up of till material

(50mm tape measure for scale)

PLATE 7.15 Site D Aberarth - till face at chng.88 + 00

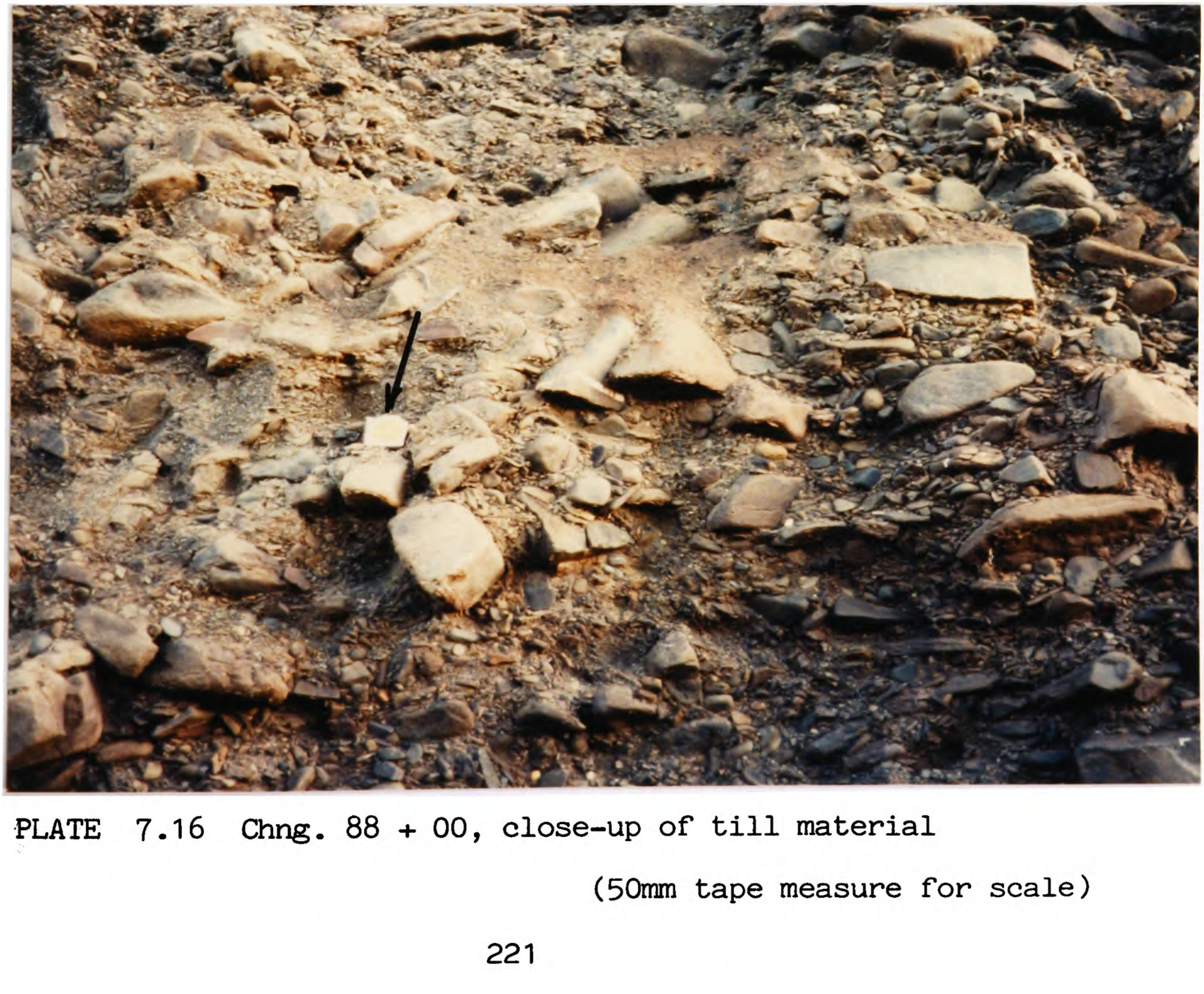


PLATE 7.16 Chng. 88 + 00, close-up of till material

(50mm tape measure for scale)

PLATE 7.17 Site D Aberarth - till face at chng.89 + 00

PLATE 7.18 Chng. 89 + 00, close-up of till material

(15cm pencil for scale)

respectively) Site B shows the greater variance in the overall gradings and also has the sample with the highest percentage of silt and clay (25% in sample no. CB/B/3, Plates 7.11 and 7.12).

The average particle size distribution for all the till in terms of the 4 fractions considered, is as follows:

Boulders and cobbles	33%
Gravel	46%
Sand	11%
Silt and clay	10%

7.7.2 Effect of weathering on grading

The effect of weathering on till material is a marginal reduction in fines content. Visual examination of the various exposures suggests that the weathering process simply produces a leaching of the finer particles from the cliff face. Clay/silt/sand particles may be displaced within the face to a lower level and often form a thin apron at the foot of the cliff.

This is mainly caused by the percolation of surface water down through the till (from rain water or land drains) but direct wave action, spray and general sub-aerial weathering also contribute to this process. The most severe erosion in this respect is noticeable where land drains from the adjoining fields discharge at the face.

7.7.3 Natural bulk density and moisture content

There are too few results to make conclusive statements but from Fig. 7.5a there appears to be little difference between sites in terms of bulk density. Values range from 2.15 to 2.40t/m^3 with a mean figure of 2.275 t/m^3. Slightly higher figures are recorded for Site B.

Bulk density values represent the mean density from a vertical profile down the face and do not distinguish between cliff top and bottom. Although unconsolidated in geological terms, it would be reasonable to expect these drift deposits to show a slight increase in density with increasing depth.

The spread of values for the natural water content is from 6 to 12% with a mean value of 8.7% (Fig. 7.5b).

7.7.4 Plasticity indices

Liquid and plastic limits were carried out on the fraction of fines passing the B.S 36 sieve. Results summarised in Fig. 7.10 indicate that the till matrix can be classified as an inorganic clay or silt of low plasticity. Several samples had non-plastic fines. These indices are not sufficient to differentiate between the tills even when taken in conjunction with particle-size distribution.

7.7.5 Shear strength

Shear strength parameters, based on the best straight lines through the stress points representing failure, show remarkable similarity. The values of ϕ'_r(angle of shearing resistance) for the four tests carried out on the till range between 26.0° and 31.6°, giving a mean value of 29.5°. Cohesion values in each case were zero or near zero.

The fines content of these tills is generally low and exhibits low plasticity. Since shear tests were carried out on the fraction of fines passing the 3.35 sieve, a consistency of result is perhaps to be expected.

There is a marked deficiency of data on the shear strength of comparable tills, partly due to the fact that the fines content of many of these is so low that they have been considered to be effectively cohesionless. The shear strength of such deposits must however, vary with grading. Laboratory experiments have indicated that the angle of friction tends to increase with increasing maximum size of the gravel fraction (Fookes et al, 1975).

In practice the relationship is not a simple one and it is evident that particle shape has a considerable effect on the shear strength (Holtz and Gibbs, 1956).

Tests on fluvoglacial gravels in West Glamorgan (Rouse, 1974) have given values of up to 36° and it seems likely that there is a limited relationship between the ϕ_r value and the clay or fines content of such materials.

7.8 Conclusion

Analysis of basic physical properties of these tills does not differentiate between them which suggests that the unweathered material is similar throughout the study area. Inherent variations within each till unit are perhaps as great as those between different units. In engineering terms it may be possible to treat the tills as one soil type with a relatively high coefficient of variation of properties. This variation of properties taken in conjunction with beach parameters and environmental factors, will be assessed in terms of cliff recession in Chapter 8.

CHAPTER 8.

STATISTICAL ANALYSIS OF COASTAL EROSION.

8.1 Introduction

Indications are that there is a strong regional trend in the occurrence of recession within the drift material along with local concentrations of occurrences within individual sections(Table 3.1).

Therefore recession is not only widely distributed along the coastline because of the ubiquitous existence of appropriate soft rock but its probability of occurrence may be enhanced in certain localities by special factors operating in these areas.

In this Chapter, what are believed to be pertinent independent variables, in terms of long-term (90 years) and contemporary short-term (2 years) recession, are isolated. It is suggested that there exists an almost linear relationship between recession rate and certain variables which is assessed by bivariate analysis while their relative influence is analysed in a regression format.

8.2 Review of processes

Although this study is mainly concerned with factors which influence variations in rates of cliff erosion it may be helpful at this stage to briefly review the processes involved.

The principal cause of coast recession is evidently that of present-day marine erosion. Studies of forces generated by breaking waves impinging on vertical barriers have been numerous in the field of coastal engineering but have been largely confined to sea walls (Bagnold, 1939; Denny, 1951; Muir-Wood, 1969). Sunamura's (1975,1977, 1981) work on model cliff erosion has implied that erosion by waves breaking directly at the cliff face is achieved by pressure variations and for waves breaking further seawards i.e broken waves, principally by shearing forces.

Most workers indicate that, for well-jointed rocks exposed in highly irregular cliffs such as those of the Aberystwyth Grits, quarrying is perhaps the most powerful mechanism involved.Quarrying was defined by King (1972) as the removal of pieces of rock by hydraulic action and may be produced by wave shock, wave hammer, air compression (Trenhaile,1980) or some form of pressure release (Clarke,1979).

Although abrasion has historically been considered the mechanical erosion process responsible for wave-cut platforms, certainly on the upper shoreward sections (Robinson, 1977, Trenhaile, 1980), when rock cliffs are almost continually exposed to alternate wetting and drying due to tidal movements,complex weathering processes may take place. These may include chemical processes such as hydration and oxidation and physical rock breakdown caused by salt crystallisation or the swelling of rock grains (Pethick, 1984).

Where the coastline is formed of tills and clays, in addition to the shear forces generated by direct wave action or by swash activity, the reworking of the cliff material by wave-generated pressure fluctuations and the abrasion by granular material present in the water column as bed or saltation load are other contributory factors.

The direct force of breaking waves was investigated by means of field instrumentation and is discussed briefly in Chapter 9. Neither of the two additional processes was examined but the reworking process must be related to wave energy expended on the coastline. Because of the relative infrequency of direct wave attack - only between 1 and 4% of all actual tides affect the cliff bases along the till sections - this process may not be sufficiently cyclic in nature to be considered important.

The role of suspended sediment has been discussed by Sunamura (1983) and investigated in detail by Kamphuis (1983) who found that critical shear stresses for initiation of erosion were substantially lowered when sediment was present in the water column. The composition of the foreshore along this length of coastline is predominantly shingle and the abrasive action due to wave-moved beach material is therefore limited to high energy conditions. Evidence of this process was to be had during periods of winter storms when pebbles and cobbles up to 150mm in size were seen deposited onto adjacent fields.

Although marine attack is the principal cause of instability the process of sub-aerial erosion must be acknowledged but is considered far less significant as it is dependent, in turn, on the amount of wave erosion. Landslips may temporarily change the cliff profile and result in slumped material being deposited at the base or toe. Wave erosion of this slumped material restores a similar profile to the cliffs but at the same time reduces the resisting movement and the cliff form becomes more susceptible to further downslope movement.

In the coastal embayments of till near Llanon and Aberarth local falls in material were observed (Plates 3.13 & 3.14) where shock pressure waves removed a few cubic metres of material at a time which was removed by subsequent spring high tides. Dessication during hot periods of weather also resulted in small falls of till. These were particularly noticeable during the summer of 1984 but these quantities were minimal when compared to those produced by direct wave attack.

Obviously if these were inland cliffs and there was no significant erosion process to remove material from the base of the slope, the slope would reach a stable angle of repose and would be affected only by relatively slow processes such as creep; a long-term equilibrium would be reached.

8.3 Principal factors affecting recession rates

The foregoing section suggests that wave-related processes taking place along the coastline may well control the long-term rate of cliff erosion. Erosion occurs infrequently, only under certain conditions and is limited by a number of factors.

Factors affecting coastal stability have been recognised and can conveniently be divided into three broad categories, namely

(i) Environmental factors
(ii) Beach
(iii) Cliff

There are inevitably a number of factors which need not or cannot be considered under the framework of the present study. These include historical factors such as sea-level rise and secular variations in wave climate (Carter and Johnson, 1982) as well as various geological and hydrological factors such as fissuring patterns and ground permeability.

8.4 Environmental factors

As period of wave contact and wave energy are obvious erosion criteria, the total duration of cliff exposure to wave attack is an important factor in assessing potential instability along this coastline.

Duration cannot be related directly to intensity of wave attack as the latter changes through the tidal cycle. Initial contact is through swash activity where waves break short of the cliff base and energy is expended by percolation and frictional effects during swash run-up. This is followed by direct wave attack and, as water deepens at the cliff base, wave reflection and clapotis (Russell and Macmillan, 1952).

Nevertheless,exposure is considered a significant parameter as it is a result of a number of environmental factors, in particular the relationship between beach height and wave-energy conditions. In this context beach height is synonymous with height of cliff base above O.D. Wave energy is governed by wave height, which in turn is determined by the strength, direction and duration of wind and the length of fetch.

From analysis of tidal and meteorological conditions associated with recorded cliff-eroding events,McGreal (1979) indicated that certain limiting conditions of wind speed and direction need to be satisfied to propagate sufficient wave energy for cliff-base erosion to occur. McGreal also suggested that atmospheric pressure was significant in tidal levels but no threshold value was identified.

Observations and recorded levels taken during the study period have suggested that deviations in meteorological conditions generally resulted in small differences between predicted and recorded tide heights except during onshore storm events when these differences became more substantial.

The estimated time of exposure for different cliff heights along the Ceredigion coastline has been calculated from actual tide levels recorded at Aberystwyth during 1980, antecedent weather conditions recorded at R.A.E Aberporth and the tidal hydrograph (Fig. 4.13).

This represents one year's actual data (Table 4.9) and takes into effect prevailing weather conditions. Exposure therefore represents the required coincidence of tidal and meteorological conditions and can be used in this analysis to represent the input environmental factors.

8.5 Beach factors

Numerous factors have an influence on the wave-related erosion forces reaching the shore. These include fetch and orientation,beach morphometry and the presence of coastal protection works. Consideration must be given to the width, slope, composition and state of erosion or accretion of the beach in terms of beach levels or volumes, the presence of backshore features such as vegetation and talus cones and beach structures such as seawalls and groynes.

8.5.1 Orientation of coastline or aspect

In terms of exposure (Fig. 3.2) the length of coastline between New Quay and Llanrhystud is governed in terms of fetch by the confines of the Irish Sea and the available window to the south-west already discussed in Chapter 4.

Coastal alignment is essentially S.W to N.E with local deviations. Bearings taken perpendicular to the shore vary between 275^{o} and 012^{o} the only exceptions being the curved sections of the crenulate bays at New Quay and Cei Bach (section 6.5.2). There are few sheltered sites in terms of storm wave attack from the north-westerly quarter. Prevailing waves from the south-west break obliquely to the shore which has the general effect of pushing the shingle in a north-easterly direction along the beaches.

8.5.2 Beach levels

For a given wave climate and physical setting, beach levels affect wave erosion by influencing the distance from shore at which the waves break. For a given wave, the lower the beach level, the closer the wave breaks to the shore and thus the greater the amount of wave energy reaching the cliffline

In theory, an inverse relationship should exist between rates of recorded cliffline erosion and incidence of beach profile lowering. McGreal (1977) noted that beach-level changes were significant in explaining variation in recession rates.

The longshore survey of beach profiles has confirmed the existence of high and low beaches predicted by the wave refraction model for this section of the Cardigan Bay coast. Sweep zones drawn for selective beach profiles (Figs. 6.4a-h) showed only minimal change over the 2-year period with the upper foreshore revealing seasonal trends of winter lowering and gradual replenishing during spring, summer and autumn. Short duration, high-energy events particularly January storms, were most destructive, being often associated with a marked lowering of beach height at the cliff base.

8.5.3 Beach profile

Although the slope of the beach initially may be a function of the underlying rock platform, the influence of the latter in terms of present-day erosion is negligible as there is a considerable cover of sediment in all beaches apart from those that fringe the cliffs of the Aberystwyth Grits.

The longshore survey, values of beach slope ranged from 3° to 12°. In Fig. 8.1 a histogram is produced of the frequency of occurrence of beach slope which shows that for the predominantly shingle beaches of the Aberaeron area the most common slope is 8° or 1.15. These differences in beach slope may influence the rates of cliff erosion, with less energy being expended along the flatter profiles. The same may be said for beach terrace slope although the latter does not deviate much being consistently near 1°.

From the surveyed profiles the width of beach face varies appreciably up to a maximum of 69m. The histogram in Fig. 8.2 indicates that nearly 80% of all profiles have beach faces between 10 and 40m in width.

8.5.4 Height of cliff base

Along the 20km stretch of coastline there is considerable variance in cliff base heights. Cliff sections of the Aberystwyth Grits are fronted by a wave-cut platform with little or no beach material whereas the till sections are fronted by relatively high shingle beaches.

The height of cliff base, defined in section 6.2 as the junction betweenthe free cliff face and beach, ranges from $\bar{0}$.1m A.O.D at Graig Ddu (chng. 68 + 00) to 7.0m A.O.D at the storm beach at Llanrhystud (chng. 7 + 00).

The highest and lowest Mean High Water Springs (M.H.W.S) predicted from tide tables for the Cardigan Bay area are only 3.0m and 0.8m A.O.D respectively. The majority of the sections have cliff base heights in excess of 3.0 A.O.D. Referring to the surveyed heights of beach at cliff base therefore it is evident that for cliff erosion to occur high tides must be supplemented by appropriate high-energy conditions.

From Table 4.9 it is seen that chng. 7 + 00 is prone to marine erosion for only 0.006% of the time while the rock cliff at chng. 68 + 00 is exposed for 55% of the time.

For the rock sections north of Aberarth (chng. 61 - 78) and at Gilfach-yr-halen (chng. 120 - 158) the height of cliff base generally coincides with the top of the shore platform and ranges between $\bar{0}$.1 and 3.9m A.O.D with a mean value of 1.64m.

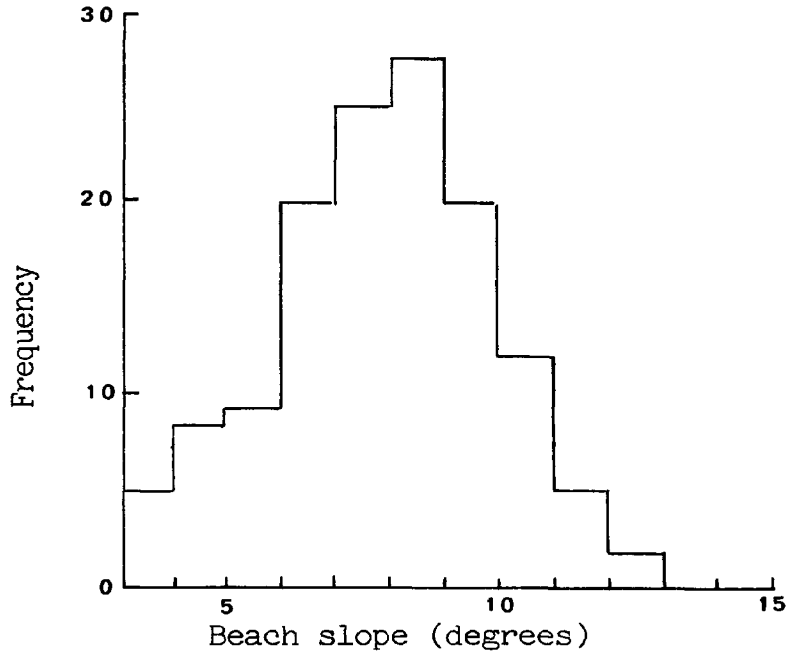


FIG. 8.1 Histogram of beach slopes

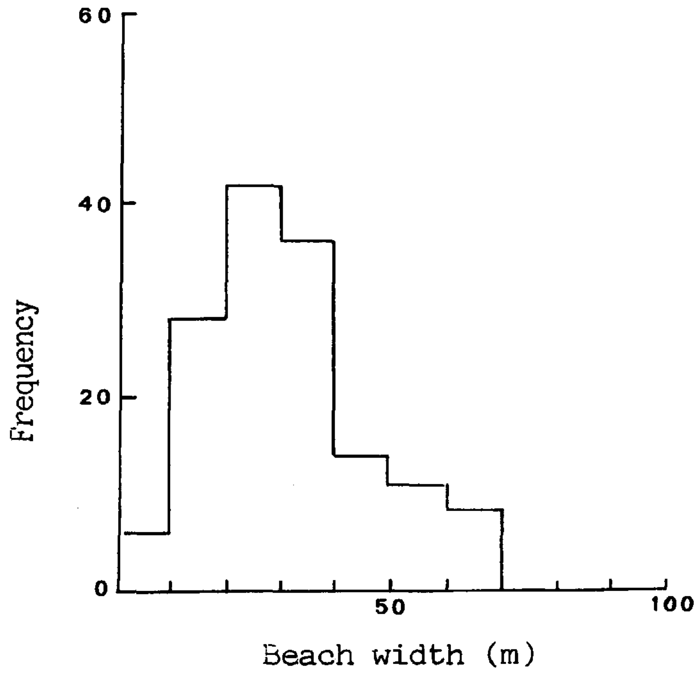


FIG. 8.2 Histogram of beach widths

The till sections show a smaller range of values for the height of cliff base. For instance site A at Llansantffraid has a mean height of 5.15m A.O.D indicating 0.08% exposure, Site B at Llanon 4.10m A.O.D with 0.28% exposure, Site C at Morfa 4.85m A.O.D with 0.13% exposure and Site D at Aberarth 3.70m A.O.D with 0.39% exposure.

It is significant that the till sections are much less prone to direct wave attack than the hard rock sections but also significant that the shock pressures from such short duration extreme events may be of far greater consequence within the weaker glacial sediments.

8.6 Cliff factors

8.6.1 Strength of cliff material

Although resistance to erosion is a complicated process and may involve a number of geotechnical parameters, the compressive strength is probably the most important (Sunamura, 1983). It is also one of the simplest measures of strength to obtain and although its application is limited it does allow comparisons. to be made between rocks and soils and affords some indication of material behaviour under more complex stress systems.

Field index tests have enabled uniaxial compressive strengths to be determined for the glacial clays and solid-rock sections within the study area. These results are listed in Tables 7.2 and 7.3 respectively. Whilst shear strength parameters have been obtained for the various till deposits, the site investigation did not allow measurements of compressive strength. In order that valid comparisons can be made between the till sections and those of clays and rock, results from various investigations into similar tills have to be relied on.

The study of glacial tills in the Taff Valley, South Wales by Fookes et al (1975) has given standard penetration 'N' values for till materials not dissimilar in character to those found in the Aberaeron area and having a "grand average" grading of

Boulders and cobbles	25%
Gravel	31%

Sand	22%
Silt and Clay	21%

The 'N' values observed were found to be dependant more on the gradings of the various tills than on their relative densities and gave a mean value of 48 with a modal range 31 to 40.

From the approximate relationship between unconfined compressive strength and 'N' value (Terzhaghi and Peck, 1967,p347) this mean value suggests a strength of 686.4 KN/m^2. Since till can also be regarded as a soft-rock mass, the lowest figure of 700KN/m^2 for such a material proposed by Brink et al (1982) is in agreement with this value.

Although this interpretation is debatable, the value of 700 KPa has been adopted as a realistic compressive strength for the tills in the area and has been used in the statistical model.

8.6.2 Protective features

These can be conveniently categorised into natural and man-made barriers. Along the Ceredigion coastline storm beaches are prevalent and afford protection to adjacent land, particularly at Llanrhystud, where the shingle ridge extends for some 1.5km and where little change has occurred in the past two decades (section 6.4.1 ii). Similar features are found at most of the river mouths and all have acquired a permanent or semi-permanent character.

Talus cones produced by sub-aerial weathering, slope processes and direct wave attack may provide temporary protection against further toe erosion but the quantities are minimal and breakdown of the debris material is not particularly difficult - the fines content being removed as suspended load, the sand and gravel fraction being integrated and re-worked within the beach material. Flotsam or seaweed build up at the cliff base have been noted (Plate 4.1) but again give only limited protection and most were removed by the sea within days.

Permanent engineering structures include harbour installations and shore-protection features. The structures at Aberaeron,consisting of jetties, breakwaters and seawalls, were built in the eighteenth century and extend for some 0.5km along the waterfront. This section (chng. 109 - 114 approximately) has not been considered in the overall model of shoreline recession.

Other groyne systems, together with the area of artificial beach fill north of Aberaeron, have been included but no attempt has been made to differentiate between natural and artificial structures. Neither have the individual longshore stations been given a degree of protection; the presence or otherwise of some form of protective feature has simply been allocated the digit 1 or 0 in the statistical analysis.

8.7 Regression and correlation

In this study to date numerous causal influences have been identified for the variance in coastal recession which is a dependent variable. Some of these influences may be significant and others not. The significance of the different variables measured was tested statistically using the S.P.S.S - X computer package.

"Regression analysis is a statistical search procedure whereby the relative influences of all the factors presumed to act on a dependent variable can be isolated and gauged" (Todd 1980, p3). Such an analysis can identify the two groups of independant variables, isolating in particular those which do have critical causal effects, in a statistical sense, and which should therefore be retained in an equation to describe the variance in recession rate.

A useful approach to the problem of which independent variable to retain in a final equation and the one used in the present study is the technique of stepwise multiple regression. This method does not feed all of the independent variables in at once but builds up the equation one extra variable at a time. For example, with 4 independent variables there are 24 different ways in which their "order of entry" can be arranged; with 5 there are 120 and with 6, 720. Some rule is therefore required to organise the procedure such that variables are entered in their order of importance in reducing the variance in recession rate, with the most important first. This ordering is indicated by the partial correlation coefficient r (denoted Multiple R in SPSS computer package), the mathematical justification for which depends on the bivariate normal distribution.

Bivariate regression analysis was used to test the hypothesis that there was a linear relationship between dependent and individual independent variables. The regression line is denoted by

$$y = a_o + a_1 x$$

and the measure of how well the straight line fits the data is denoted by one of several coefficients.

T statistics and their 2-tailed observed significance are given, as are F statistics and significant F values. If the observed significance level associated with the slope of the regression line is very small i.e. approaching zero, then one can deduce that dependent and independent variables are linearly related.

The coefficient of determination r^2 (R Square in SPSS computer package) is the ratio of the explained variation to the total variation and is a further measure of the fit of the estimated regression line to the data. This ratio must lie between 0 and 1, the closer the coefficient is to 1, the closer the points lie to an exact straight line. The sample r^2 tends to be an optimistic estimate as the model usually does not fit the population as well as it fits the sample from which it is derived. The statistically adjusted r^2 attempts to correct r^2 so that it more closely reflects the goodness of fit of the model in the overall population.

8.7.1 Long-term recession of coastline

This model makes the assumption that coastline erosion over the period 1880-1970 is applicable to present-day conditions of beach and cliff morphology. For the glacial sediments, measurements of contemporary recession (Table 3.1) corroborate those from long-term map evidence; for the solid-rock sections the long-term rates may be an over-estimation of current rates (see section 9.3.4).

Quantitative data from 144 profiles, together with computer print-outs of statistical analysis are tabulated in the Appendix.

Data from each profile represented 11 variables, each of which in turn was tested against the mean annual recession rate.

Bivariate relationships between site variables and recession were poor. Protective features in the form of storm ridges gave the highest correlation coefficient ($r = 0.407$), the strength of cliff material the lowest ($r = 0.0243$). Several beach variables - beach height, beach-face volume, beach-face width, beach-terrace height and aspect.- were significant at the 95% confidence level.

Multi-regression analysis showed that all the considered variables only accounted for 27% of the total variation on rates, protective features being responsible for 16.5% of this figure. Since protective features were not represented by finite quantities the data column representing this variable was deleted and the recession model tested using the remaining ten variables. This procedure did not substantially alter the ranking order of significance except that beach face volume became the dominant explanatory variable (Sig F = 0.0593). Tidal coverage and total beach volume were also significant (Sig F = 0.0607 and 0.0985 respectively). Statistically, the strength properties of cliff material as represented by the uniaxial compressive strength, was insignificant in explaining spatial variation in coastal erosion. (Sig F = 0.6075).

8.7.2 Contemporary short-term recession of till sections

Data was collated from 18 profiles within the four sites A, B C and D (Figs. 3.12a and 3.12b) and is tabulated in the Appendix. Because these sites have almost identical aspect and till of similar character the influence of beach parameters on cliff erosion may be more easily identified. Whereas tills within the overall study area have been allocated the same arbitrary compressive strength of 700 KN/m^2, sieve analysis has distinguished between the material at these specific sites by virtue of percentage of total fines (Figs.7.6a-d).

A preliminary examination of the data has suggested that a linear relationship exists between recession rate and certain beach and cliff parameters. In Figs. 8.3a-c, cliff recession in cm yr^{-1} have been plotted against the independent variables of percentage total fines of cliff material, beach volumes and percentage tidal coverage

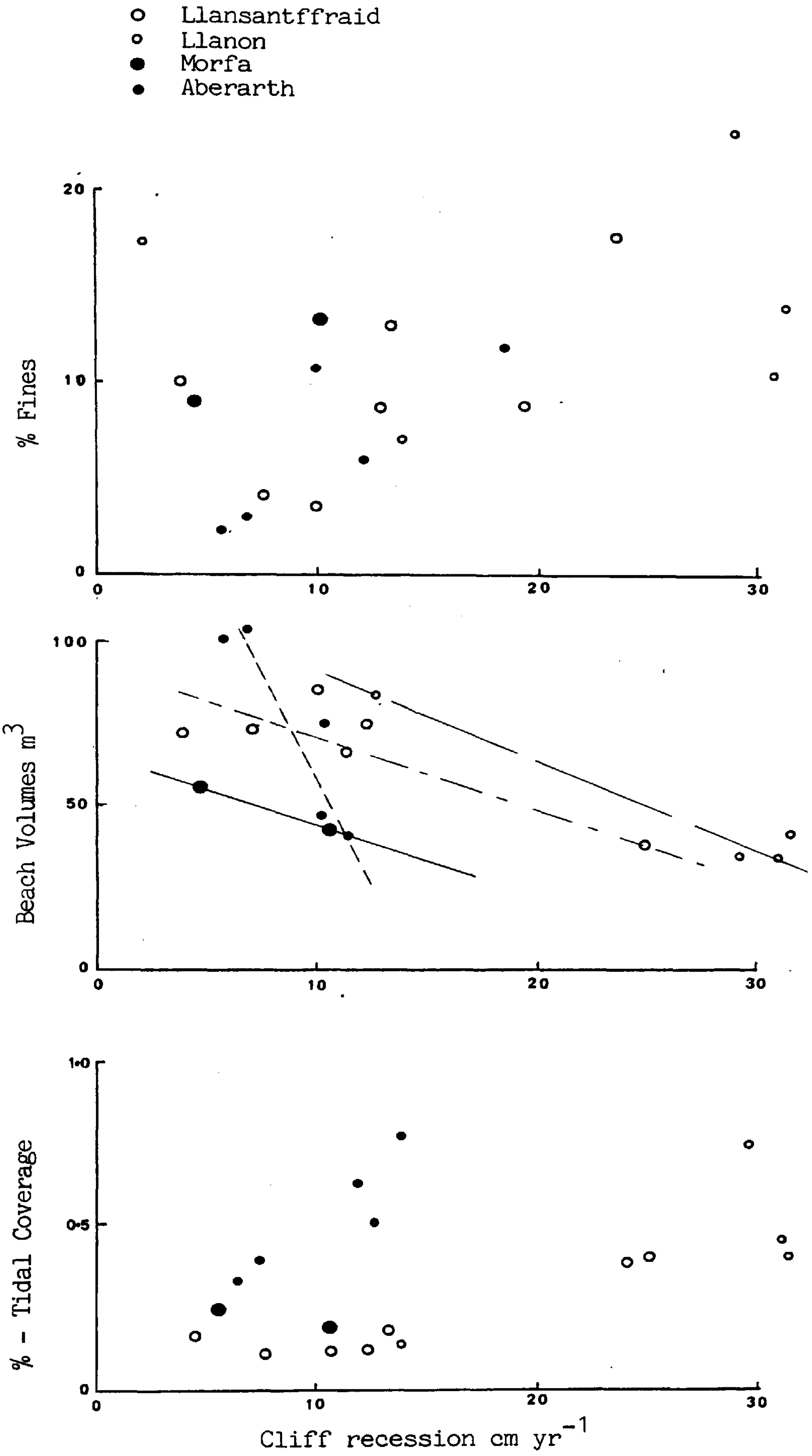


FIG. 8.3 a–c Relationship between contemporary cliff recession and independent variables

respectively. Fig. 8.3a indicates a positive correlation, Fig. 8.3b low negative correlation while Fig. 8.3c shows no discernible degree of correlation.

Bivariate analysis has confirmed a much stronger relationship between recession rate and several of the independent variables. Beach variables had high correlation viz. beach terrace slope ($r = 0.7053$), beach-face volume ($r = 0.6448$), total beach volume ($r = 0.5019$), beach-face width ($r = 0.5601$), beach-terrace height ($r = 0.5112$).

Percentage total fines is also relevant ($r = 0.6200$) while cliff height is not ($r = 0.2045$).

Together all the eleven variables entered into the multiple regression analysis accounted for 92.0% of the spatial variation. Only beach-terrace slope was significant at the 95% confidence level (Sig. F = 0.0293) and explained 49.7% of the total variation. Additional variables beach face volume and total beach volume increased this figure to 86.1%.

8.8 Discussion

The ranking order of significance for the 10 variables considered in the long-term analysis has been extracted from the computed data and is given in Table 8.1.

Although these variables in total did not satisfactorily explain the variance in erosion along the 20km of coastline, beach and environmental variables, particularly beach face volume and tidal coverage, were statistically important.

From Fig. 3.9 the highest rates of erosion should be associated with the weakest deposits but as a variable in the multi-regressional equation the strength properties of the cliff material was the least significant.

While the short-term statistical model has indicated a very high coefficient of determination ($r^2 = 0.9156$) the theoretical high correlation between recession and cliff material properties - in

RANKING	VARIABLE	SIG F
1	Beach Face Volume	0.0593
2	Tidal Coverage	0.0607
3	Total Beach Volume	0.0985
4	Beach Face Width	0.0991
5	Beach Face Slope	0.1056
6	Beach Terrace Height	0.1316
7	Height of Beach	0.2656
8	Aspect	0.3337
9	Beach Terrace Slope	0.3521
10	Strength of Cliff Material	0.6075

TABLE 8.1 Significance ranking of different variables (from SPSS-X computer package)

terms of percentage total fines - has again not been substantiated (Sig F = 0.3432). Total beach volume and height of beach explained 24.1% of the spatial variation in rates.

Differences in the explanatory variables given by the two statistical analyses could be attributed to the amount of data available for each. Sample sizes were arrived at arbitrarily rather than through scientific choice and it is doubtful whether the sample size for contemporary localised erosion (18) was large enough to give a guarantee of unbiased results.

CHAPTER 9.

MECHANISMS OF EROSION

9.1 Introduction

The quantitative model presented in the previous chapter was intended to provide a rational explanation for the recession of cliff slopes. As the study progressed, however, it became apparent that there were situations where coastal erosion could not be reconciled with the model.

As intimated in Chapter 8, marine processes are not the only factors which affect the stability of the Cardigan Bay cliffline. For instance, notch development in glacial sediments near Aberarth is a result of marine undercutting but slope failure may be influenced by other causative factors. Ample evidence was present in several locations to suggest mechanisms were operative which did not require the presence of tidal forces. Various morphological features imply a number of different sub-aerial processes are active throughout the area although any quantitative assessment of actual rates is virtually impossible.

In the following case studies, observations are applied to several sites where erosion is a problem and where the mechanisms responsible and features resulting can be identified. Attempts were made to measure, by field instrumentation, shock pressures due to wave impact upon the coastline. Rockfall activity in the Aberystywth Grits was considered in terms of local relief, where the degree to which the rocks are traversed by discontinuities - in particular the attitude of joints and bedding planes - is a factor which may influence the rate at which erosion takes place. The behaviour of unconsolidated materials when exposed to sub-aerial processes, particularly wetting and drying and freeze-thaw action, together with their slope stability and likelihood to sliding is also assessed.

9.2 Direct wave attack and the measurement of wave forces

Direct wave attack along the till sections is an infrequent process. From an analysis of tidal and climatic records there is an incidence on average of less than 20 tides per year attacking the cliff base.

Nevertheless, direct wave attack is the most powerful erosion mechanism because of the high energies involved (section 4.3.4).

Studies of wave forces active in cliff and beach erosion are difficult to measure acurately in the field because of the complexity of the environment. The traditional approach to the subject has involved model studies conducted in wave tanks, for example, Bagnold (1939), Denny (1951), Mitsuyasu (1962) and Sunamura (1978). Laboratory and field data are often not validly comparable; as Muir-Wood (1969,p15) has noted "in practice, it is apparent that there are many factors to modify such laboratory results" but suggested that maximum slamming force per unit length of wave crest could be approximated from:

$$P_m = \frac{1}{2} \rho_w g^{\frac{1}{2}} H_b^{5/2}$$

where ρ_w = density of water
g = gravitational acceleration
H_b = breaker height

According to Zenkovich (1967), the force of a wave (P) can be calculated indirectly by noting the maximum height (H) on the cliff to which water is thrown when it breaks. This can be expressed by the formula:

$$P = 10.8H \text{ kPa}$$

At the caravan site near Llanon (chng. 42 + 00) waves have been observed to break over the 3 - 4m low lying cliffs. This suggests a slamming force of 32.4 to 43.2 kPa. The writer is aware of a winter storm in 1979 at Nash Point on the South Wales coast of the Bristol Channel when storm waves breaking over the 35m high limestone cliffs would indicate wave forces in that environment 10 x those in Cardigan Bay.

Recent attempts at measurement of beach erosion forces have led to the design of more sophisticated instrument systems. In the West Wales study,attempts were made to measure wave forces breaking on cliffs using two types of data gathering units.

9.2.1 Dynamometer - type wave transducer

Kirk (1973) developed a type of dynamometer to investigate swash zone processes on shingle beaches. This was based on the instrument used by Shiffman (1965) and measured the net force exerted on two discs by determining the resultant displacement of a central rod coupled to a shore-based analogue chart recorder. Caldwell et al., (1982) considered Kirk's instrument to be a force transducer (or load cell) rather than a dynamometer and recognised several shortcomings in the design. A new instrument, based on Kirk's model and developed by the Physics section of the Science Department at the Polytechnic of Wales to record swash and backwash flow velocities, was used by Caldwell (1983) to measure surf-zone parameters.

Prior to subsequent instrument failure, Caldwell (1983) recorded a maximum dynamic pressure of only 2.5 kPa in the surf zone for mixed spilling and plunging waves on a South Wales beach directly exposed to dominant westerly waves, where H_b = 1.2m, T_b = 7.6 seconds. Most workers, including Minikin (1962), have considered that forces generated by breaking waves impinging on vertical cliffs may be orders of magnitude higher than those measured by Caldwell (1983) in the swash zone.

A later prototype of the same instrument was based on the measurement of variable resistance across strain gauges as they distorted in response to stresses applied to a solid steel support rod via a sensing head. This model has incorporated a micro-processor controlled digital recording system in the form of a cassette tape recorder housed beneath the sensing head and, as such, is self-contained. After extensive preparatory work in January and February 1985 trials with this modified version of the instrument at Aberarth proved unsuccessful through continued failure of the magnetic tape when activated to record impulses on the head (Plate 9.1).

9.2.2 Pressure transducer

Experiments were carried out with a more conventional pressure transducer system which used a fluid-filled sensing head housed inside a watertight steel box coupled to a shore unit and DC power

PLATE 9.1   Swash transducer at Aberarth (Feb 85)

PLATE 9.2   Pressure transducer at Llanon 9.3.85

supply by 30m of three-core PVC cable. The head was a National IC signal conditioned hybrid absolute pressure transducer (Fig. 9.1) with operating pressure range of 0 - 1000 psi. The shore unit consisted of a JJ Instruments model CR652 single channel chart recorder powered by 2 x 12 volt batteries, the output signal being controlled by an amplifier working off a 9V dry-cell battery. The transducer was calibrated in the laboratory with static loadings.

9.2.3 Operational proceedure

Establishing a secure anchorage for the pressure transducer head on site was problematic. A disused concrete ramp situated between sections of till near Llanon (chng. 45 + 00) was selected and the instrument head was mounted on a steel template which was, in turn, secured to the ramp with six 12mm rawl bolts. The position of the head at 2.15m A.O.D was considered representative of medium to high tides breaking at or near to the base of the adjacent cliffs.

Preliminary trials commenced in February 1985 and the first meaningful results were obtained on March 9th, 1985. Conditions of high spring tides were chosen and recordings were taken as far as was possible over the period that the waves broke against or over the head. Initial observations were made of breaker height, wave period, state of the tide and wind conditions for each event.

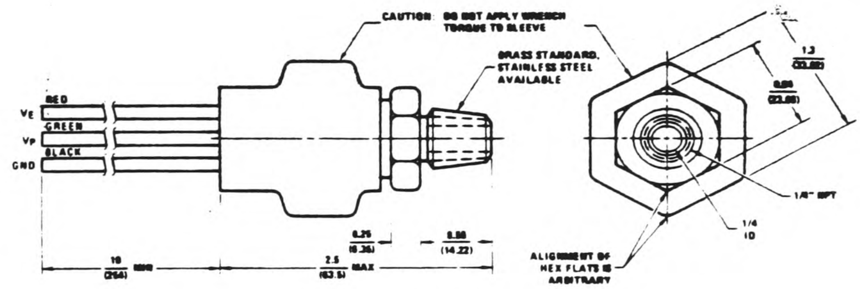
9.2.4 Results

Six separate experiments were carried out at Llanon to measure wave impulses of which three gave useful results. Of these three, only one gave values indicative of waves breaking directly on the cliff face. The results are shown in the form of sections of the recorder chart traces in Figs 9.2(a - b), 9.3(a - b) and 9.4(a - b).

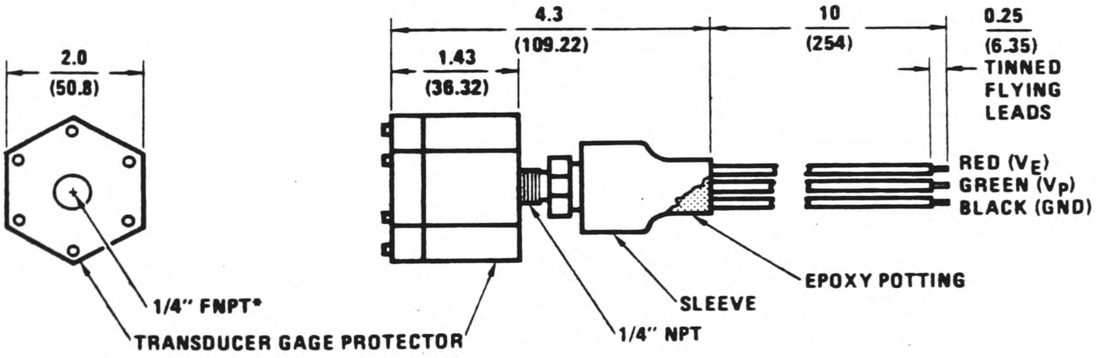
9.2.4.1 9th March 1985

Recordings were started at 0905 hrs as waves were breaking against the transducer head. A south-westerly wave field prevailed with H_b = 2.0m and T_b = 10 secs. Wind conditions were Beaufort scale force 5 gusting to force 6 to 7 from a southerly (160^o - 180^o) direction.

Physical Dimensions inches (millimeters)



Package for LX14XXA(S) Series Pressure Transducers
Weight: 105 grams



* Insertion of sharp objects into ports will result in permanent damage and, ultimately, device malfunction.

FIG. 9.1 Details of high pressure signal conditioned hybrid absolute pressure transducer

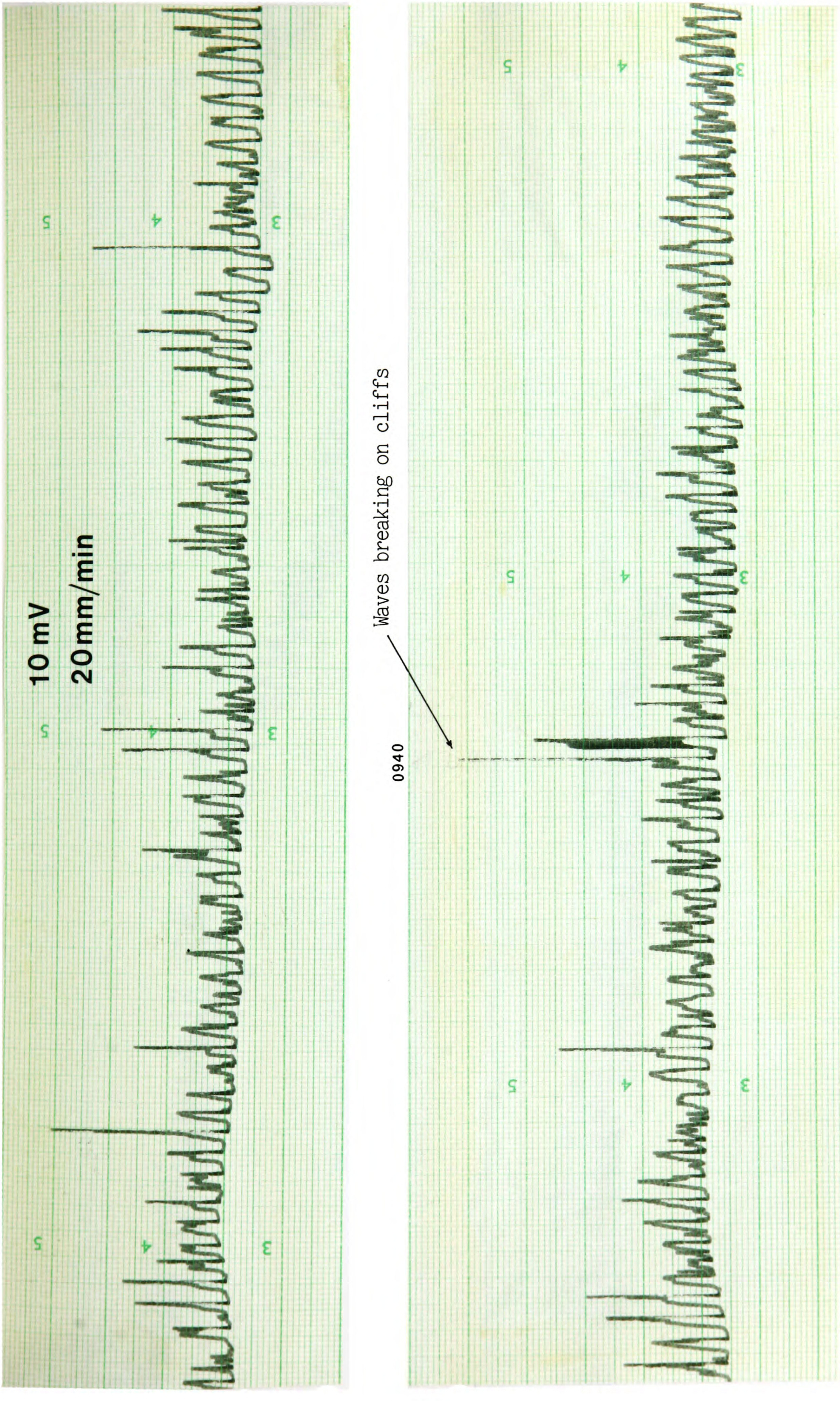


FIG. 9.2 a-b Recorder chart traces for pressure transducer 9. 3. 85

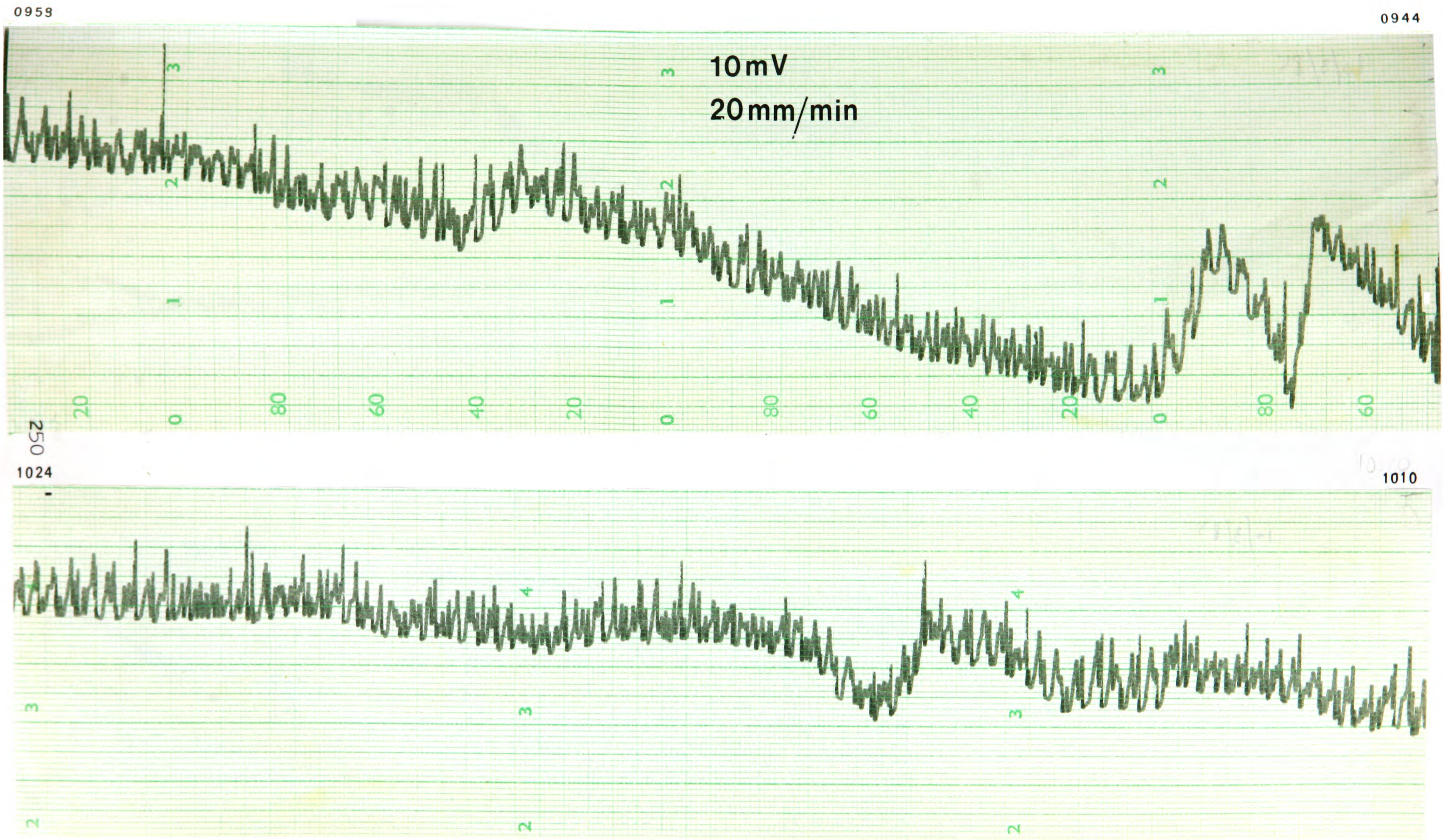


FIG. 9.3 a-b Recorder chart traces for pressure transducer 10. 3. 85

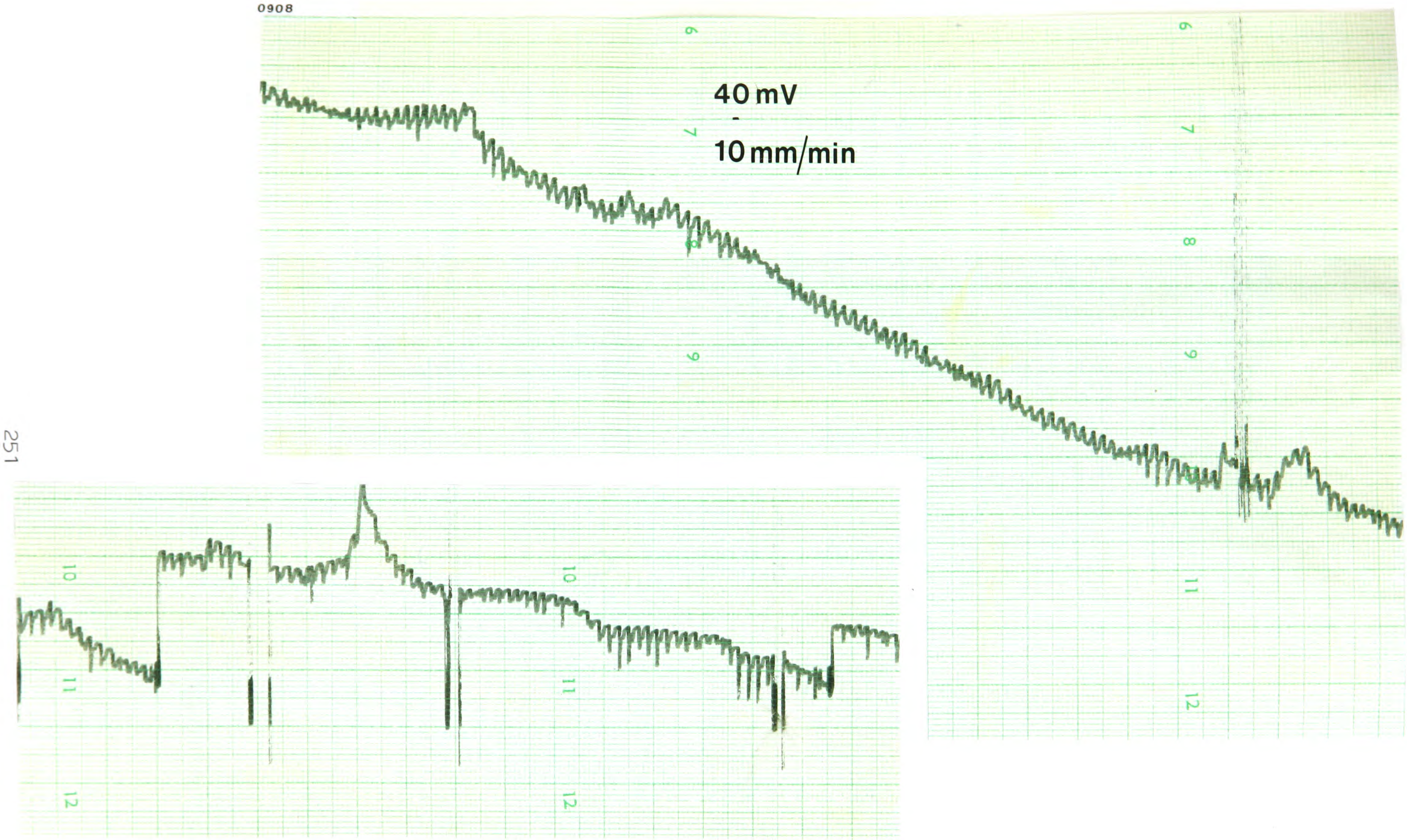


FIG. 9.4 a-b Recorder chart traces for pressure transducer 5. 4. 85

Signal sensitivity was established at 10mv and chart speed at 10mm/sec which was increased to 20mm/sec at 0910 hrs to give a constant trace. At 0925 hrs, when waves were breaking over and above the head, swash wave forces were recorded at 29.5 kPa. These forces increased with tide level and at the time of highest tide (0940 hrs) a maximum value of 38.1 kPa was attained.

At this time waves were breaking against the adjacent cliffs (Plate 9.2) at a level of 3.9m A.O.D, 1m or 35% above the predicted high tide value of 2.9m. Actual high tide also lagged behind the high tide time of 0906 hrs predicted by the 1985 Ceredigion Tide Tables.

At 1005 hrs waves were again breaking directly on the transducer head at 27.7 kPa pressure. By 1015 hrs waves were breaking off the head and of the total time of 70 mins that waves registered on the chart, 10 mins were spent directly on the till face.

9.2.4.2 10th March 1985

Conditions prevailing on the following day were very similar with a south-westerly swell predominating (H_b = 1.5m, T_b = 10secs). Winds were southerly (170°), force 5 (18 knots).

At 1944 hrs, when waves were already breaking against the head, swash pressure corresponded to 22mm deflection at 10mv sensitivity which represented an effective force of 19.1 kPa. Maximum force was recorded at 0958 hrs the estimated time of high tide which was measured at 3.0m A.O.D, marginally higher than the predicted height of 2.8m.

Waves advanced to within 2 metres of the cliff base and were breaking off the sensor head at 1040 hrs after a period of 56 mins.

9.2.4.3 5th April 1985

Waves were again long period (T_b = 11 secs) south-westerlies following antecedent southerly, veering south-westerly, winds of 18 knots hourly mean.

The chart trace for the period of recording 0858 - 1010 hrs showed a strong lateral drift but indicated consistent deflections between 6.1mm and 8.00mm at 40mv sensitivity, (Figs. 9.4a-) with no obvious peak. These values represent wave pressures of between 21.1 and 27.7 kPa.

Actual high tide was recorded at 3m A.O.D, again well short of the cliff face.

9.3 Rockfall activity

Rock falls are localised but prevalent along the base of the Aberystwyth Grit cliffs particularly in the section between Gilfach-yr-Halen and Cei Bach where indentations and caves are numerous and are generally associated with highly fractured and jointed areas. Throughout the rock sections the only fall activated and subsequently measured and monitored during the study period occurred at Graig Ddu near the northern end of the Aberarth section sometime in February 1984 (Plate 9.3).

From the photograph it is seen that translational failure has taken place on one plane or a set of planes within the rock mass. This resulted in a slide of a mass of rock parallel to the rock face, some 1.5m deep, 20m wide and extending the full height of the face. The volume of the resulting talus cone at the toe was measured at $1000m^3$.

9.3.1 Effect of local geology on slope stability

Rock type has an important influence on the behaviour of rock slopes not only because of its durability with regard to weathering but also because natural discontinuities control its mass properties. Workers in Europe have emphasised for many years the fact that a rock fall is not a continuous mass and that its behaviour is dominated by discontinuities which are essentially, therefore, structural weakness planes upon which movement can take place. The representation of discontinuity orientation data with its application to rock slope stability has been described in detail by Hoek and Bray (1977).

The local rocks were given the term Aberystwyth Grits by Keeping (1881), who was the first to make a serious study of these beds. The sedimentation and sedimentary history of the Aberystwyth Grits has since been well documented by Jones (1912,1938), Rich (1950), Kuenen (1953) and notably by Wood and Smith (1957). The most marked lithological

PLATE 9.3 Rockfall near Graig Ddu (Mar 1984)

feature of the Grits is the regular alternation of greywacke beds with mudstone, the junction between the base of a greywacke bed and the underlying mudstone always being well defined and abrupt (Plate 9.4). Wood (1959), describing post-glacial marine erosion of these cliffs, has considered that lithology is roughly uniform and that any difference of cliff slope or height is due either to geological structure or to a variation in the erosional history of the cliff face.

North of Aberarth, the coastal bevel described by Wood (1959) is transected by 30m high near-vertical cliffs. At the Graig Ddu end of the section the angle of slope of the modern cliff is generally 70° steepening in places to 80°. The strike of the beds is nearly parallel to the coast (235° - 055°) with a dip of some 27° inland. The greywacke beds are parallel to each other and give an impression of considerable horizontal extent. Generally an increase in the proportion of greywacke is discernible as one travels southwards. At this locality the cliff section is dominantly composed of thick greywackes, the ratio of greywacke to mudstone being approximately 4:1.

Planar structures (bedding,laminations,foliations) range in spacing from thick (600mm-2m) to thinly laminated (<6mm). Vertical discontinuities (mainly joints) are narrowly to widely spaced (60mm - 2m). Terminology used in this respect is that proposed in Table 19 of the I.C.E Manual (1978, p225). A detailed measurement of discontinuities was discouraged as any attempt to differentiate between the horizontal population which represented bedding planes in the mudstone would be abortive (Plate 9.4).

Rock strength was measured by Schmidt hammer (section 7.5-3.2). Rebound values were determined from alternating beds of greywacke and mudstone at 10 different locations within 2m of M.H.W.M of ordinary tides (Table 7.2). Values of uniaxial compressive strength for the mainly unweathered greywacke beds ranged from 100 to 125 MPa with a mean of 118MPa. The average strength of the mudstone tested was 23MPa. These Schmidt hammer values probably represent intact strength rather than fractured strength and may therefore lead to an overestimation of rock strength where discontinuities are present.

PLATE 9.4 Alternating beds of greywacke and mudstone near Graig Ddu rockfall

Although no precise guide lines can be given, any rock with an unconfined strength of about 30MPa or less must be viewed as potentially subject to weathering (I.C.E. 1978, p245).

At the present time no obvious notching, caused by the weathering of the weaker mudstone layer, is apparent and it is clear that natural undercutting of the cliff face has not encouraged failure in this instance.

9.3.2 Climatic conditions for winter 1983/4

Rockfalls are usually associated with particularly severe weather conditions. Although 1983/4 was the wettest winter of the study period with 254.8mm recorded at R.A.E. Aberporth (Table 4.2), the weather records suggest that this was not exceptional. The mean figure for winter months over the 12 year period 1970-81 is only marginally lower at 246.9mm. However, the December 1983 rainfall figures of 122.1mm was 52% higher than average and was followed by 7 and 13 days of ground frost in January and February respectively (Table 4.1).

Such conditions are likely to have led to increased water content in discontinuities followed by freeze-thaw conditions. Ice trapped in vertical joints and horizontal bedding planes will exert lateral pressures and open these discontinuities.

External vibrations caused by gale-force winds or high-energy wave attack can influence near-surface rock stability, particularly if the rock is already in a marginally stable situation. Analysis of wind records for Aberporth show that January and February 1984 had particularly stormy wind conditions, with 293 hours in January having gusts of 34kt and 96 hours with gusts of 48kt. The first week of February had 109 hours with gusts of 34kt and 25 hours with gusts of 48kt. Almost all gale-force winds veered from an arc S.W. to N.W. with highest gusts recorded at over 70kt.

Of the eight storm events recognised from the climatic data for the period summer 1982 to summer 1985, three were recorded during the winter months of 1983/4 (Table 4.7). The storm of 9th December 1983 had a duration of 19 hours with a maximum hourly wind speed of

44 knots and cumulative wave energy calculated at 6.3 x 10^5 Joules/m crest width. Winds from directly north meant limited effective fetch.

The storm event of 3rd January, 1984 was from the north westerly quadrant, that of highest storm frequency. Southerly winds on the 2nd veered through westerly to north-westerly and increased in force. Hourly means of 36 knots were recorded throughout the 3rd with gusts of over 60 knots. Storm duration was 46 hours in total and generated total wave energy of 23.8 x 10^5 Joules/m crest width, as calculated by the S-M-B significant wave approach (Hale and Greenwood, 1980). This storm also coincided with spring tides; a predicted maximum height of 2.1m A.O.D was measured at 5.8 A.O.D at Llansantffraid beach. Assuming a comparable storm surge at Graig Ddu, where the height of beach is 3.5m A.O.D, wave attack would directly affect some 1.3m of the cliff face. Cliffs striking south-west/north-east are orientated at right angles to the 290° direction and exposed to the full impact of high-energy waves. Both these facts are significant in instigating rock face disturbance.

On the 6th February 1984 prevailing winds coincided with the direction of dominant wave approach at 260°. Winds of 38 knots maximum hourly speed blowing over effectively limitless fetch generated total wave energy of 19.7 x 10^5 Joules/m crest width.

Of the 33 storm-wave generating events hindcasted for the period 1971-85, the two storms of January and February 1984, were ranked third and fourth in terms of measured intensity (Tables 4.6 and 4.7). It does not seem an unreasonable assumption therefore that either or both these two events had a significant impact on the coastal zone particularly with regard to rockfall activity.

9.3.3 Toe protection and longshore drift

Coastal erosion process rates along this section of Aberystwyth Grits may be influenced by cliff height. The higher the cliff the more material is likely to fall when its base is undermined. This in turn means that a greater amount of debris has to be broken down and removed before the cliff is once again attacked with the same energy. Removal of this protective talus cone is usually accomplished by longshore drift, which can be defined as the flow of coastal sediment produced by wave and current action when waves approach at an angle to the coastline.

From the theoretical model of longshore sediment transport discussed in Chapter 5, a northerly transport of material is predicted along the 2 km length of cliffs between Aberarth and Morfa (Fig. 5.9b). At Graig Ddu the model indicates a small cell of southerly drift but the validity of this cell is questionable because of its size (0.2km). North from Graig Ddu around the Morfa Farm headland the overall northerly drift of sediment is again confirmed by the model (Fig. 5.9c).

By February 1987 marine action had removed little of the protective cone although removal of fines and some weathering of the larger boulders had occurred (Plate 9.5). This apparent lack of debris dispersal invites comparison with the study carried out by Williams and Davies (1980) on remedial blasting of Liassic limestone cliffs at Llantwit Major in South Wales. In 1969 bulk blasting techniques to realign some 250m of cliff face resulted in a calculated talus cone volume at the toe of 23,000 yd^3 ($17{,}500m^3$). By 1978 a levelling survey showed the remaining volume to be only 8,300 yd^3 ($6{,}300m^3$),this 64% reduction in volume reflected the severity of wave attack and the efficiency of longshore drifting. The area lies in the high-energy storm environment of the Bristol Channel where wave activity is dominated by open fetch in a south westerly direction to the North Atlantic and a tidal range that can reach over 6m with a 10 year recurrence interval.

Although the size of material in any blast cone is smaller in comparison to natural rock fall debris in the greywacke suite and would therefore contribute to more rapid dispersal, it is apparent that removal of the talus material is a direct response to contemporary marine processes.

In the Llantwit study rapid lateral dispersal of rockfall material by marine agencies was verified by measurements of pebble tracer movement over a single winter season where pebbles moved onshore in a north easterly direction for all beach positions with very rapid dispersal occurring at high-tide position.

PLATE 9.5   Rockfall near Graig Ddu (Feb 1987

Near Graig Ddu, one hundred pebbles collected, coloured and replaced at high tide position on the adjacent beach at Morfa in June 1984 revealed little or no movement during the winter of 1984/5 and 1985/6. By comparison with the predominantly high-energy beaches along the Bristol Channel, the beaches along this section of the Cardigan Bay coast may be classed as low energy, where the transporting capabilities of local wave and tidal conditions are minimal.

At the time of writing (March 1987) the tracer population has completely disappeared as a result of the stormy conditions of the winter of 1986/7. Observation of the base of the cliffline along this beach reveals a series of interesting morphological features which can be described as micro embayments (Plate 9.6). In plan view these features represent a bay headland configuration within the cliffline, the embayments themselves being separated by beach cusps.

Similar rhythmic beach features were noted on Llansantffraid and Aberarth beaches after storm conditions (Plate 9.7). These typically have dimensions of the order 8 - 10m long and perhaps 5m in width or amplitude. They consist of coarse shingle cusps (or horns) separated from each other by bays whose floor is of finer material. The processes of beach-cusp formation have generated a large literature, the interpretation now accepted is that of edge-wave theory which, despite problems, does explain the regularity of cusp spacing.

At Morfa beach cusps and cliff embayments occur in tandem and may have formed in response to the presence of edge waves. Such features can develop over a matter of minutes with a perfectly regular spacing longshore and result in highly variable rates of cliff retreat within a short stretch of beach. Along a long straight cliffline at Aberarth (Plate 9.7) the formation of beach cusps, again inshore of the beach M.H.W.M, are not associated with pockets of erosion within the till face.

It is interesting to note that the beaches where these phenomena have been observed have almost exactly the same orientation and face the most destructive storm approach direction of 290°-335°. These localised centres of erosive action could therefore be related to some

PLATE 9.6 Beach cusps at Morfa beach. Feb 1987

PLATE 9.7 Cusp formation along a straight cliffline at Aberarth

focusing of wave energy (Healy, 1987). The episode of erosion at Morfa is a function of either higher energy levels or weaker "resisting forces" within the cliff material.

9.3.4 Contemporary recession rate in rock sections

The process of rock fall is a very sporadic process and it is very difficult to establish a reliable frequency of occurrence from the records of a few years, (Carson and Kirkby, 1972). It is easy to calculate the amount of material involved in a specific rockfall but not so easy to relate this to long-term recession rates.

Long-term retreat rates for this cliffline were obtained by comparing successive positions of M.H.W.M from 1:2500 O.S maps (1880, 1905 and 1974). Using this technique a mean recession rate of 0.14m/year was noted for this section (Fig 3.9).

During the 30 month study period (1983-1985) active recession is represented by the one major rockfall recorded at ch. 62 + 00 in February 1984. Since the area of near vertical rocks extends for some 1.75km at an average height of 20m, the average amount of rockfall retreat can be calculated as

$$\frac{1000}{1750 \times 20 \times 2.5} \quad \text{or } 0.01\text{m/year}$$

It is seen that this figure cannot be considered representative of the long-term rate. It may be that observations over a 30 month period will not give a reasonable estimate of contemporary process rates. For instance, a particularly severe winter may result in far more rockfalls than in an average year. It follows that any records in a short period of time which fail to include rockfalls of this frequency will underestimate the process rate.

However, a similar differential between field and map monitoring has been noted by Williams and Davies (1987) for Liassic limestone cliffs along the South Wales coast and this must question the validity of using M.H.W.M as recession indicator when applied to solid rock sections. Inaccuracies in long-term rates calculated from map evidence can also be attributed to the use of nineteenth century maps as datum bases (Carr, 1962).

9.4 Undercutting due to wave action of glacial deposits near Aberarth

For some 500m north of the mouth of the river Arth (chng. 78-83 approximately) the coastline consists of weakly consolidated sediments whose composition ranges in size from gravels to clay (Plate 9.8). These materials have been designated solifluction deposits by Watson (1971) and are banked against the rock surface of the Aberystwyth Grits sloping at some 45° seawards.

Where these more easily eroded deposits form the shoreline materials, extensive recession has occurred. Map evidence has indicated annual retreat of 0.63m/year over a 90-year period (Fig. 3.9). Active erosion along this section appears to be two fold-erosion at the base is due primarily to wave action causing notching, erosion of the upper section is sub-aerial and is probably secondary in importance.

9.4.1 Processes

Undercutting by waves and tidal currents is significant (Plate 9.8) and most of the erosion can be attributed to this effect. Notches and cavities extend along the whole of this section and have typical dimensions 1.5m in height and up to 1m in depth. Formation and development of these undercut features, which is dependant upon intensive and continuous marine activity, will lead to loss of support at the cliff base and ultimate failure.

The beach in this location is small and narrow and offers little defence against marine attack. The height of beach/foot of cliff is 2.7m A.O.D and is therefore prone to coverage by some 150 tides/year which represent 1.2% duration. The lack of sediment along this beach and consequently the lack of protection that it affords may be explained by the presence of extensive protection works immediately to the south in an area of northerly longshore drift.

The most significant erosion at the top of the cliff is due to run off. Substantial flows of water coming off the agricultural land

PLATE 9.8 Undercutting of glacial cliffs north of Aberarth

behind cut deep channels into the slope face and result in rills and gullies (Plate 9.9).

Where the till is more permeable, percolation of groundwater downwards through the soil mass results in numerous small seepages emerging from the lower face of the cliff. These occur where an impervious layer of clay lies within the till deposit and forms a barrier to the downward movement of groundwater resulting in a localised outward flow.

Both these slope processes, particularly run-off, result in gravitational transport of sediment which produce temporary talus cones at the foot of the cliff. Since they very much depend on climatological factors they are erratic and difficult to monitor.

9.4.2 Stability analysis

Apart from local collapses of overhang material caused by notching, no large-scale failure was activated during the period of field study. Using the laboratory data for the residual shear strength properties of the Aberarth deposits, slope stability as described by critical height can be calculated.

Cliffs can only be supported to certain critical heights depending upon the relationship between shear strength and angle of slope. Carson and Kirkby (1972) used Culmann's formula to link critical height (H_c) and slope angle (i) for the analysis of wedge-shaped failures.

Assuming a planar failure surface involving the complete length of slope and passing through the toe

$$H_c = \frac{4c}{\gamma} \, \frac{\sin i \cos \phi}{[1-\cos(i-\phi)]}$$

where γ = bulk density
c = cohesion
ϕ = angle of internal friction.

PLATE 9.9 Extensive gullying of till material chng. 80 + 00 approx.

Slope height and angle were measured with a clinometer as 12m and 70^{o} respectively. Substituting the relevant data in the equation

$$H_c = \frac{4 \times 28}{20.69} \; \frac{\sin 70 \times \cos 21.4}{[1 - \cos (70 - 21.4)]}$$

$$= 14\text{m}$$

It is evident, therefore, that these slopes are barely within the critical limits imposed by their shear strength parameters.

9.5. Sub-aerial erosion processes

While various workers, including Hutchinson (1969), have considered sub-aerial processes to be of little or no significance in coastal cliff erosion, McGreal (1977) has ranked wash or run-off as the dominant erosional process in glacial sediments, being responsible for greater removal of material than any other single marine or mass-movement process.

Within the 20km coastal section between Llanrhystud and New Quay, surface water run-off appears to be relevant in specific localities where glacial deposits are banked against the solid rock. The importance of this process is very much dependant on slope parameters, namely slope height and angle, material properties and lack or otherwise of vegetation cover.

On the steeper slopes (>70) near Aberarth (section 9.4.1) sub-aerial erosion of the clayey tills takes the forms of gullying (Plate 9.9) while at Gilfach-yr-halen even more severe gullying of the near-vertical deposits of sands and gravels has resulted in columnar, almost "earth pillar" structures (Plate 9.10).

The boulder clay cliff sections around Cei Bach are disturbed by former landslides and at their base the talus slopes are well vegetated with shrubs and trees and can be deemed "inactive" in terms of Emery and Kuhn's (1982) sea cliff classification. At New Quay the 20m high clay slopes have a shallower inclination (between 35 and 40 degrees) (Plate 9.11) and are therefore more exposed to conventional weathering processes that involve physical and chemical changes within soil due to climatic variations of rainfall, temperature etc.

PLATE 9. 10 'Earth pillars' at Gilfach-yr-halen

PLATE 9. 11 Sub-aerial erosion of boulder clay slopes at New Quay

Within the embayments at Llanon and Aberarth the tills form low vertical faces at the shoreline and sub-aerial erosion is restricted. Agricultural land gently sloping towards the sea is generally ploughed to within a few metres of the cliff edge, a fallow strip being left adjacent to the beach. Run off is diminished by land drainage although some local erosion is evident in the form of vertical channels where land drains discharge from the cliff face.

If run-off is the predominant sub-aerial process throughout the research area, mainly active during periods of heavy rainfall, other weathering processes were observed, particularly on the clay slopes at New Quay. These include freeze-thawing activity and desiccation.

9.5.1 Freeze thaw activity

During winter months freezing of the surface layer followed by thawing and consequent downslope movement of material was identified. Although of low amplitude, daily frost cycles, if repeated often enough, can produce substantial amounts of slurried material which accumulates at the toe.

Soil freezing is a complex phenomenon (Taber, 1930;Beskow,1935) determined by numerous parameters which include intensity and duration of frost exposure, depth of water table,soil porosity and quantity of rain falling prior to the frost. Casagrande's (1931) approximate equation states that the depth of freezing of the soil layer is proportional to the square root of the number of accumulated days below freezing. Severe winters in the New Quay area are rare and during the period 1970-85 the number of successive days with freezing temperatures was never more than 17 (Table 4.1). It follows that freeze thaw activity can be regarded as a minor erosional process.

9.5.2 Desiccation

Desiccation is the process of "evaporation of water from a surface exposed to the atmosphere" (Terzaghi and Peck 1967,p138). The desiccation of a clay proceeds from the exposed surface in a downward direction and leads to the formation of a crust. Within this depth the clay is broken up by shrinkage cracks. During succeeding rain, the outer layers of clay become saturated and air is trapped in the layers of dried clay below. Pressure due to the air produces a tension in the clay that causes failure in tension along some surfaces. This process known as slaking is often responsible for the breaking up and sliding of unprotected clay slopes and was observed at New Quay during the summer of 1984.

As a result of high summer temperatures and abnormally low rainfall figures during June to August extensive shrinkage cracks were produced in the surface layers. At the end of August some on the mid section of the slopes were measured at 15cm in width (Plate 9.12). Resulting heavy rainfall in September (152mm total) caused slurried till to flow down the slope face and form an apron at the toe (Plate 9.13).

Drying of clayey tills to very low moisture contents, normally below the shrinkage limit, produces a very hard but very unstable, erodible soil as discussed in detail by Gelinas (1974). At moisture contents above and slightly below the shrinkage limit the till is very resistant to erosion. Measurements on undisturbed samples of New Quay clay, taken above the ground water table, indicate an average natural moisture content of 17.8%. From the writer's experience of soils testing, the shrinkage limits of soils in the British Isles is relatively constant at between 12 and 14 percent. Moisture contents taken of the surface strata at the end of August gave a mean value of 10.2%,well below the shrinkage limit.

Fig 9.5 clearly illustrates that erosion of clay tills is negligible until the moisture content is reduced by desiccation to a percentage below the shrinkage limit. At these lower moisture contents (9-13%) the hydration energy of the dry soil is very high and the soil slakes when wetted resulting in potentially high erosion rates.

PLATE 9.12 Desiccation cracks in clay slopes at New Quay. Aug '84

PLATE 9.13 Slurried material at toe, New Quay, Oct '84

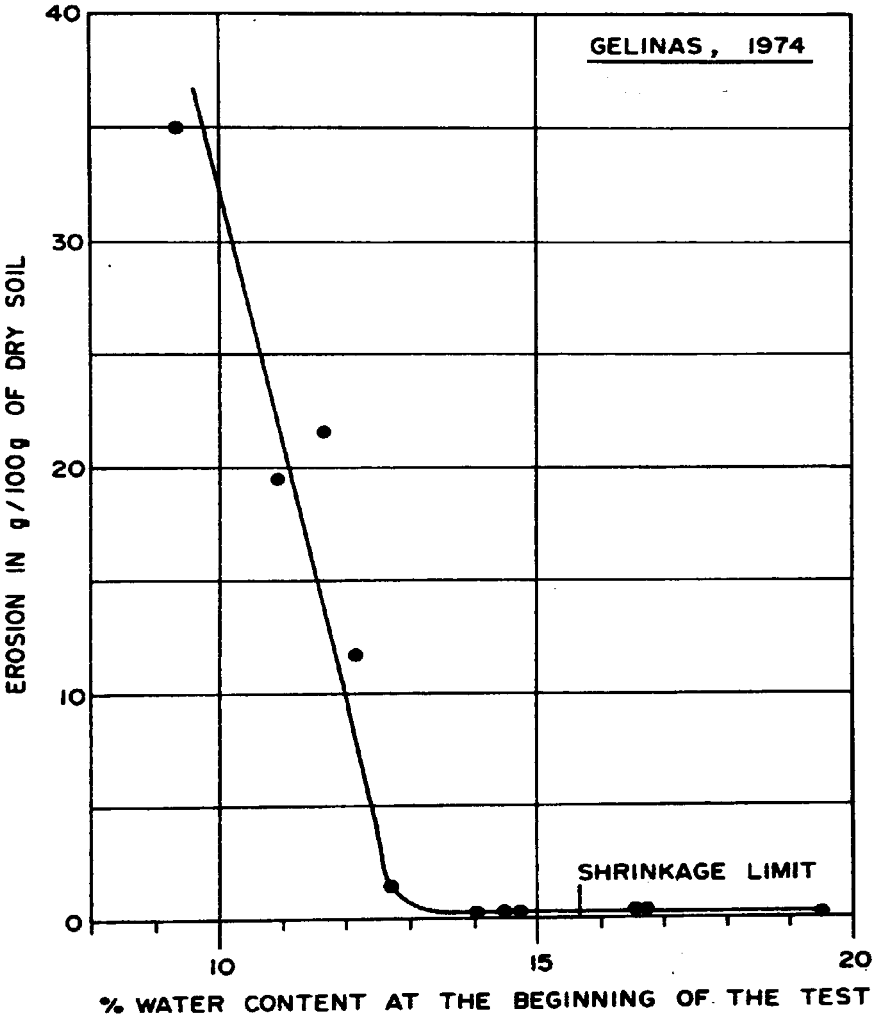


FIG. 9.5 Erosion of till (directly from Gelinas)

9.6 Mudslopes at New Quay

At New Quay a combination of toe erosion and surface slides has produced some complex slope phenomena. At the eastern end of the bay, which is associated with high rates of long-term recession (Fig. 3.9) the exposed boulder clay slopes extend over a length of some 300m and reach a maximum height of 25m A.O.D with an average overall inclination of 38°.

Three sections of the slopes (Profiles X,Y and Z were surveyed by level and staff in February 1983 (Plate 9.14). Subsequent surveys were carried out in February 1984 and March 1985. Cross-sectional details are shown in Figs 9.6a-c although on such a small scale subtle changes in slope geometry are not detectable. Interpretation of actual recession from these surveys was difficult because of amount of debris material at the toe. Direct measurement of short-term toe erosion using erosion pins proved non-productive. A series of 10mm steel pins hammered into the clay face 1m above beach level (Plate 9.15) were either dislodged or completely removed within days due to a combination of surface processes and direct marine attack.

Over the 2 year period average toe erosion from profiles was measured at 0.28m/yr whereas no change was discernible at the cliff top.

9.6.1 Processes

There is no evidence of a tendency for any deep-seated slides - the in-situ boulder clay appears to weather rapidly in a thin surface layer which becomes involved in shallow slides approaching mudflow conditions (section 9.5). These are prevalent in the mid-section of the slopes and result in a downward movement of weathered material accumulating at the toe. Removal of these accumulated clays by tidal activity can stimulate further shallow sliding on the slope which leads in turn to further weathering as the protective surface layer is removed.

An equilibrium condition can clearly be reached when, on average, the rate of removal of debris by erosion is in balance with the rate at which

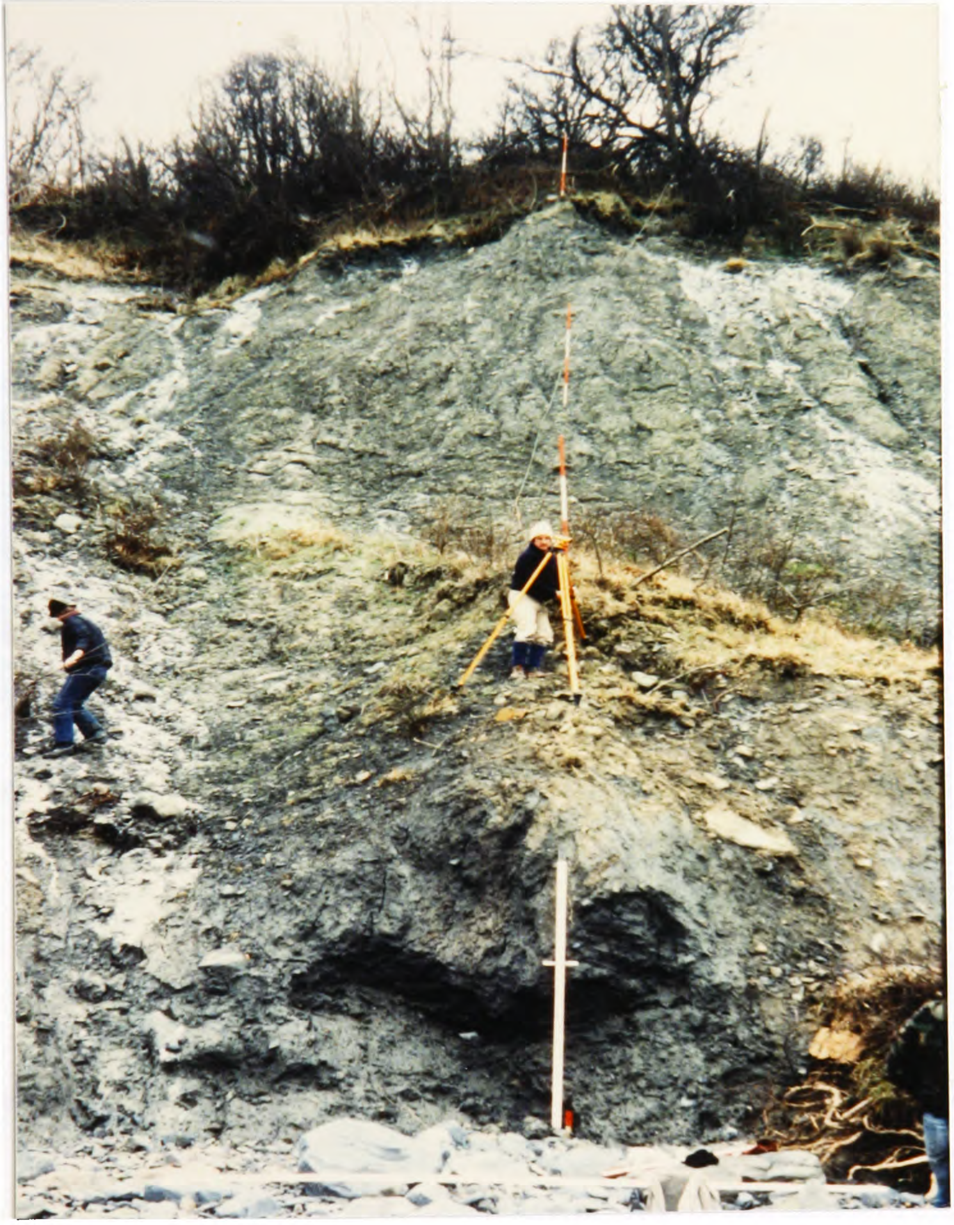


PLATE 9. 14 Surveying profile X at New Quay, Feb '84

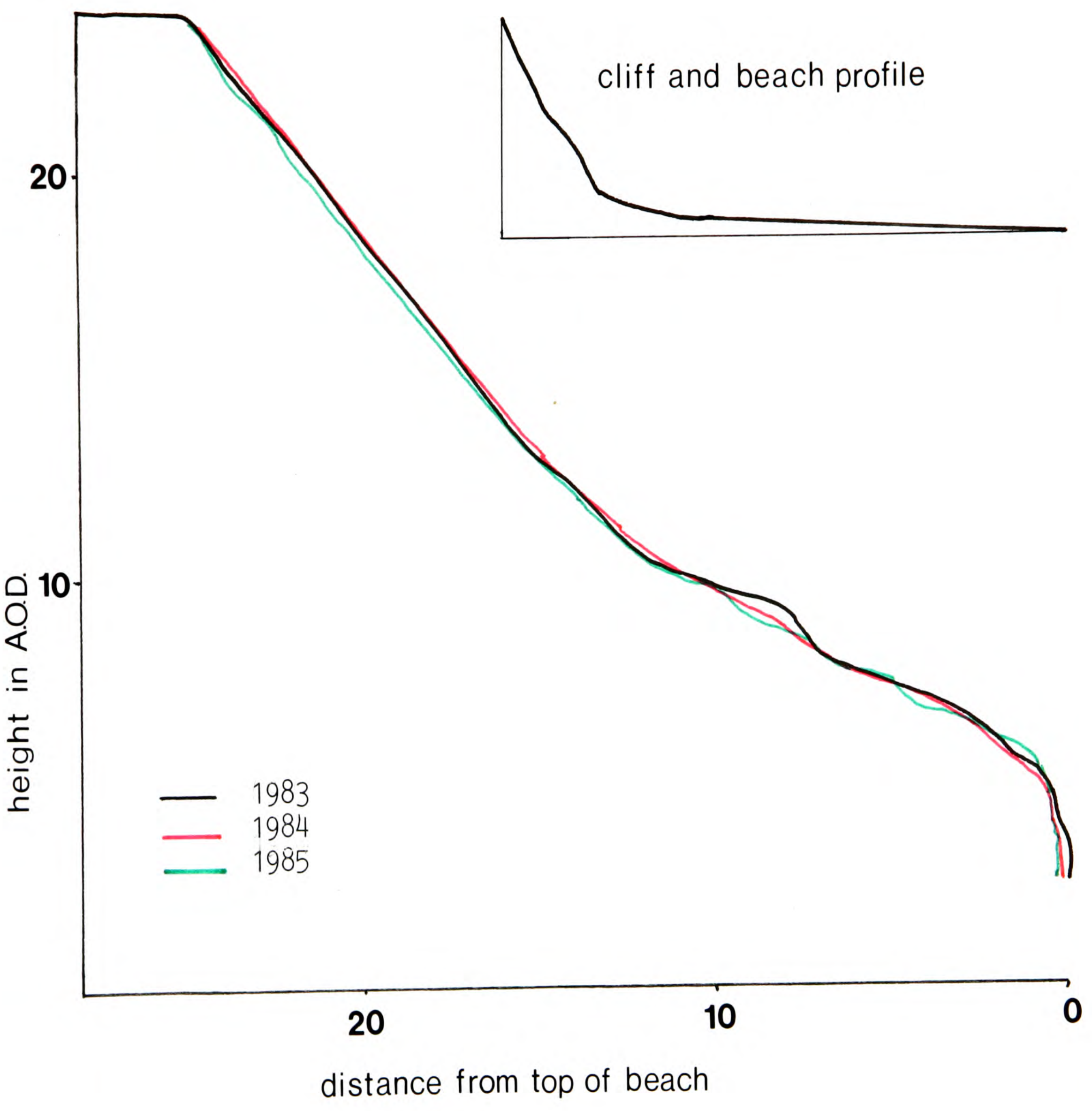


FIG. 9. 6 a   Surveyed profile X, New Quay

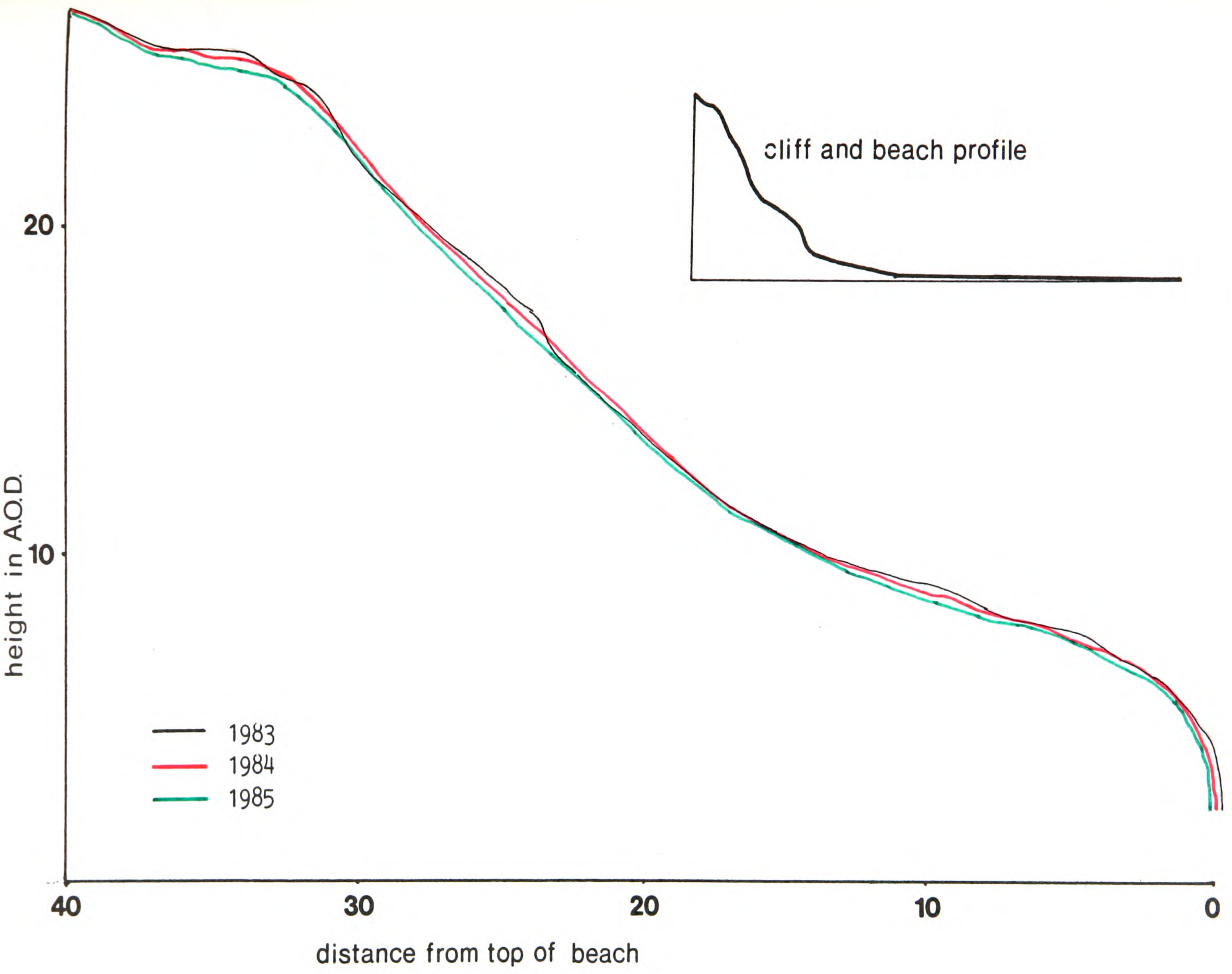


FIG. 9. 6 b Surveyed profile Y, New Quay

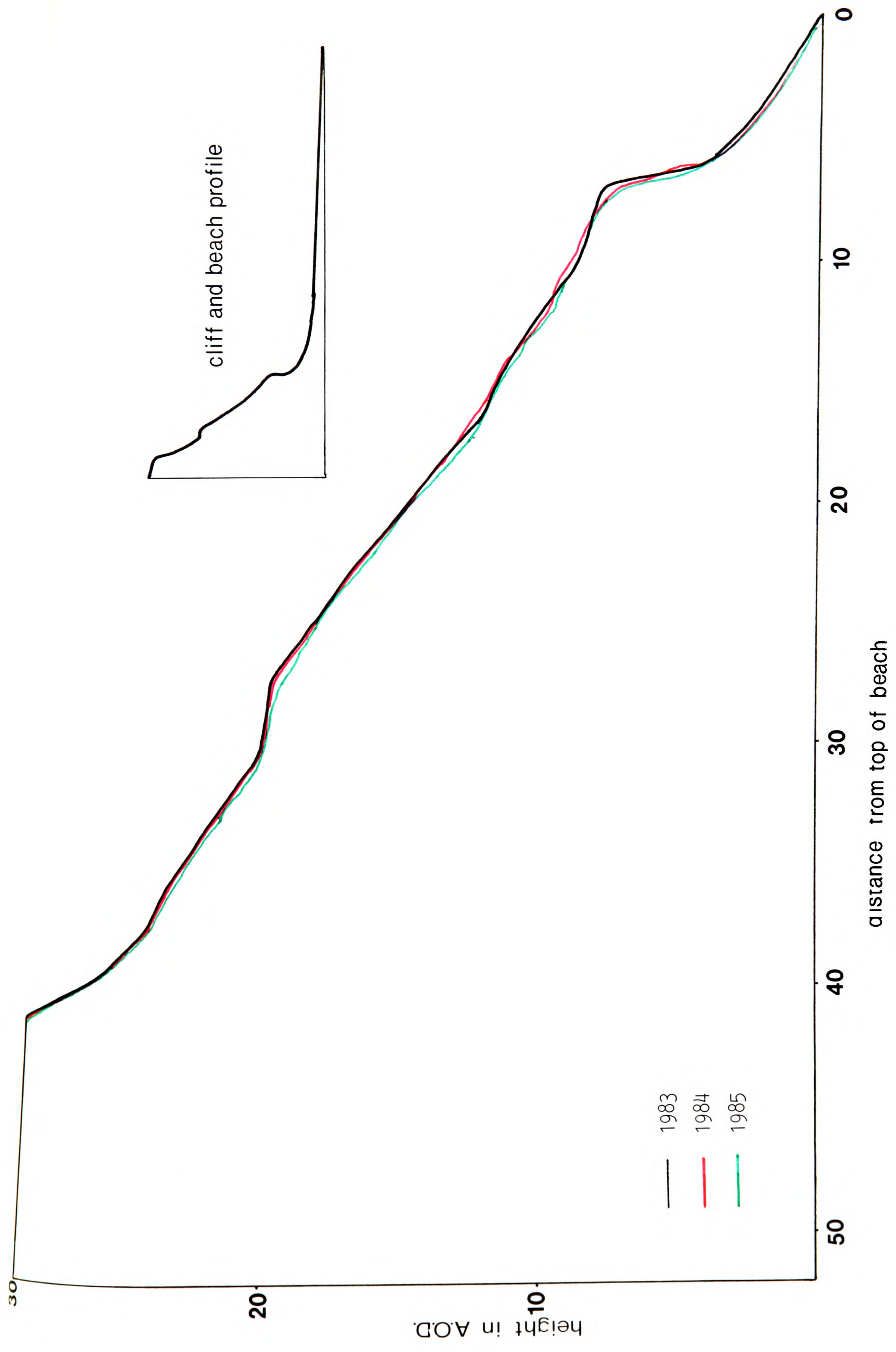


FIG. 9. 6 c Surveyed profile Z, New Quay

PLATE 9.15 Erosion pin in boulder clay 1m above beach level - New Quay, Sept '84

PLATE 9. 16 Local collapse of boulder clay at New Quay, Dec '84

debris is delivered to the toe by weathering processes and subsequent sliding. In this condition, which is the Type I mode of behaviour described by Hutchinson (1973), the slope will be undergoing parallel retreat under a predominantly shallow translational pattern of landsliding and toe erosion will only remove slide debris, never the in-situ clay.

At New Quay it appears that direct wave attack removes more material from the toe than is being discharged from the slope by mudslides and that removal of the in-situ boulder clay is an on-going process. This means that the parallel cliff retreat suggested above is replaced by a gradual steepening of slope accompanied by gradual increases in shear stress within the slope leading eventually to a possible rotational failure.

Marine erosion is evidently strong throughout the length of these cliffs and results frequently in individual collapses of near-vertical banks of clay at the toe (Plate 9.16). The gently sloping sandy beach offers little protection and over a typical year the area of cliff below 3.0m A.O.D is exposed for some 0.8% duration and that below 2.0m A.O.D for 3.9%.

9.6.2 Geotechnical properties of clay

The clay is a bluish-grey stiff boulder clay having an unconfined compressive strength measured at 250 KN/m^2. Particle-size distribution showed 40% stone content, some of the clasts being of flint and indicative of Irish Sea till. Index tests gave liquid limit of 36% plastic limit of 20% and a plasticity index of 16. Undisturbed samples tested in a reversible direct shear box gave ϕ'_r value of 29.6° with zero cohesion (Fig. 9.7).

9.6.3. Stability analysis

For the given geometry of the slope and the shear strength parameters the factor of safety was determined using Bishop's (1955) conventional method of slices. As in other analyses, a circular arc slip plane is assumed, starting beyond the top of the slope and ending at or near the toe. In practice a number of trial slip circles would have to be drawn in order to find the minimum value for F. The one giving the lowest value of F is known as the critical circle and its centre was located using Fellenius's construction shown on Fig. 9.8. The sector above the failure plane is divided into a convenient number of vertical slices of equal width.

Considering the stability of any one strip of unit thickness, the forces acting are shown on Fig 9.8. The force due to the mass of the slice W can be split into two components

$W \sin\theta$ acting tangentially to the base of the slice and
$W \cos\theta$ acting normally to the base of the slice

The disturbing force will be $W \sin\theta$ and its moment about 0 = $W \sin\theta\, R$.

The resisting force will be the shearing resistance along the base of the slice made up of the frictional component $W \cos\theta \tan\theta$ and the cohesive component c.1 and the resisting moment about 0

$$= (W \cos\theta \tan\phi + c.1)R$$

The disturbing moment and the resisting moment for the whole section will then be the sum of these moments for each slice

$$F = \frac{\sum \text{Resisting moments}}{\sum \text{Disturbing moments}}$$

$$= \frac{\sum (W \cos\theta \tan\phi + c.1)R}{W \sin\theta\, R.}$$

$$= \frac{\sum (W \cos\theta \tan\phi + c.1)}{W \sin\theta}$$

The values obtained from each slice were tabulated and the results summed from Fig. 9.7, $C = 0, \phi = 29$.

$$\therefore\ F = \frac{2077 \tan 29}{957} = 1.20$$

In terms of landslide hazard classification this figure of 1.2 suggests MEDIUM potential to slippage.

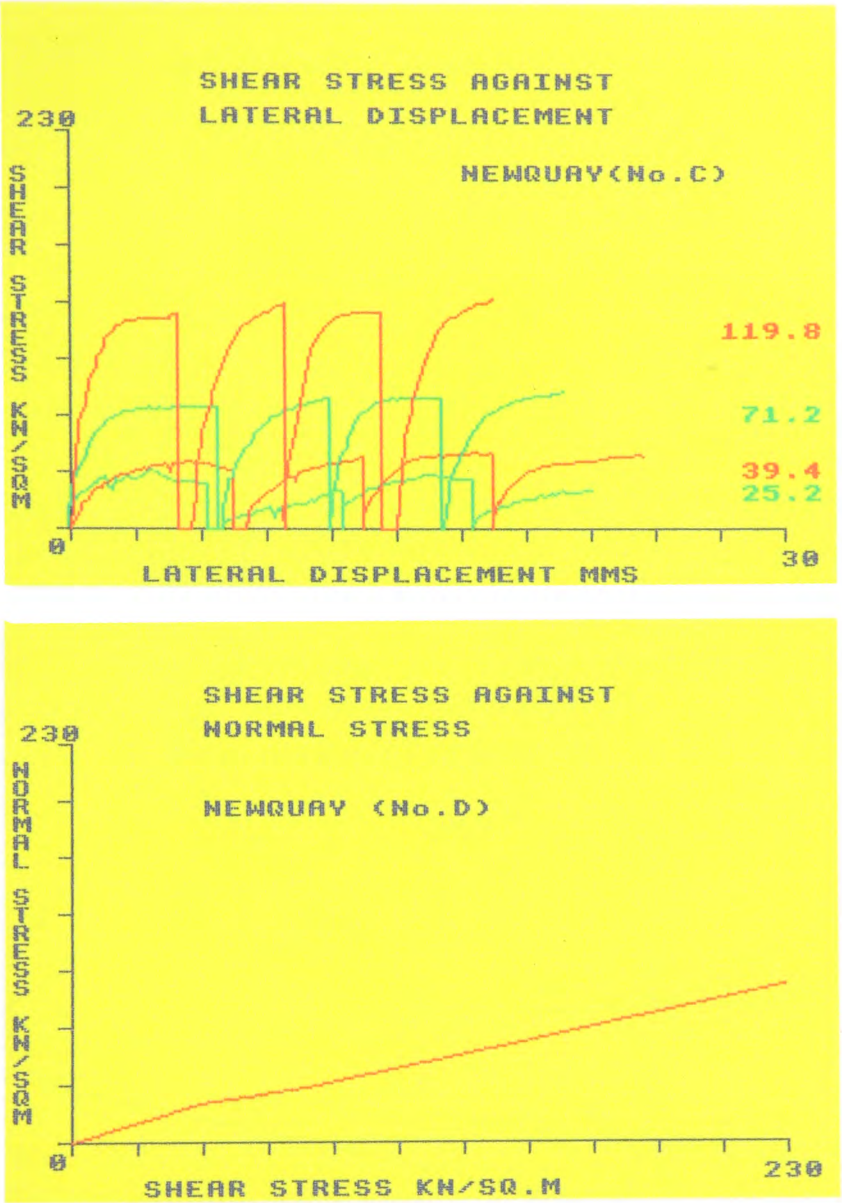


FIG. 9.7 Shear strength curves: New Quay clay

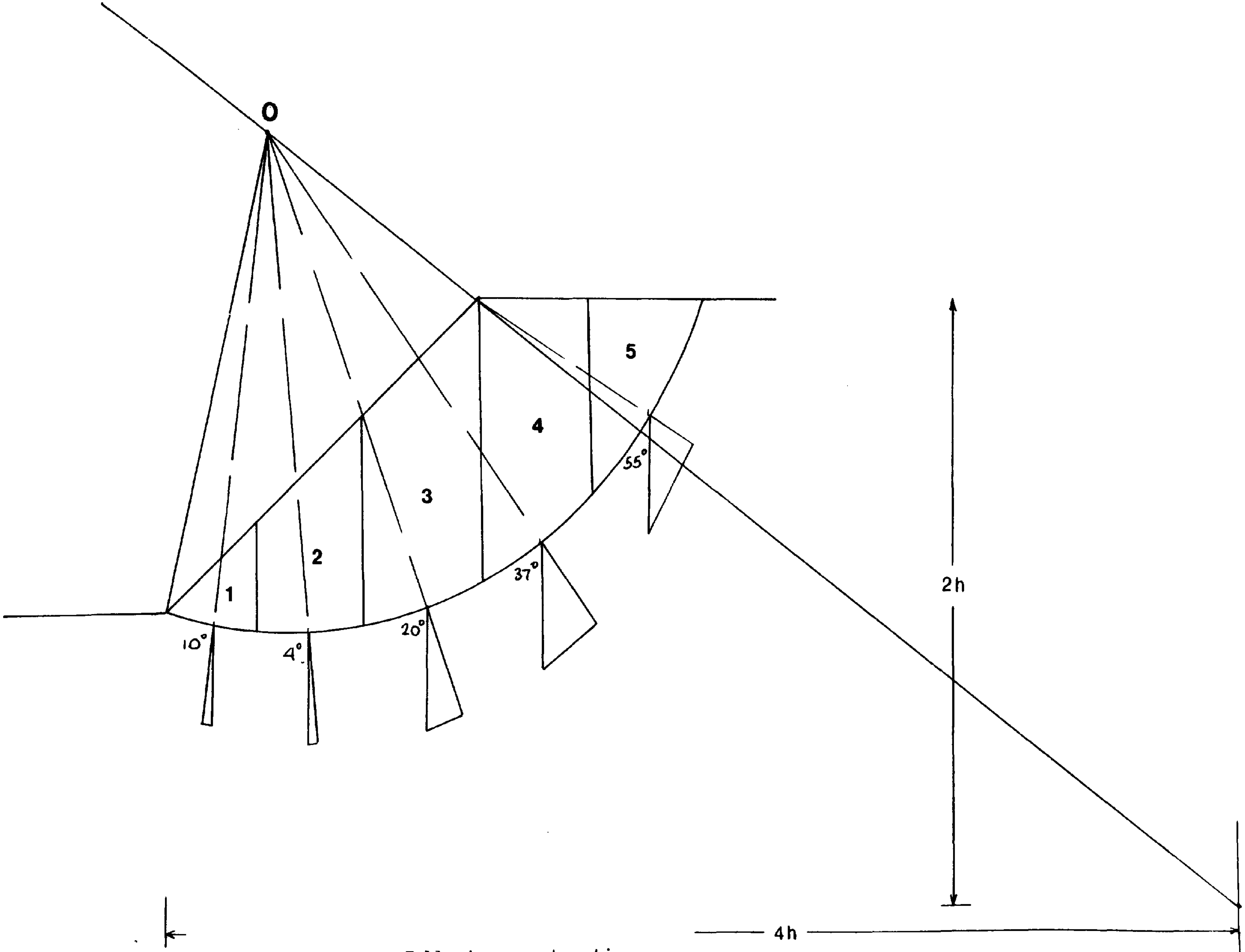


FIG. 9. 8 Bishop's method of slices and Fellenius construction

CHAPTER 10

CONCLUSIONS

This study has focused on the factors and conditions which influence cliff stability and erosional processes along a 20km section of the Cardigan Bay coastline.

The initial hypothesis was that numerous factors (particularly the strength of cliff material and the role of the beach profile as a natural buffer between sea and land) were responsible for differing recession rates and that these could be identified and interpreted by intensive field surveys and ranked in order of importance by mathematical regression and correlation techniques. Because of the length of coastline considered and the variability in cliff and beach morphology, aspects of the work have inevitably been qualitative, where processes have often been inferred from phenomena observed.

Discussion of the processes operating has suggested that marine action was the dominant mechanism influencing erosion along the till embayments between Llanrhystud and Aberaeron and responsible for the undercutting of boulder clay cliffs north of Aberarth. Sub-aerial erosion was very much a contributory factor at Gilfach-yr-halen and especially at New Quay, where surface slides and shallow rotational failure influence slope stability.

10.1 Recession rates

This coastal area of Ceredigion is an active environment which has experienced almost continuous change over the last century. Geomorphic changes in the shoreline between 1880 and 1970 have been evaluated from the positions of MHWM and MLWM as indicated on large scale O.S maps for the period. Long-term recession rates as represented by the MHWM exhibit considerable spatial variability, ranging from 0.06 m yr^{-1} in sections of the Aberystwyth Grits south of Aberaeron to 0.65 m yr^{-1} in glacial clays near Aberarth. Mean values of 0.16 m yr^{-1}, with individual peaks of 0.50 m yr^{-1}, were recorded for the till sections between Llanon and Llanrhystud.

The results of this investigation have provided, for the first time, the quantitative data necessary to estimate the future short-term recession within the glacial embayments of the Aberaeron area where erosion is problematic (Table 3.1). Highest erosion was identified south of Llanon (site B) where a mean annual figure of 0.25 m yr^{-1} was recorded for the 30-month period. Differences in annual retreat rates within the Aberarth embayment (site D) have been related to a distinct change in cliff material. The contemporary figure of 0.12 m yr^{-1} for north of Llanon (site A) was in agreement with the long-term value of 0.16 m yr^{-1} and implies that changes in the coastline have been consistent over time.

For the rock sections the contemporary rates were at variance with the long-term figures. Calculation of present-day recession of the cliffs between Morfa and Aberarth has given a mean value of 0.01 m yr^{-1}, considerably less than the long-term retreat rate of 0.14 m yr^{-1} obtained from map evidence. This discrepancy could be attributed to unusually low rockfall activity during the study period or to inadequacies in long-term map measurements (section 9.3.4).

It was also noticeable that long-term erosion rates for hard rock sections were often little different from those for the softer tills and clays and this must cast further doubts on the validity of using MHWM as recession indicator when applied to rock cliffs fronted by wave-cut platform.

10.2 Significance of specific storm events

Incidence of cliff erosion within the till materials was found to occur under specific tidal and climatic conditions and temporal variations in erosion rates could therefore be explained by differences in environmental energy inputs. In geomorphological time scale the period of observation was short and did not include the extreme low frequency, high magnitude event of cliff recession suggested by local residents which would have resulted in the removal of several metres of the till face.

By using limited climatic conditions necessary for erosion it was possible to hindcast past frequencies of potential cliff-eroding events. Measured wave data (Draper and Wills, 1977) was of limited value for analysis purposes and use was made of the Sverdrup-Munk-Bretschneider method to produce theoretical wave energies for specific wave events within the Cardigan Bay area, based on hourly wind data for R.A.E Aberporth. Predictions for the periods (1971-81) and (1982-85) indicated a total of 33 significant events, averaging 2.2 per year.

The maximum predicted storm occurred between 28-30/1/78 when total wave energy of 47.8×10^5 jm^{-1} crest width was calculated.This largest magnitude event was from the north-west quadrant which contributed 82% of all destructive waves. The computed data also confirmed the dominance of south-westerly winds (Table 4.7).

The moderate to high storm events predicted may not effect change along the Ceredigion coastline unless such events coincide with periods of high tide. From Fig. 4.12 it is seen that high tide was consistently different from the predicted value, the discrepancies in height being attributed to meteorological conditions.

Tidal coverage of different heights of cliff along the coastline were calculated from tidal data and gave an indication of the infrequency with which the tide reaches the areas of cliff above 3m A.O.D. The significance of these figures is that much of the cliffline, even at lower levels, was potentially more subject to sub-aerial rather than marine processes.

10.3 Theoretical prediction of beach levels

The role of the beach as a buffer to cliff erosion has been considered in terms of sediment cell delimitation, the spatial position of such cell boundaries dictating the longshore magnitude of beaches (Davies, 1974).

The position of sediment compartments or cells alongshore has been identified using the WAVENRG computer programme for wave refraction modelling. A series of fifteen cells have been theoretically predicted for the length of coastline between Llanrhystud and New Quay, most of which indicate separate zones of deposition and erosion with an overall northerly residual drift direction.

Most applications of wave refraction models have been on coasts of relatively simple and regular plan-view composed of sand. Applying the model to this length of coastline has added to present knowledge on the subject in that it has identified cell boundaries along an irregular coastline with high gravel or shingle content in its beach sediment.

Zones of deposition and erosion in the form of "high" and "low" beaches have been interpolated from data obtained by longshore survey of beach profiles. Comparison of predicted to field data has shown good correlation (Fig. 6. 10) with most of the differences between them being accountable.

Given the imperfections and limitations of the theoretical base and interpretation, the results of this study have demonstrated the value of such a model in predicting longshore beach levels and consequently identifying potential erosion zones.

10.4 Beach and cliff morphology

Monitoring surveys of selected beach profiles over a 2-year period have shown limited variation in beach levels, the maximum range of movement on the upper foreshore being restricted to 1.5m. Sweep zones generally show a gradual build-up of beach volumes during late autumn and erosion of the beach face in January storms.

Longshore patterns of sediment distribution in terms of "high" and "low" beaches have been confirmed. It is suggested that the beaches studied are generally stable in terms of longshore sediment movement but future surveys are necessary to deduce whether present day conditions are characteristic of the longer term.

Using the 'b' axis as indicator, direct measurement of pebble characteristics along the major shingle beaches have indicated a coarsening of beach material from S.W to N.E i.e the direction of predominant littoral drift. This increase in particle size corresponded with higher beach levels at the northern end of crenulate bays like New Quay and Cei Bach.

The physical properties of the cliff materials (Chapter 7) have been examined using standard engineering classification tests; the till material presented particular problems in sampling and testing.

Fabric analysis data has revealed little difference in tills within the area, each exposure showing a consistency of particle shape, confined mainly to discs and blades with few spheres. Clast orientation within each site was predominantly parallel to the slope of the land and at right angles to the existing coastline which could be used as an argument for deposition by west-flowing ice. This is in agreement with Watson (1970) who related a constancy in preferred stone orientation in the coastal area between Morfa Bychan and New Quay to a very gradual change in orientation of the coastal slope.

Field index tests showed only minimal variation in unconfined compressive strength within the rock sections while laboratory tests confirmed that the unweathered till material is similar throughout the area. Shear strength parameters showed consistency, values of ϕ_r for the passing 3.5mm fraction ranging between 26.4 and 31.6. Atterberg tests classified the fines fraction as an inorganic clay or silt of low plasticity. Differences in grading were considered sufficient to distinguish both between and within the various exposures.

10.5 Causal influences on erosion of independent parameters

From the statistical analysis, strength of cliff material was not found to be significant in explaining variation in recession rates.

Results suggest that erosion is controlled spatially by the extent of beach deposits at the cliff base, beach-face volume being the dominant explanatory variable (Sig F = 0.0593).

It is also suggested that temporal erosion as a result of extreme storm events outweighs in terms of importance the erosional effects of higher frequency, low magnitude marine exposure.

In terms of contemporary short-term recession of specific till exposures, beach parameters were again important and explained some 86% of total variation.

10.6 Final Comment

In conclusion, this investigation has shown that the till embayments in the Aberaeron area are retreating on average by some 13cm per year.

Although several farmers and caravan site owners are losing appreciable amounts of land, it is doubtful whether any remedial measures would be economically justified considering the low population density and the low risk to property.

Recent engineering works have ensured stability in areas such as Aberarth although, like other coastal protection works in the past, full knowledge of what adverse affect it may have on adjacent beaches is not clear. Certainly depletion of beach material is evident in several areas to the northerly leeward drift side of such structures.

In the future low-cost protection measures may be considered - the most viable and cost effective for this area being beach replenishment, although any management strategy for maintaining the stability of the present coastline must be considered in terms of long-term trends rather than short-term observations.

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APPENDIX

KEY TO SUMMARY TABLES ON PAGES No 319 - 322

COLUMN	VARIABLE
1	Chainage point
2	Recession (m)
3	Aspect
4	Strength of cliff material kPa
5	Protective feature
6	Height of beach m A.O.D
7	Tidal coverage % time
8	Beach face width
9	Beach face slope
10	Beach face volume m^3
11	Beach terrace height m A.O.D
12	Beach terrace slope
13	Total beach volume

1	2	3	4	5	6	7	8	9	10	11	12	13
0.0	16.7	313.0	700.0	0.0	5.7	0.0440	33.0	9.5	90.0	0.2	0.7	97.0
1.0	11.1	334.0	700.0	0.0	4.5	0.2000	26.0	8.1	48.0	0.8	0.9	90.0
2.0	5.5	353.0	700.0	0.0	5.1	0.0850	12.0	13.6	17.0	2.2	1.3	149.0
3.0	3.3	341.0	700.0	0.0	5.2	0.0750	15.0	9.5	19.0	2.7	1.6	187.0
4.0	0.0	291.0	700.0	0.0	4.6	0.1800	13.0	10.9	16.0	2.1	1.2	147.0
5.0	5.5	294.0	700.0	0.0	5.7	0.0440	25.0	10.2	56.0	1.2	0.9	129.0
6.0	3.3	289.0	700.0	0.0	6.8	0.0090	28.0	11.1	77.0	1.3	1.0	162.0
7.0	5.5	288.0	700.0	0.0	7.0	0.0050	47.0	8.6	167.0	0.0	1.0	167.0
8.0	5.5	288.0	700.0	1.0	7.2	0.0050	57.0	7.7	238.0	-0.5	1.0	174.0
9.0	0.0	289.0	700.0	1.0	7.6	0.0050	69.0	6.6	228.0	-0.4	1.4	186.0
10.0	0.0	291.0	700.0	1.0	7.6	0.0050	58.0	7.4	203.0	0.1	1.0	206.0
11.0	-2.2	292.0	700.0	1.0	7.7	0.0050	53.0	8.1	186.0	0.2	0.9	194.0
12.0	-2.2	295.0	700.0	1.0	6.9	0.0075	57.0	7.0	228.0	-0.1	0.8	223.0
13.0	-3.3	298.0	700.0	1.0	7.8	0.0050	60.0	6.6	216.0	0.8	0.8	268.0
14.0	-3.3	299.0	700.0	1.0	7.8	0.0050	61.0	6.4	217.0	0.9	0.8	280.0
15.0	-3.3	302.0	700.0	1.0	7.7	0.0050	60.0	7.8	231.0	-0.5	0.8	194.0
16.0	-4.4	307.0	700.0	1.0	7.3	0.0050	66.0	6.5	250.0	-0.2	0.5	237.0
17.0	-4.4	311.0	700.0	1.0	7.6	0.0050	48.0	9.2	172.0	-0.2	0.5	161.0
18.0	3.3	317.0	700.0	0.0	5.8	0.0390	36.0	8.9	101.0	0.2	0.7	110.0
19.0	11.1	323.0	700.0	0.0	6.1	0.0270	37.0	8.9	102.0	0.3	0.7	117.0
20.0	13.3	325.0	700.0	0.0	6.2	0.0240	34.0	9.4	95.0	0.6	0.7	124.0
21.0	15.5	333.0	700.0	0.0	5.1	0.0850	26.0	9.6	52.0	0.7	0.7	82.0
22.0	11.1	345.0	700.0	0.0	5.2	0.0750	28.0	8.8	49.0	0.9	0.7	104.0
23.0	16.7	349.0	700.0	0.0	4.4	0.2200	30.0	6.1	38.0	1.2	0.6	144.0
24.0	15.5	357.0	700.0	0.0	4.7	0.1600	29.0	6.9	35.0	1.2	0.6	154.0
25.0	48.9	350.0	700.0	0.0	5.4	0.0600	25.0	8.4	31.0	1.7	0.8	180.0
26.0	32.2	331.0	700.0	0.0	4.9	0.1200	18.0	9.4	27.0	1.9	0.7	213.0
27.0	16.7	350.0	700.0	0.0	4.5	0.2000	18.0	8.8	25.0	1.7	1.0	140.0
28.0	21.1	323.0	700.0	0.0	3.9	0.3300	17.0	8.8	22.0	1.3	0.7	108.0
29.0	25.5	307.0	700.0	0.0	4.5	0.2000	20.0	9.4	33.0	1.2	0.9	99.0
30.0	26.7	283.0	700.0	0.0	5.6	0.0490	28.0	10.9	67.0	0.2	0.4	85.0
31.0	27.8	275.0	700.0	0.0	4.2	0.2600	30.0	8.4	66.0	-0.2	0.9	57.0
32.0	25.5	289.0	700.0	0.0	4.0	0.3000	26.0	8.5	51.0	0.1	1.1	54.0
33.0	22.2	297.0	700.0	0.0	4.4	0.2200	26.0	8.3	49.0	0.6	1.0	76.0
34.0	24.4	302.0	700.0	0.0	3.4	0.5200	60.0	3.0	78.0	0.3	0.9	92.0
35.0	20.0	293.0	700.0	1.0	5.7	0.0440	32.0	9.5	132.0	0.3	0.9	148.0
36.0	20.0	280.0	700.0	0.0	5.5	0.0540	34.0	9.3	76.0	-0.1	0.7	74.0

1	2	3	4	5	6	7	8	9	10	11	12	13
37.0	20.0	285.0	700.0	0.0	5.5	0.0540	33.0	9.5	79.0	0.0	0.8	79.0
38.0	18.9	287.0	700.0	0.0	5.4	0.0600	32.0	9.2	74.0	0.2	0.7	80.0
39.0	17.8	289.0	700.0	0.0	5.6	0.0490	29.0	10.0	65.0	0.5	0.6	80.0
40.0	18.9	289.0	700.0	0.0	5.3	0.0670	32.0	9.4	72.0	0.0	0.5	72.0
41.0	11.1	290.0	700.0	0.0	5.0	0.1000	33.0	8.8	74.0	-0.1	0.3	72.0
42.0	18.9	296.0	700.0	0.0	3.8	0.3600	23.0	7.9	33.0	0.6	0.8	58.0
43.0	18.9	299.0	700.0	1.0	5.2	0.0750	30.0	8.4	90.0	0.8	1.5	134.0
44.0	20.0	304.0	700.0	0.0	5.6	0.0490	40.0	8.4	82.0	-0.3	1.5	70.0
45.0	18.9	305.0	700.0	0.0	3.8	0.3600	26.0	7.5	39.0	0.4	1.5	51.0
46.0	20.0	320.0	700.0	0.0	3.7	0.3900	23.0	7.4	35.0	0.7	2.0	58.0
47.0	18.9	347.0	700.0	0.0	3.2	0.6400	17.0	10.3	34.0	1.2	1.3	74.0
48.0	20.0	332.0	700.0	0.0	3.6	0.4200	15.0	8.4	17.0	1.4	0.9	94.0
49.0	18.9	323.0	700.0	0.0	3.6	0.4200	16.0	8.2	18.0	1.3	0.9	95.0
50.0	20.0	316.0	700.0	0.0	4.4	0.2200	25.0	8.0	44.0	0.9	0.9	92.0
51.0	13.3	313.0	700.0	0.0	5.0	0.1000	24.0	9.4	42.0	1.0	1.2	82.0
52.0	13.3	311.0	700.0	0.0	4.7	0.1600	28.0	8.1	56.0	0.7	1.0	88.0
53.0	13.3	296.0	700.0	0.0	5.5	0.0540	31.0	9.5	63.0	0.3	0.6	77.0
54.0	13.3	293.0	700.0	0.0	5.9	0.0340	32.0	10.4	74.0	0.0	1.1	74.0
55.0	13.3	293.0	700.0	0.0	5.2	0.0750	35.0	8.4	75.0	0.0	1.1	75.0
56.0	13.3	290.0	700.0	0.0	5.4	0.0600	38.0	8.1	87.0	0.0	1.3	87.0
57.0	9.0	294.0	700.0	0.0	4.8	0.1400	38.0	7.4	82.0	-0.1	0.9	79.0
58.0	5.5	300.0	700.0	0.0	4.5	0.2000	40.0	7.0	84.0	-0.4	0.7	67.0
59.0	5.5	304.0	700.0	0.0	3.8	0.3600	41.0	6.0	82.0	-0.5	1.0	73.0
60.0	5.5	309.0	700.0	0.0	4.3	0.2400	38.0	6.6	74.0	-0.1	1.3	70.0
61.0	18.7	313.0	23000.0	0.0	3.7	0.3900	36.0	6.1	67.0	-0.1	0.6	64.0
62.0	18.7	322.0	23000.0	0.0	3.5	0.4700	25.0	7.7	35.0	0.1	1.2	38.0
63.0	18.7	312.0	23000.0	0.0	2.1	3.3000	23.0	6.2	29.0	-0.4	1.6	20.0
64.0	18.7	313.0	23000.0	0.0	3.6	0.4200	29.0	6.7	43.0	-0.2	1.6	50.0
65.0	18.7	328.0	23000.0	0.0	2.1	3.3000	24.0	5.0	20.0	0.0	2.1	20.0
66.0	18.7	334.0	23000.0	0.0	1.6	7.9000	43.0	3.8	10.0	0.0	1.3	10.0
67.0	2.2	341.0	23000.0	0.0	0.9	24.0000	27.0	4.2	4.0	0.0	1.3	4.0
68.0	11.1	329.0	23000.0	0.0	-0.1	55.0000	10.0	3.4	0.0	0.0	1.3	0.0
69.0	20.0	311.0	23000.0	0.0	1.0	21.0000	16.0	7.1	3.0	0.0	1.3	3.0
70.0	22.2	318.0	23000.0	0.0	2.0	3.9000	11.0	10.8	10.0	0.0	1.3	10.0
71.0	23.8	321.0	23000.0	0.0	2.0	3.9000	11.0	7.8	16.0	0.0	1.3	16.0
72.0	25.5	323.0	23000.0	0.0	2.4	2.0000	15.0	8.0	16.0	0.3	1.4	19.0

1	2	3	4	5	6	7	8	9	10	11	12	13
73.0	25.5	334.0	23000.0	0.0	3.2	0.6400	27.0	7.0	37.0	-0.1	0.7	36.0
74.0	25.5	332.0	23000.0	0.0	1.0	21.0000	18.0	4.4	10.0	-0.4	1.0	7.0
75.0	18.9	329.0	23000.0	0.0	1.2	15.2000	17.0	4.7	10.0	-0.2	1.0	8.0
76.0	12.2	325.0	23000.0	0.0	1.4	11.1000	9.0	7.6	7.0	0.2	1.1	8.0
77.0	19.4	324.0	23000.0	0.0	3.1	0.7200	22.0	7.7	31.0	0.1	0.9	33.0
78.0	26.7	332.0	200.0	0.0	3.5	0.4700	18.0	8.2	20.0	0.9	1.0	60.0
79.0	31.0	323.0	200.0	0.0	3.0	0.8000	20.0	7.7	24.0	0.3	0.7	32.0
80.0	35.5	323.0	200.0	0.0	2.7	1.2000	22.0	6.5	22.0	0.2	0.9	28.0
81.0	40.0	331.0	200.0	0.0	3.1	0.7200	16.0	7.8	15.0	0.9	1.1	49.0
82.0	10.0	344.0	200.0	0.0	3.3	0.5700	10.0	9.6	8.0	1.6	1.4	78.0
83.0	0.0	330.0	700.0	1.0	5.0	0.1000	26.0	7.4	44.0	1.6	1.5	130.0
84.0	0.0	294.0	700.0	1.0	5.5	0.0540	34.0	10.1	90.0	-0.6	0.8	68.0
85.0	0.0	312.0	700.0	1.0	6.4	0.0180	42.0	9.7	132.0	-0.8	0.7	100.0
86.0	0.0	322.0	700.0	1.0	6.6	0.0130	40.0	10.3	126.0	-0.7	0.5	80.0
87.0	-11.1	325.0	700.0	1.0	6.1	0.0270	38.0	10.0	106.0	-0.6	0.3	86.0
88.0	8.9	331.0	700.0	0.0	4.2	0.2600	44.0	6.5	110.0	-0.8	0.3	76.0
89.0	8.9	333.0	700.0	0.0	4.3	0.2400	41.0	7.4	109.0	-1.0	0.1	73.0
90.0	0.0	336.0	700.0	0.0	3.3	0.5700	55.0	3.8	71.0	-0.3	0.7	57.0
91.0	-8.9	330.0	700.0	0.0	3.1	0.7200	33.0	5.2	40.0	0.1	0.3	44.0
92.0	4.5	348.0	700.0	0.0	3.5	0.4700	31.0	5.7	45.0	0.4	0.5	68.0
93.0	0.0	348.0	700.0	0.0	5.5	0.0540	15.0	9.1	18.0	3.1	1.1	328.0
94.0	20.5	347.0	700.0	0.0	6.4	0.0180	19.0	9.3	30.0	3.3	1.5	300.0
95.0	41.1	348.0	700.0	0.0	5.8	0.0390	20.0	8.5	30.0	2.8	0.9	335.0
96.0	52.8	343.0	700.0	0.0	4.8	0.1400	17.0	7.7	20.0	2.5	0.9	251.0
97.0	64.4	341.0	700.0	0.0	4.3	0.2400	27.0	4.5	23.0	2.2	0.6	259.0
98.0	43.0	372.0	700.0	0.0	3.8	0.3600	28.0	4.7	25.0	1.5	1.4	130.0
99.0	21.5	354.0	700.0	0.0	2.9	0.9000	50.0	0.9	5.0	2.1	1.5	186.0
100.0	0.0	352.0	700.0	1.0	4.1	0.2800	39.0	11.3	85.0	2.0	2.1	240.0
101.0	-5.6	25.0	700.0	1.0	4.5	0.2000	21.0	12.2	60.0	1.9	1.2	210.0
102.0	-11.1	360.0	700.0	1.0	4.6	0.1800	35.0	11.7	108.0	1.7	1.0	281.0
109.0	-15.5	325.0	700.0	1.0	4.4	0.2200	24.0	7.8	40.0	1.1	0.8	107.0
114.0	9.4	295.0	700.0	1.0	6.8	0.0090	53.0	11.3	265.0	-0.6	0.9	215.0
116.0	18.9	303.0	700.0	1.0	6.6	0.0130	50.0	11.2	260.0	-0.5	0.9	210.0
118.0	15.5	360.0	700.0	0.0	2.6	1.4000	30.0	6.0	43.0	-0.3	1.0	34.0
120.0	12.2	351.0	23000.0	0.0	0.8	27.0000	15.0	4.5	8.0	-0.2	1.1	7.0
122.0	5.5	322.0	23000.0	0.0	1.1	18.1000	16.0	3.9	10.0	0.0	0.9	10.0

1	2	3	4	5	6	7	8	9	10	11	12	13
124.0	2.2	319.0	23000.0	0.0	1.8	5.3000	20.0	5.5	20.0	-0.2	1.0	16.0
126.0	0.0	314.0	23000.0	0.0	2.5	1.7000	20.0	5.8	25.0	0.0	1.0	25.0
128.0	7.8	312.0	23000.0	0.0	1.2	15.2000	10.0	5.0	7.0	-0.2	0.9	6.0
130.0	7.8	330.0	23000.0	0.0	1.5	9.5000	16.0	5.5	12.0	0.0	1.0	12.0
132.0	7.8	329.0	23000.0	0.0	1.5	9.5000	9.0	6.0	8.0	0.6	1.3	21.0
134.0	7.8	321.0	23000.0	0.0	1.1	18.1000	16.0	3.8	10.0	0.0	1.5	10.0
136.0	11.1	315.0	700.0	0.0	1.2	15.2000	14.0	5.5	10.0	-0.1	0.3	8.0
138.0	3.3	321.0	700.0	0.0	5.0	0.1000	55.0	4.7	116.0	0.1	0.6	122.0
140.0	0.0	341.0	23000.0	0.0	1.0	21.0000	10.0	6.7	7.0	-0.4	0.8	5.0
142.0	6.7	325.0	23000.0	0.0	1.0	21.0000	14.0	6.1	10.0	-0.5	0.9	4.0
144.0	2.2	322.0	23000.0	0.0	1.5	9.5000	20.0	6.7	20.0	-0.5	1.0	14.0
146.0	8.9	319.0	23000.0	0.0	1.3	10.3000	21.0	5.3	11.0	-0.7	0.8	12.0
148.0	13.3	318.0	23000.0	0.0	1.2	15.2000	24.0	5.2	26.0	-1.0	0.9	7.0
150.0	16.7	322.0	23000.0	0.0	2.0	3.9000	21.0	6.8	31.0	-1.0	0.9	11.0
152.0	13.3	322.0	23000.0	0.0	3.4	0.5200	28.0	8.5	59.0	-0.8	0.9	36.0
154.0	13.3	323.0	23000.0	0.0	3.8	0.3600	23.0	9.3	43.0	0.0	0.9	43.0
156.0	13.3	324.0	23000.0	0.0	1.0	21.0000	14.0	6.1	10.0	-0.5	0.9	3.0
158.0	13.3	326.0	23000.0	0.0	3.9	0.3300	24.0	10.1	52.0	-0.4	0.9	39.0
160.0	7.8	327.0	170.0	1.0	6.0	0.0300	40.0	9.2	130.0	-0.5	0.9	108.0
162.0	2.2	330.0	170.0	1.0	4.2	0.2600	34.0	7.7	75.0	-0.4	0.9	58.0
164.0	22.2	332.0	170.0	1.0	4.9	0.1200	34.0	8.0	70.0	0.1	0.9	73.0
166.0	2.2	343.0	170.0	1.0	1.8	5.3000	8.0	8.5	5.0	0.6	1.0	19.0
168.0	20.0	353.0	170.0	1.0	4.2	0.2600	41.0	5.7	68.0	0.1	0.9	72.0
170.0	2.2	370.0	170.0	1.0	4.6	0.1800	22.0	7.9	31.0	1.5	0.9	130.0
172.0	18.9	433.0	170.0	1.0	2.9	0.9000	14.0	7.4	13.0	1.1	0.9	76.0
174.0	7.8	333.0	190.0	0.0	4.3	0.2400	33.0	6.5	63.0	0.2	1.0	70.0
176.0	7.8	322.0	120.0	0.0	3.1	0.7200	30.0	5.2	42.0	-0.1	1.1	38.0
178.0	-5.5	327.0	170.0	0.0	3.0	0.8000	30.0	4.9	39.0	-0.2	1.1	34.0
180.0	-3.3	331.0	150.0	0.0	3.0	0.8000	32.0	6.1	51.0	-0.2	0.9	42.0
182.0	-11.1	340.0	220.0	0.0	2.8	1.0000	28.0	5.5	36.0	-0.1	0.9	34.0
184.0	5.5	355.0	160.0	0.0	2.5	1.7000	30.0	4.7	37.0	0.0	1.1	37.0
186.0	53.3	372.0	110.0	0.0	3.3	0.5700	32.0	6.0	54.0	-0.1	1.0	50.0
188.0	38.9	388.0	250.0	0.0	2.6	1.4000	24.0	6.7	34.0	-0.2	0.9	29.0
190.0	24.4	405.0	23000.0	0.0	1.9	4.5000	18.0	7.9	23.0	-0.5	0.7	13.0
192.0	11.1	436.0	23000.0	0.0	2.2	2.8000	25.0	5.7	33.0	-0.4	0.8	23.0

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Equation Number 1    Dependent Variable..   RRATE   RECESSION RATE

  Descriptive Statistics are printed on Page    1

Beginning Block Number  1.  Method:  Enter      ASPECT


Variable(s) Entered on Step Number  1..    ASPECT    ASPECT (BEARING PERPENDICULAR TO SHORE)


Multiple R           .20673                                        Analysis of Variance
R Square             .04274        R Square Change    .04274                             DF      Sum of Squares      Mean Square
Adjusted R Square    .03600        F Change          6.33991       Regression             1          1052.57654       1052.57654
Standard Error     12.88503        Signif F Change    .0129        Residual             142         23575.41006        166.02401

                                                                   F =       6.33991        Signif F =  .0129


------------------------------------ Variables in the Equation ------------------------------------

Variable              B          SE B       Beta     Correl Part Cor  Partial  Tolerance         T  Sig T

ASPECT          .074731       .029680    .206734  .206734  .206734  .206734   1.000000     2.518  .0129
(Constant)   -10.901327      9.594420                                                       -1.136  .2578


------------------ Variables not in the Equation ------------------

Variable      Beta In  Partial  Tolerance  Min Toler         T  Sig T

STRENGT    -.002215 -.002245    .983588    .983588     -.027  .9788
PROTECT    -.383701 -.387013    .973858    .973858    -4.984  .0000
HTBEACH    -.109958 -.107172    .909370    .909370    -1.280  .2027
TIDAL      -.071955 -.073210    .990946    .990946     -.872  .3849
BFWIDTH    -.254500 -.253999    .953497    .953497    -3.118  .0022
BFSLOPE    -.001524 -.001487    .911335    .911335     -.018  .9859
BFVOLUM    -.303563 -.294804    .902810    .902810    -3.663  .0004
BTHEIGH     .202250  .205928    .992399    .992399     2.499  .0136
BTSLOPE     .071416  .072984    .999762    .999762      .869  .3863
BTVOLUM    -.015012 -.015200    .981440    .981440     -.181  .8570

End Block Number   1   All requested variables entered.
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Beginning Block Number  2.  Method:  Enter     STRENGT

Variable(s) Entered on Step Number  2..    STRENGT   STRENGTH OF CLIFF FACIES

Multiple R           .20675                                                Analysis of Variance
R Square             .04274          R Square Change     .00000                                 DF       Sum of Squares       Mean Square
Adjusted R Square    .02917          F Change            .00071            Regression            2           1052.69534         526.34767
Standard Error     12.93061          Signif F Change     .9788             Residual            141          23575.29126         167.20065

                                                                           F =       3.14800       Signif F =  .0460

------------------------------------ Variables in the Equation ------------------------------------

Variable              B         SE B        Beta   Correl Part Cor  Partial  Tolerance          T  Sig T

ASPECT          .074833      .030032     .207018  .206734  .205312  .205373    .983588      2.492  .0139
STRENGT   -2.95887E-06  1.1100E-04    -.002215  .024307 -.002196 -.002245    .983588      -.027  .9788
(Constant)  -10.915461     9.642948                                                        -1.132  .2596

------------------ Variables not in the Equation ------------------

Variable     Beta In  Partial  Tolerance  Min Toler          T  Sig T

PROTECT     -.419212 -.404864    .892855    .892855     -5.239  .0000
HTBEACH     -.210577 -.149373    .481671    .481671     -1.787  .0760
TIDAL       -.111001 -.090085    .630490    .625808     -1.070  .2863
BFWIDTH     -.304408 -.278283    .799996    .799996     -3.428  .0008
BFSLOPE     -.002605 -.002391    .806335    .806335      -.028  .9775
BFVOLUM     -.356374 -.319884    .771259    .771259     -3.995  .0001
BTHEIGH      .236915  .222408    .843616    .836126      2.699  .0078
BTSLOPE      .078161  .076681    .921353    .906447       .910  .3644
BTVOLUM     -.023300 -.019692    .683746    .683746      -.233  .8161

End Block Number   2   All requested variables entered.
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Beginning Block Number  3.  Method:  Enter      PROTECT

Variable(s) Entered on Step Number  3..    PROTECT   PROTECTIVE FEATURES

Multiple R           .44683                                         Analysis of Variance
R Square             .19965        R Square Change     .15691                            DF        Sum of Squares        Mean Square
Adjusted R Square    .18250        F Change          27.44713       Regression            3            4917.04413         1639.01471
Standard Error     11.86560        Signif F Change     .0000        Residual            140           19710.94247          140.79245

                                                                    F =        11.64135       Signif F =  .0000

------------------------------------ Variables in the Equation ------------------------------------

Variable              B         SE B        Beta    Correl Part Cor  Partial  Tolerance        T  Sig T

ASPECT          .055903      .027794     .154649  .206734  .152073  .167582    .966964    2.011  .0462
STRENGT    -1.63693E-04  1.0638E-04    -.122518  .024307 -.116345 -.128964    .901775   -1.539  .1261
PROTECT      -13.499447     2.576722   -.419212 -.407096 -.396117 -.404864    .892855   -5.239  .0000
(Constant)    12.499305     9.913359                                                     1.261  .2095

------------------ Variables not in the Equation ------------------

Variable      Beta In  Partial  Tolerance  Min Toler         T  Sig T

HTBEACH       .016405  .011701    .407186    .407186      .138  .8905
TIDAL        -.117319 -.104120    .630390    .593672    -1.234  .2192
BFWIDTH      -.151766 -.139111    .672443    .672443    -1.656  .0999
BFSLOPE       .056222  .055944    .792463    .792463      .661  .5100
BFVOLUM      -.136374 -.107629    .498513    .498513    -1.276  .2040
BTHEIGH       .169453  .171517    .819963    .746062     2.053  .0420
BTSLOPE       .087732  .094106    .920862    .833565     1.114  .2670
BTVOLUM       .153820  .134013    .607502    .607502     1.594  .1131

End Block Number   3   All requested variables entered.
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Beginning Block Number  4.  Method:  Enter      HTBEACH

Variable(s) Entered on Step Number  4..    HTBEACH   HEIGHT OF BEACH AT FOOT OF CLIFF

Multiple R            .44695                                         Analysis of Variance
R Square              .19976         R Square Change    .00011                      DF      Sum of Squares      Mean Square
Adjusted R Square     .17673         F Change           .01903       Regression      4          4919.74285       1229.93571
Standard Error      11.90739         Signif F Change    .8905        Residual      139         19708.24374        141.78593

                                                                     F =       8.67460       Signif F =  .0000

------------------------------------ Variables in the Equation ------------------------------------

Variable              B          SE B        Beta    Correl Part Cor  Partial  Tolerance         T  Sig T

ASPECT          .056973       .028951     .157610  .206734  .149317  .164639    .897531     1.968  .0511
STRENGT    -1.51057E-04   1.4066E-04    -.113060  .024307 -.081483 -.090712    .519417    -1.074  .2847
PROTECT      -13.652027      2.812378    -.423950 -.407096 -.368320 -.380725    .754783    -4.854  .0000
HTBEACH         .116430       .843921     .016405 -.162230  .010468  .011701    .407186      .138  .8905
(Constant)    11.785230     11.214166                                                       1.051  .2951

------------------ Variables not in the Equation ------------------

Variable      Beta In  Partial  Tolerance  Min Toler        T  Sig T

TIDAL       -.139632 -.110690    .502885    .324827   -1.308  .1929
BFWIDTH     -.202175 -.163707    .524682    .317712   -1.949  .0533
BFSLOPE      .060619  .055718    .676059    .347374     .656  .5132
BFVOLUM     -.263955 -.155088    .276256    .225646   -1.844  .0673
BTHEIGH      .169259  .171205    .818740    .406578    2.041  .0431
BTSLOPE      .091921  .097300    .896625    .396468    1.148  .2528
BTVOLUM      .208992  .152444    .425773    .285379    1.812  .0722

End Block Number   4   All requested variables entered.
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Beginning Block Number  5.  Method:  Enter      TIDAL


Variable(s) Entered on Step Number  5..    TIDAL     TIDAL COVERAGE %


Multiple R            .45778                                           Analysis of Variance
R Square              .20957        R Square Change    .00980                          DF       Sum of Squares       Mean Square
Adjusted R Square     .18093        F Change          1.71179          Regression        5           5161.21437        1032.24287
Standard Error      11.87702        Signif F Change    .1929           Residual        138          19466.77223         141.06357

                                                                       F =       7.31757       Signif F =  .0000


------------------------------------ Variables in the Equation ------------------------------------

Variable              B          SE B       Beta    Correl Part Cor   Partial  Tolerance        T  Sig T

ASPECT          .052697       .029062    .145780  .206734  .137232  .152550    .886177    1.813  .0720
STRENGT    -9.88757E-05   1.4586E-04   -.074004  .024307 -.051303 -.057609    .480583    -.678  .4990
PROTECT      -12.972994      2.852811   -.402863 -.407096 -.344160 -.361000    .729802   -4.547  .0000
HTBEACH        -.438127       .942459   -.061731 -.162230 -.035183 -.039542    .324827    -.465  .6428
TIDAL          -.252549       .193028   -.139632 -.051633 -.099019 -.110690    .502885   -1.308  .1929
(Constant)    15.032758     11.457655                                                       1.312  .1917


------------------ Variables not in the Equation -------------------

Variable      Beta In  Partial  Tolerance  Min Toler          T  Sig T

BFWIDTH     -.200615 -.163437    .524611    .264159     -1.939  .0546
BFSLOPE      .040530  .036888    .654780    .298738       .432  .6664
BFVOLUM     -.237697 -.138215    .267258    .179994     -1.633  .1047
BTHEIGH      .168213  .171190    .818663    .324532      2.034  .0439
BTSLOPE      .091860  .097836    .896624    .317946      1.151  .2519
BTVOLUM      .232102  .168958    .418857    .229163      2.006  .0468


End Block Number   5   All requested variables entered.
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Beginning Block Number  6.  Method:  Enter      BFWIDTH


Variable(s) Entered on Step Number  6..    BFWIDTH   BEACH FACE WIDTH


Multiple R           .48029                                          Analysis of Variance
R Square             .23068          R Square Change    .02111                          DF      Sum of Squares      Mean Square
Adjusted R Square    .19699          F Change          3.75992       Regression          6         5681.20291        946.86715
Standard Error     11.76000          Signif F Change    .0546        Residual          137        18946.78369        138.29769

                                                                     F =       6.84659        Signif F =  .0000


------------------------------------ Variables in the Equation ------------------------------------

Variable              B          SE B       Beta    Correl Part Cor  Partial  Tolerance         T  Sig T

ASPECT          .052110       .028777    .144157  .206734  .135697  .152891    .886079     1.811  .0724
STRENGT    -8.34887E-05    1.4464E-04   -.062488  .024307 -.043254 -.049254    .479137     -.577  .5647
PROTECT      -11.666834      2.903912   -.362302 -.407096 -.301067 -.324656    .690533    -4.018  .0001
HTBEACH         .429035      1.034800    .060450 -.162230  .031069  .035400    .264159      .415  .6791
TIDAL          -.248246       .191139   -.137253 -.051633 -.097325 -.110285    .502817    -1.299  .1962
BFWIDTH        -.198648       .102446   -.200615 -.287246 -.145306 -.163437    .524611    -1.939  .0546
(Constant)    15.775529     11.351238                                                       1.390  .1669


------------------ Variables not in the Equation ------------------

Variable     Beta In  Partial  Tolerance  Min Toler        T  Sig T

BFSLOPE     -.193528 -.122089    .306178    .153229   -1.435  .1537
BFVOLUM     -.058577 -.022577    .114283    .114283    -.263  .7927
BTHEIGH      .113316  .095583    .547376    .237144    1.120  .2648
BTSLOPE      .076759  .082419    .886964    .262116     .964  .3365
BTVOLUM      .202341  .147522    .408936    .184515    1.739  .0842


End Block Number   6   All requested variables entered.
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Beginning Block Number  7.  Method:  Enter      BFSLOPE


Variable(s) Entered on Step Number  7..    BFSLOPE   BEACH FACE SLOPE


Multiple R           .49209                                            Analysis of Variance
R Square             .24215        R Square Change    .01147                                  DF      Sum of Squares      Mean Square
Adjusted R Square    .20314        F Change          2.05785           Regression              7         5963.61867        851.94552
Standard Error     11.71486        Signif F Change    .1537            Residual              136        18664.36792        137.23800

                                                                       F =       6.20780       Signif F =  .0000


------------------------------------ Variables in the Equation ------------------------------------

Variable              B          SE B        Beta    Correl Part Cor  Partial  Tolerance         T  Sig T

ASPECT          .040367      .029812     .111671  .206734  .101078  .115334    .819273     1.354  .1780
STRENGT   -5.20396E-05  1.4575E-04   -.038950  .024307 -.026654 -.030603    .468296     -.357  .7216
PROTECT      -10.631748     2.981397   -.330158 -.407096 -.266200 -.292419    .650087    -3.566  .0005
HTBEACH        1.687231     1.353470    .237727 -.162230  .093057  .106289    .153229     1.247  .2147
TIDAL          -.316864      .196321   -.175191 -.051633 -.120484 -.137093    .472968    -1.614  .1088
BFWIDTH        -.354858      .149240   -.358372 -.287246 -.177498 -.199782    .245311    -2.378  .0188
BFSLOPE       -1.216423      .847964   -.193528 -.062947 -.107085 -.122089    .306178    -1.435  .1537
(Constant)    26.966060    13.737430                                                    1.963  .0517

------------------ Variables not in the Equation ------------------

Variable     Beta In  Partial  Tolerance  Min Toler        T  Sig T

BFVOLUM      .051146  .018756    .101919    .101919     .218  .8278
BTHEIGH      .075054  .060513    .492649    .123860     .704  .4824
BTSLOPE      .076627  .082898    .886963    .152554     .967  .3355
BTVOLUM      .173787  .124492    .388895    .106714    1.458  .1472

End Block Number   7   All requested variables entered.
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Beginning Block Number  8.  Method:  Enter      BFVOLUM

Variable(s) Entered on Step Number  8..    BFVOLUM   BEACH FACE VOLUME

Multiple R            .49236                                      Analysis of Variance
R Square              .24241        R Square Change     .00027                        DF      Sum of Squares      Mean Square
Adjusted R Square     .19752        F Change            .04751    Regression           8          5970.18477        746.27310
Standard Error      11.75610        Signif F Change     .8278     Residual           135         18657.80183        138.20594

                                                                  F =       5.39972       Signif F =  .0000

------------------------------------ Variables in the Equation ------------------------------------

Variable                B         SE B        Beta   Correl Part Cor  Partial  Tolerance        T  Sig T

ASPECT            .040609      .029938     .112340  .206734  .101613  .115957    .818149    1.356  .1772
STRENGT      -6.06491E-05   1.5150E-04    -.045393  .024307 -.029989 -.034434    .436463    -.400  .6895
PROTECT        -10.922525     3.275836    -.339188 -.407096 -.249776 -.275835    .542274   -3.334  .0011
HTBEACH          1.578073     1.447620     .222347 -.162230  .081662  .093412    .134890    1.090  .2776
TIDAL            -.332290      .209339    -.183720 -.051633 -.118909 -.135358    .418908   -1.587  .1148
BFWIDTH          -.390502      .221746    -.394369 -.287246 -.131922 -.149854    .111899   -1.761  .0805
BFSLOPE         -1.281024      .901086    -.203805 -.062947 -.106498 -.121450    .273054   -1.422  .1574
BFVOLUM           .011259      .051656     .051146 -.338510  .016328  .018756    .101919     .218  .8278
(Constant)      28.618685    15.733239                                                      1.819  .0711

------------------ Variables not in the Equation -------------------

Variable      Beta In  Partial  Tolerance  Min Toler         T  Sig T

BTHEIGH       .097844  .073042    .422196    .087344      .848  .3981
BTSLOPE       .082582  .087841    .857142    .098493     1.021  .3092
BTVOLUM       .174850  .125206    .388466    .096452     1.461  .1464

End Block Number   8   All requested variables entered.
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Beginning Block Number  9.  Method:  Enter      BTHEIGH

Variable(s) Entered on Step Number  9..    BTHEIGH   BEACH TERRACE HEIGHT

                                                                       Analysis of Variance
Multiple R            .49644                                                              DF      Sum of Squares      Mean Square
R Square              .24646           R Square Change     .00404      Regression          9          6069.72755        674.41417
Adjusted R Square     .19585           F Change            .71875      Residual          134         18558.25904        138.49447
Standard Error      11.76837           Signif F Change     .3981
                                                                       F =        4.86961        Signif F =  .0000

------------------------------------ Variables in the Equation ------------------------------------

Variable              B          SE B         Beta     Correl Part Cor  Partial  Tolerance        T   Sig T

ASPECT          .039270       .030011      .108635   .206734  .098126  .112324    .815881     1.309  .1929
STRENGT    -3.40966E-05    1.5486E-04    -.025520   .024307 -.016511 -.019017    .418610     -.220  .8261
PROTECT      -11.507558      3.351074    -.357356 -.407096 -.257514 -.284402    .519279    -3.434  .0008
HTBEACH         .798125      1.716489     .112454 -.162230  .034868  .040135    .096142      .465  .6427
TIDAL          -.341476       .209837    -.188799 -.051633 -.122034 -.139212    .417791    -1.627  .1060
BFWIDTH        -.344134       .228616    -.347542 -.287246 -.112882 -.128952    .105495    -1.505  .1346
BFSLOPE       -1.123765       .920901    -.178786 -.062947 -.091509 -.104836    .261975    -1.220  .2245
BFVOLUM         .029167       .055858     .132495 -.338510  .039158  .045063    .087344      .522  .6024
BTHEIGH        1.456572      1.718080     .097844  .218737  .063576  .073042    .422196      .848  .3981
(Constant)    28.622103     15.749654                                                       1.817  .0714

------------------ Variables not in the Equation ------------------

Variable      Beta In  Partial  Tolerance  Min Toler        T  Sig T

BTSLOPE       .065413  .063608    .712540    .087312      .735  .4636
BTVOLUM       .402008  .132057    .081314    .060410     1.536  .1268

End Block Number   9   All requested variables entered.
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Beginning Block Number 10.  Method:  Enter      BTSLOPE


Variable(s) Entered on Step Number 10..    BTSLOPE   BEACH TERRACE SLOPE


Multiple R           .49951                                          Analysis of Variance
R Square             .24951          R Square Change     .00305                          DF        Sum of Squares       Mean Square
Adjusted R Square    .19308          F Change            .54030      Regression          10            6144.81413         614.48141
Standard Error     11.78861          Signif F Change     .4636       Residual           133           18483.17247         138.97122

                                                                     F =        4.42165         Signif F =  .0000


------------------------------------ Variables in the Equation ------------------------------------

Variable                  B        SE B         Beta    Correl Part Cor  Partial  Tolerance          T  Sig T

ASPECT              .041458     .030209      .114690   .206734  .103091  .118166    .807954      1.372  .1723
STRENGT        -6.41330E-05  1.6041E-04    -.048001   .024307 -.030032 -.034646    .391447      -.400  .6899
PROTECT          -11.736375    3.371239    -.364461  -.407096 -.261512 -.288989    .514852     -3.481  .0007
HTBEACH            1.102029    1.768450     .155273  -.162230  .046811  .053956    .090887       .623  .5342
TIDAL              -.348606     .210422    -.192741  -.051633 -.124449 -.142194    .416903     -1.657  .0999
BFWIDTH            -.378041     .233608    -.381784  -.287246 -.121562 -.138960    .101382     -1.618  .1080
BFSLOPE           -1.229171     .933564    -.195556  -.062947 -.098905 -.113431    .255794     -1.317  .1902
BFVOLUM             .029950     .055964     .136050  -.338510  .040201  .046355    .087312       .535  .5934
BTHEIGH             .886681    1.887607     .059562   .218737  .035286  .040698    .350970       .470  .6393
BTSLOPE            2.372613    3.227812     .065413   .074591  .055216  .063608    .712540       .735  .4636
(Constant)        26.796307   15.971075                                                         1.678  .0957


------------------ Variables not in the Equation ------------------

Variable      Beta In  Partial  Tolerance  Min Toler         T  Sig T

BTVOLUM       .526597  .163249    .072126    .058486     1.901  .0595


End Block Number  10   All requested variables entered.
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Beginning Block Number 11.  Method:  Enter      BTVOLUM


Variable(s) Entered on Step Number 11..    BTVOLUM   BEACH TERRACE VOLUME


Multiple R           .51914                                          Analysis of Variance
R Square             .26951          R Square Change     .02000                       DF       Sum of Squares      Mean Square
Adjusted R Square    .20863          F Change           3.61415      Regression       11           6637.39550        603.39959
Standard Error     11.67443          Signif F Change     .0595       Residual        132          17990.59110        136.29236

                                                                     F =       4.42724       Signif F =  .0000


------------------------------------ Variables in the Equation ------------------------------------

Variable              B         SE B       Beta    Correl Part Cor  Partial  Tolerance        T  Sig T

ASPECT          .038880      .029947    .107558  .206734  .096581  .112286    .806297    1.298  .1965
STRENGT    -1.66525E-04   1.6774E-04   -.124637  .024307 -.073851 -.086086    .351090    -.993  .3227
PROTECT      -12.029251     3.342141   -.373556 -.407096 -.267753 -.298949    .513758   -3.599  .0005
HTBEACH         .956279     1.752999    .134738 -.162230  .040581  .047427    .090713     .546  .5863
TIDAL          -.388739      .209451   -.214930 -.051633 -.138070 -.159476    .412668   -1.856  .0657
BFWIDTH        -.465253      .235850   -.469860 -.287246 -.146749 -.169222    .097546   -1.973  .0506
BFSLOPE       -1.243785      .924554   -.197881 -.062947 -.100077 -.116297    .255777   -1.345  .1808
BFVOLUM        -.044020      .067716   -.199964 -.338510 -.048359 -.056491    .058486    -.650  .5168
BTHEIGH       -6.320761     4.227015   -.424591  .218737 -.111239 -.129063    .068639   -1.495  .1372
BTSLOPE        4.541527     3.394044    .125209  .074591  .099542  .115684    .632029    1.338  .1832
BTVOLUM         .090747      .047734    .526597 -.042898  .141424  .163249    .072126    1.901  .0595
(Constant)    28.783140    15.850884                                                     1.816  .0717


End Block Number  11   All requested variables entered.
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                                  * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

Equation Number 1    Dependent Variable..   RRATE   RECESSION RATE

  Descriptive Statistics are printed on Page    1

Beginning Block Number  1.  Method:  Enter      ASPECT


Variable(s) Entered on Step Number  1..    ASPECT    ASPECT (BEARING PERPENDICULAR TO SHORE)


Multiple R            .20673                                        Analysis of Variance
R Square              .04274         R Square Change     .04274                         DF      Sum of Squares       Mean Square
Adjusted R Square     .03600         F Change           6.33991     Regression           1          1052.57654        1052.57654
Standard Error      12.88503         Signif F Change     .0129      Residual           142         23575.41006         166.02401

                                                                    F =       6.33991      Signif F =  .0129


------------------------------------ Variables in the Equation ------------------------------------

Variable              B         SE B       Beta   Correl Part Cor  Partial  Tolerance         T  Sig T

ASPECT          .074731      .029680    .206734  .206734  .206734  .206734   1.000000     2.518  .0129
(Constant)   -10.901327     9.594420                                                     -1.136  .2578


------------------ Variables not in the Equation ------------------

Variable      Beta In  Partial  Tolerance  Min Toler        T  Sig T

STRENGT     -.002215 -.002245    .983588    .983588    -.027  .9788
HTBEACH     -.109958 -.107172    .909370    .909370   -1.280  .2027
TIDAL       -.071955 -.073210    .990946    .990946    -.872  .3849
BFWIDTH     -.254500 -.253999    .953497    .953497   -3.118  .0022
BFSLOPE     -.001524 -.001487    .911335    .911335    -.018  .9859
BFVOLUM     -.303563 -.294804    .902810    .902810   -3.663  .0004
BTHEIGH      .202250  .205928    .992399    .992399    2.499  .0136
BTSLOPE      .071416  .072984    .999762    .999762     .869  .3863
BTVOLUM     -.015012 -.015200    .981440    .981440    -.181  .8570

End Block Number   1   All requested variables entered.
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Beginning Block Number  2.  Method:  Enter      STRENGT


Variable(s) Entered on Step Number  2..    STRENGT   STRENGTH OF CLIFF FACIES


Multiple R           .20675                                        Analysis of Variance
R Square             .04274          R Square Change     .00000                       DF      Sum of Squares      Mean Square
Adjusted R Square    .02917          F Change            .00071    Regression          2         1052.69534        526.34767
Standard Error     12.93061          Signif F Change     .9788     Residual          141        23575.29126        167.20065

                                                                   F =       3.14800       Signif F =  .0460


------------------------------------ Variables in the Equation ------------------------------------

Variable              B         SE B       Beta    Correl Part Cor  Partial  Tolerance       T  Sig T

ASPECT          .074833      .030032    .207018  .206734  .205312  .205373    .983588    2.492  .0139
STRENGT    -2.95887E-06   1.1100E-04   -.002215  .024307 -.002196 -.002245    .983588    -.027  .9788
(Constant)   -10.915461     9.642948                                                    -1.132  .2596


----------------- Variables not in the Equation ------------------

Variable     Beta In  Partial  Tolerance  Min Toler         T  Sig T

HTBEACH     -.210577 -.149373    .481671    .481671    -1.787  .0760
TIDAL       -.111001 -.090085    .630490    .625808    -1.070  .2863
BFWIDTH     -.304408 -.278283    .799996    .799996    -3.428  .0008
BFSLOPE     -.002605 -.002391    .806335    .806335     -.028  .9775
BFVOLUM     -.356374 -.319884    .771259    .771259    -3.995  .0001
BTHEIGH      .236915  .222408    .843616    .836126     2.699  .0078
BTSLOPE      .078161  .076681    .921353    .906447      .910  .3644
BTVOLUM     -.023300 -.019692    .683746    .683746     -.233  .8161

End Block Number   2   All requested variables entered.
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Beginning Block Number  3.  Method:  Enter      HTBEACH


Variable(s) Entered on Step Number  3..    HTBEACH   HEIGHT OF BEACH AT FOOT OF CLIFF


Multiple R            .25318                                          Analysis of Variance
R Square              .06410      R Square Change     .02136                               DF      Sum of Squares      Mean Square
Adjusted R Square     .04405      F Change           3.19501          Regression            3          1578.71479        526.23826
Standard Error      12.83112      Signif F Change     .0760           Residual            140         23049.27181        164.63766

                                                                      F =       3.19634       Signif F =  .0255


------------------------------------- Variables in the Equation --------------------------------------

Variable               B         SE B        Beta    Correl Part Cor  Partial  Tolerance        T  Sig T

ASPECT           .058348      .031195     .161413  .206734  .152927  .156139    .897617    1.870  .0635
STRENGT     -1.88485E-04   1.5135E-04    -.141073  .024307 -.101826 -.104677    .520983   -1.245  .2151
HTBEACH        -1.494537      .836123    -.210577 -.162230 -.146146 -.149373    .481671   -1.787  .0760
(Constant)      1.647821    11.872735                                                        .139  .8898


------------------ Variables not in the Equation -------------------

Variable      Beta In  Partial  Tolerance  Min Toler        T  Sig T

TIDAL        -.227923 -.169909    .520099    .397336   -2.033  .0440
BFWIDTH      -.308132 -.237517    .556085    .334815   -2.883  .0046
BFSLOPE       .074644  .063473    .676728    .404250     .750  .4546
BFVOLUM      -.499772 -.311318    .363154    .226799   -3.862  .0002
BTHEIGH       .232230  .220379    .842814    .470674    2.664  .0086
BTSLOPE       .057975  .056956    .903281    .472224     .673  .5023
BTVOLUM       .132083  .089863    .433210    .305179    1.064  .2893

End Block Number   3   All requested variables entered.
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Beginning Block Number  4.  Method:  Enter      TIDAL


Variable(s) Entered on Step Number  4..    TIDAL     TIDAL COVERAGE %


Multiple R           .30186                                        Analysis of Variance
R Square             .09112          R Square Change    .02702                         DF      Sum of Squares      Mean Square
Adjusted R Square    .06497          F Change          4.13210     Regression           4          2244.12763        561.03191
Standard Error     12.68995          Signif F Change    .0440      Residual           139         22383.85897        161.03496

                                                                   F =       3.48391       Signif F =  .0096


------------------------------------ Variables in the Equation ------------------------------------

Variable               B        SE B       Beta     Correl Part Cor  Partial  Tolerance       T  Sig T

ASPECT           .051256     .031049    .141793   .206734  .133488  .138667    .886282    1.651  .1010
STRENGT     -1.00270E-04  1.5584E-04   -.075048   .024307 -.052026 -.054491    .480585    -.643  .5210
HTBEACH        -2.268957     .910463   -.319691 -.162230 -.201516 -.206807    .397336   -2.492  .0139
TIDAL           -.412239     .202798   -.227923 -.051633 -.164373 -.169909    .520099   -2.033  .0440
(Constant)      7.771859   12.122435                                                       .641  .5225


------------------ Variables not in the Equation ------------------

Variable     Beta In  Partial  Tolerance  Min Toler          T  Sig T

BFWIDTH     -.297035 -.231998    .554445    .285681     -2.802  .0058
BFSLOPE      .039956  .033914    .654781    .358853       .399  .6908
BFVOLUM     -.460654 -.282399    .341572    .180158     -3.458  .0007
BTHEIGH      .225404  .216882    .841455    .396539      2.610  .0101
BTSLOPE      .060590  .060397    .903077    .391492       .711  .4784
BTVOLUM      .172853  .118021    .423711    .251606      1.396  .1649


End Block Number   4   All requested variables entered.
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Beginning Block Number  5.  Method:  Enter      BFWIDTH


Variable(s) Entered on Step Number  5..    BFWIDTH   BEACH FACE WIDTH


Multiple R            .37422                                          Analysis of Variance
R Square              .14004          R Square Change     .04892                          DF      Sum of Squares      Mean Square
Adjusted R Square     .10888          F Change           7.85009      Regression           5          3448.89462        689.77892
Standard Error      12.38837          Signif F Change     .0058       Residual           138         21179.09198        153.47168

                                                                      F =        4.49450       Signif F =  .0008


------------------------------------ Variables in the Equation ------------------------------------

Variable              B          SE B        Beta     Correl Part Cor  Partial  Tolerance        T  Sig T

ASPECT           .050602      .030312     .139984   .206734  .131781  .140693    .886230     1.669  .0973
STRENGT     -7.72798E-05   1.5236E-04    -.057841   .024307 -.040039 -.043137    .479191     -.507  .6128
HTBEACH         -.712088     1.048225    -.100332 -.162230 -.053626 -.057732    .285681     -.679  .4981
TIDAL           -.382063      .198271    -.211239 -.051633 -.152116 -.161871    .518564    -1.927  .0560
BFWIDTH         -.294123      .104976    -.297035 -.287246 -.221176 -.231998    .554445    -2.802  .0058
(Constant)      9.954029    11.859938                                                         .839  .4028


------------------ Variables not in the Equation ------------------

Variable     Beta In  Partial  Tolerance  Min Toler         T  Sig T

BFSLOPE     -.309959 -.190616    .325228    .153553    -2.273  .0246
BFVOLUM     -.409179 -.167853    .144714    .144714    -1.993  .0483
BTHEIGH      .127477  .101767    .548054    .255963     1.197  .2332
BTSLOPE      .042015  .042914    .897153    .284627      .503  .6159
BTVOLUM      .132755  .092466    .417194    .188754     1.087  .2790

End Block Number   5   All requested variables entered.
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Beginning Block Number  6.  Method:  Enter      BFSLOPE


Variable(s) Entered on Step Number  6..    BFSLOPE   BEACH FACE SLOPE


Multiple R           .41387                                                 Analysis of Variance
R Square             .17129        R Square Change     .03125                                  DF      Sum of Squares      Mean Square
Adjusted R Square    .13499        F Change           5.16549               Regression          6          4218.42309        703.07051
Standard Error     12.20553        Signif F Change     .0246                Residual          137         20409.56351        148.97492

                                                                            F =        4.71939       Signif F =  .0002


------------------------------------ Variables in the Equation ------------------------------------

Variable              B        SE B       Beta   Correl Part Cor  Partial  Tolerance        T  Sig T

ASPECT          .032008     .030965    .088548  .206734  .080397  .087973    .824369    1.034  .3031
STRENGT    -2.77924E-05  1.5168E-04   -.020801  .024307 -.014250 -.015652    .469317    -.183  .8549
HTBEACH        1.465221    1.408666    .206446 -.162230  .080898  .088517    .153553    1.040  .3001
TIDAL          -.472948     .199396   -.261489 -.051633 -.184476 -.198609    .497707   -2.372  .0191
BFWIDTH        -.530747     .146753   -.536002 -.287246 -.281282 -.295215    .275391   -3.617  .0004
BFSLOPE       -1.948254     .857215   -.309959 -.062947 -.176766 -.190616    .325228   -2.273  .0246
(Constant)    28.704295   14.303796                                                     2.007  .0467


------------------ Variables not in the Equation ------------------

Variable     Beta In  Partial  Tolerance  Min Toler        T  Sig T

BFVOLUM     -.267472 -.102702    .122182    .112950   -1.204  .2307
BTHEIGH      .057994  .044759    .493632    .123918     .523  .6022
BTSLOPE      .046647  .048520    .896607    .152976     .567  .5720
BTVOLUM      .086640  .060485    .403886    .107217     .707  .4810

End Block Number   6   All requested variables entered.
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Beginning Block Number  7.  Method:  Enter      BFVOLUM

Variable(s) Entered on Step Number  7..    BFVOLUM   BEACH FACE VOLUME

Multiple R           .42430                                                Analysis of Variance
R Square             .18003           R Square Change     .00874                              DF       Sum of Squares          Mean Square
Adjusted R Square    .13782           F Change           1.44979           Regression           7           4433.69862            633.38552
Standard Error     12.18554           Signif F Change     .2307            Residual           136          20194.28797            148.48741

                                                                           F =        4.26558       Signif F =  .0003

------------------------------------ Variables in the Equation ------------------------------------

Variable              B          SE B         Beta   Correl Part Cor  Partial  Tolerance        T  Sig T

ASPECT          .031940       .030914      .088358  .206734  .080224  .088248    .824367    1.033  .3034
STRENGT     1.37633E-05    1.5532E-04      .010301  .024307  .006881  .007598    .446145     .089  .9295
HTBEACH        2.067826      1.492756      .291352 -.162230  .107561  .117954    .136293    1.385  .1682
TIDAL          -.369950       .216670     -.204542 -.051633 -.132579 -.144867    .420131   -1.707  .0900
BFWIDTH        -.319187       .228774     -.322348 -.287246 -.108335 -.118791    .112950   -1.395  .1652
BFSLOPE       -1.505741       .931386     -.239557 -.062947 -.125531 -.137315    .274590   -1.617  .1083
BFVOLUM        -.058881       .048902     -.267472 -.338510 -.093494 -.102702    .122182   -1.204  .2307
(Constant)    19.813126     16.076572                                                        1.232  .2199

----------------- Variables not in the Equation ------------------

Variable      Beta In  Partial  Tolerance  Min Toler         T  Sig T

BTHEIGH       .016232  .011903    .440892    .099910      .138  .8902
BTSLOPE       .034911  .036222    .882747    .112391      .421  .6743
BTVOLUM       .094024  .065910    .402929    .099884      .767  .4441

End Block Number   7   All requested variables entered.
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Beginning Block Number  8.  Method:  Enter      BTHEIGH


Variable(s) Entered on Step Number  8..    BTHEIGH   BEACH TERRACE HEIGHT


Multiple R           .42443                                        Analysis of Variance
R Square             .18014         R Square Change     .00012                          DF      Sum of Squares       Mean Square
Adjusted R Square    .13156         F Change            .01913     Regression            8          4436.55968         554.56996
Standard Error     12.22972         Signif F Change     .8902      Residual            135         20191.42692         149.56613

                                                                   F =        3.70786       Signif F =  .0006


------------------------------------ Variables in the Equation ------------------------------------

Variable              B         SE B         Beta    Correl Part Cor  Partial  Tolerance         T  Sig T

ASPECT          .031640      .031102      .087530  .206734  .079280  .087224    .820377     1.017  .3108
STRENGT     1.88296E-05   1.6013E-04      .014093  .024307  .009164  .010120    .422798      .118  .9066
HTBEACH        1.942784     1.749823      .273734 -.162230  .086523  .095124    .099910     1.110  .2689
TIDAL          -.371809      .217870     -.205570 -.051633 -.132991 -.145318    .418532    -1.707  .0902
BFWIDTH        -.310861      .237365     -.313939 -.287246 -.102059 -.112006    .105685    -1.310  .1925
BFSLOPE       -1.481649      .950855     -.235724 -.062947 -.121432 -.132921    .265374    -1.558  .1215
BFVOLUM        -.056534      .051932     -.256808 -.338510 -.084835 -.093284    .109128    -1.089  .2783
BTHEIGH         .241647     1.747169      .016232  .218737  .010778  .011903    .440892      .138  .8902
(Constant)    19.735447    16.144634                                                         1.222  .2237


------------------ Variables not in the Equation ------------------

Variable     Beta In  Partial  Tolerance  Min Toler          T  Sig T

BTSLOPE      .036806  .034460    .718667    .093476       .399  .6904
BTVOLUM      .390682  .123047    .081326    .069673      1.435  .1535


End Block Number   8   All requested variables entered.
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Beginning Block Number  9.  Method:  Enter      BTSLOPE


Variable(s) Entered on Step Number  9..    BTSLOPE   BEACH TERRACE SLOPE


Multiple R           .42558                                     Analysis of Variance
R Square             .18112      R Square Change     .00097                          DF      Sum of Squares       Mean Square
Adjusted R Square    .12612      F Change            .15931     Regression            9          4460.53666         495.61518
Standard Error     12.26798      Signif F Change     .6904      Residual            134         20167.44994         150.50336

                                                                F =       3.29305        Signif F =  .0012


------------------------------------ Variables in the Equation ------------------------------------

Variable              B          SE B        Beta    Correl Part Cor  Partial  Tolerance        T  Sig T

ASPECT          .032787       .031331     .090701   .206734  .081806  .090034    .813485    1.046  .2972
STRENGT     2.52103E-06    1.6574E-04     .001887   .024307  .001189  .001314    .397103     .015  .9879
HTBEACH        2.126590      1.814699     .299632 -.162230  .091609  .100719    .093476    1.172  .2433
TIDAL          -.376160       .218824    -.207975 -.051633 -.134381 -.146889    .417494   -1.719  .0879
BFWIDTH        -.329567       .242676    -.332830 -.287246 -.106164 -.116519    .101743   -1.358  .1767
BFSLOPE       -1.544962       .966930    -.245797 -.062947 -.124906 -.136733    .258232   -1.598  .1124
BFVOLUM        -.057052       .052110    -.259163 -.338510 -.085587 -.094159    .109060   -1.095  .2756
BTHEIGH        -.092609      1.942431    -.006221  .218737 -.003727 -.004119    .358942    -.048  .9620
BTSLOPE        1.335007      3.344718     .036806  .074591  .031202  .034460    .718667     .399  .6904
(Constant)    18.608693     16.439332                                                        1.132  .2597


------------------ Variables not in the Equation ------------------

Variable     Beta In  Partial  Tolerance  Min Toler         T  Sig T

BTVOLUM      .480641  .142796    .072280    .066060     1.664  .0985


End Block Number   9   All requested variables entered.
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Beginning Block Number 10.  Method:  Enter      BTVOLUM

Variable(s) Entered on Step Number 10..    BTVOLUM   BEACH TERRACE VOLUME

Multiple R           .44476                                         Analysis of Variance
R Square             .19781       R Square Change     .01670                          DF      Sum of Squares      Mean Square
Adjusted R Square    .13750       F Change          2.76843        Regression          10          4871.76773        487.17677
Standard Error     12.18782       Signif F Change     .0985        Residual           133         19756.21887        148.54300

                                                                   F =        3.27970       Signif F =  .0008

------------------------------------ Variables in the Equation ------------------------------------

Variable              B          SE B         Beta    Correl Part Cor  Partial  Tolerance          T  Sig T

ASPECT          .030236       .031164      .083645  .206734  .075351  .083834    .811516       .970  .3337
STRENGT     -8.94170E-05   1.7369E-04    -.066925  .024307 -.039982 -.044596    .356912      -.515  .6075
HTBEACH        2.016896      1.804047      .284176 -.162230  .086825  .096489    .093351      1.118  .2656
TIDAL          -.413418       .218544     -.228575 -.051633 -.146914 -.161867    .413111     -1.892  .0607
BFWIDTH        -.408064       .245663     -.412105 -.287246 -.129003 -.142562    .097991     -1.661  .0991
BFSLOPE       -1.565493       .960691     -.249063 -.062947 -.126555 -.139910    .258190     -1.630  .1056
BFVOLUM        -.126548       .066518     -.574855 -.338510 -.147750 -.162764    .066060     -1.902  .0593
BTHEIGH       -6.693359      4.411577     -.449620  .218737 -.117832 -.130436    .068680     -1.517  .1316
BTSLOPE        3.291005      3.524685      .090733  .074591  .072514  .080698    .638722       .934  .3521
BTVOLUM         .082827       .049780      .480641 -.042898  .129220  .142796    .072280      1.664  .0985
(Constant)    20.235646     16.361163                                                          1.237  .2183

End Block Number  10   All requested variables entered.
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Equation Number 1    Dependent Variable..   RRATE   RECESSION RATE

  Descriptive Statistics are printed on Page    1

Beginning Block Number  1.  Method:  Enter      TIDAL


Variable(s) Entered on Step Number  1..    TIDAL     TIDAL COVERAGE IN %


Multiple R           .26796                                               Analysis of Variance
R Square             .07180         R Square Change    .07180                                DF      Sum of Squares       Mean Square
Adjusted R Square    .01379         F Change          1.23770             Regression          1            87.16668          87.16668
Standard Error      8.39203         Signif F Change    .2824              Residual           16          1126.81777          70.42611

                                                                          F =       1.23770       Signif F =  .2824


------------------------------------ Variables in the Equation ------------------------------------

Variable             B         SE B       Beta   Correl Part Cor  Partial  Tolerance        T  Sig T

TIDAL       117.226037  105.369688    .267959  .267959  .267959  .267959   1.000000     1.113  .2824
(Constant)    8.629775    4.922392                                                      1.753  .0987


------------------ Variables not in the Equation ------------------

Variable     Beta In  Partial  Tolerance  Min Toler        T  Sig T

BFHEIGH    -.353915 -.364761    .985956    .985956   -1.517  .1500
BFWIDTH    -.581298 -.601933    .995265    .995265   -2.919  .0106
BFSLOPE     .139585  .144643    .996678    .996678     .566  .5797
BFVOLUM    -.620183 -.638057    .982472    .982472   -3.209  .0059
BTHEIGH     .505909  .525000    .999575    .999575    2.389  .0305
BTSLOPE     .711308  .738143    .999553    .999553    4.238  .0007
TVOLUM     -.464225 -.454284    .888869    .888869   -1.975  .0670
CHEIGH      .139004  .138195    .917429    .917429     .540  .5968
CFINES      .595239  .612561    .983009    .983009    3.001  .0089
ASPECT      .046420  .048181    .999959    .999959     .187  .8543

End Block Number   1   All requested variables entered.
```

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                                   * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

Beginning Block Number  2.  Method:  Enter      BFHEIGH

Variable(s) Entered on Step Number  2..    BFHEIGH   BEACH FACE HEIGHT

Multiple R           .44193                                        Analysis of Variance
R Square             .19530          R Square Change    .12350                           DF      Sum of Squares      Mean Square
Adjusted R Square    .08801          F Change          2.30204     Regression             2           237.09011        118.54505
Standard Error      8.07009          Signif F Change    .1500      Residual              15           976.89434         65.12629

                                                                   F =       1.82023       Signif F =  .1960

------------------------------------ Variables in the Equation ------------------------------------

Variable              B         SE B       Beta    Correl Part Cor  Partial  Tolerance        T  Sig T

TIDAL         98.877839   102.046507    .226018  .267959  .224426  .242701    .985956     .969  .3479
BFHEIGH       -3.268212     2.154039   -.353915 -.380700 -.351421 -.364761    .985956   -1.517  .1500
(Constant)    24.030840    11.200107                                                     2.146  .0487


------------------ Variables not in the Equation ------------------

Variable      Beta In  Partial  Tolerance  Min Toler        T  Sig T

BFWIDTH      -.560167 -.621568    .990776    .980202   -2.969  .0102
BFSLOPE       .680735  .562560    .549562    .543650    2.546  .0233
BFVOLUM      -.580896 -.568299    .770179    .770179   -2.584  .0216
BTHEIGH       .458478  .503119    .969035    .955833    2.178  .0470
BTSLOPE       .688737  .765426    .993881    .980361    4.450  .0005
TVOLUM       -.391390 -.302442    .480507    .480507   -1.187  .2549
CHEIGH       -.244694 -.184043    .455223    .455223    -.701  .4950
CFINES        .539643  .547194    .827377    .827377    2.446  .0283
ASPECT       -.694375 -.453521    .343274    .338467   -1.904  .0777

End Block Number   2   All requested variables entered.
```

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                                   * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

Beginning Block Number  3.  Method:  Enter      BFWIDTH

Variable(s) Entered on Step Number  3..     BFWIDTH   BEACH FACE WIDTH

                                                                      Analysis of Variance
Multiple R           .71147                                                              DF      Sum of Squares      Mean Square
R Square             .50619            R Square Change     .31089     Regression          3           614.50979        204.83660
Adjusted R Square    .40038            F Change           8.81418     Residual           14           599.47465         42.81962
Standard Error      6.54367            Signif F Change     .0102
                                                                      F =       4.78371        Signif F =  .0169


------------------------------------ Variables in the Equation ------------------------------------

Variable               B          SE B         Beta    Correl Part Cor  Partial  Tolerance        T  Sig T

TIDAL         117.699950     82.987446      .269042  .267959  .266366  .354444    .980202    1.418  .1780
BFHEIGH        -2.919178      1.750566     -.316118 -.380700 -.313182 -.407077    .981510   -1.668  .1176
BFWIDTH         -.533620       .179739     -.560167 -.560107 -.557578 -.621568    .990776   -2.969  .0102
(Constant)     38.799861     10.354881                                                         3.747  .0022


------------------ Variables not in the Equation ------------------

Variable      Beta In  Partial   Tolerance  Min Toler         T  Sig T

BFSLOPE       .162712  .092558     .159788    .159788      .335  .7429
BFVOLUM      -.194895 -.143529     .267816    .267816     -.523  .6098
BTHEIGH      -.077352 -.057458     .272471    .272471     -.208  .8388
BTSLOPE       .546805  .686001     .777219    .774791     3.399  .0047
TVOLUM       -.511756 -.500016     .471410    .471410    -2.082  .0577
CHEIGH        .302578  .242427     .316991    .316991      .901  .3840
CFINES        .285451  .305749     .566532    .566532     1.158  .2678
ASPECT       -.441390 -.349816     .310164    .309442    -1.346  .2012

End Block Number   3   All requested variables entered.
```

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Beginning Block Number  4.  Method:  Enter      BFSLOPE


Variable(s) Entered on Step Number  4..    BFSLOPE   BEACH FACE SLOPE


Multiple R             .71444                                           Analysis of Variance
R Square               .51042          R Square Change     .00423                          DF      Sum of Squares      Mean Square
Adjusted R Square      .35978          F Change            .11233       Regression          4           619.64546        154.91136
Standard Error        6.76154          Signif F Change     .7429        Residual           13           594.33899         45.71838

                                                                        F =       3.38838       Signif F =  .0416


------------------------------------ Variables in the Equation ------------------------------------

Variable             B          SE B        Beta    Correl Part Cor  Partial  Tolerance         T  Sig T

TIDAL        112.693002    87.042020     .257597  .267959  .251250  .337956    .951329     1.295  .2179
BFHEIGH       -3.994607     3.683434   -.432577 -.380700 -.210455 -.288033    .236698    -1.084  .2979
BFWIDTH        -.436401      .344430   -.458112 -.560107 -.245880 -.331534    .288074    -1.267  .2274
BFSLOPE         .775826     2.314789    .162712  .123677  .065042  .092558    .159788      .335  .7429
(Constant)    34.503800    16.696748                                                     2.066  .0593


------------------ Variables not in the Equation ------------------

Variable      Beta In  Partial  Tolerance  Min Toler         T  Sig T

BFVOLUM     -.410658 -.245719    .175282    .086642      -.878  .3971
BTHEIGH     -.056641 -.041556    .263532    .139535      -.144  .8878
BTSLOPE      .559393  .701433    .769766    .158256      3.409  .0052
TVOLUM      -.693641 -.608415    .376662    .127672     -2.656  .0210
CHEIGH       .293034  .226607    .292775    .132233       .806  .4359
CFINES       .299304  .294604    .474322    .133781      1.068  .3066
ASPECT      -.505171 -.388471    .289508    .120526     -1.460  .1699

End Block Number   4   All requested variables entered.
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Beginning Block Number  5.  Method:  Enter      BFVOLUM

Variable(s) Entered on Step Number  5..    BFVOLUM   BEACH FACE VOLUM

Multiple R            .73484                                         Analysis of Variance
R Square              .53998        R Square Change     .02956                           DF      Sum of Squares      Mean Square
Adjusted R Square     .34831        F Change            .77109       Regression           5          655.53035        131.10607
Standard Error       6.82186        Signif F Change     .3971        Residual            12          558.45410         46.53784

                                                                     F =       2.81719       Signif F =  .0657

------------------------------------ Variables in the Equation ------------------------------------

Variable              B           SE B        Beta     Correl Part Cor   Partial  Tolerance        T  Sig T

TIDAL          79.345535     95.678075     .181371   .267959  .162370   .232819    .801455      .829  .4231
BFHEIGH        -4.482616      3.757622   -.485423 -.380700 -.233569 -.325606    .231520    -1.193  .2559
BFWIDTH          .028877       .633647    .030313 -.560107  .008923   .013154    .086642      .046  .9644
BFSLOPE         2.265880      2.886810    .475217  .123677  .153679   .220982    .104580      .785  .4477
BFVOLUM         -.143472       .163386   -.410658 -.644788 -.171929 -.245719    .175282     -.878  .3971
(Constant)     20.323026     23.336033                                                        .871  .4009

------------------ Variables not in the Equation -------------------

Variable      Beta In  Partial  Tolerance  Min Toler         T  Sig T

BTHEIGH     -.977575 -.429477    .088788    .059055    -1.577  .1430
BTSLOPE      .575781  .679406    .640499    .084638     3.071  .0106
TVOLUM      -.664891 -.592154    .364874    .086514    -2.437  .0330
CHEIGH       .810780  .503972    .177738    .081868     1.935  .0791
CFINES       .254913  .172429    .210480    .043132      .581  .5732
ASPECT      -.455946 -.352124    .274372    .086547    -1.248  .2380

End Block Number   5   All requested variables entered.
```

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                              * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

Beginning Block Number  6.  Method:  Enter      BTHEIGH

Variable(s) Entered on Step Number  6..    BTHEIGH   BEACH TERRACE HEIGH

Multiple R           .79046                                          Analysis of Variance
R Square             .62483         R Square Change    .08485                          DF      Sum of Squares      Mean Square
Adjusted R Square    .42020         F Change          2.48784        Regression         6          758.53749        126.42291
Standard Error      6.43461         Signif F Change    .1430         Residual          11          455.44696         41.40427

                                                                     F =       3.05338       Signif F =  .0520

------------------------------------ Variables in the Equation ------------------------------------

Variable              B          SE B       Beta    Correl Part Cor  Partial  Tolerance         T  Sig T

TIDAL         34.640167     94.592933    .079182  .267959  .067630  .109747    .729500      .366  .7212
BFHEIGH       -5.192330      3.572764   -.562278 -.380700 -.268395 -.401349    .227848    -1.453  .1741
BFWIDTH         .215785       .609311    .226520 -.560107  .065403  .106175    .083365      .354  .7299
BFSLOPE        4.705016      3.131417    .986770  .123677  .277483  .412656    .079075     1.503  .1611
BFVOLUM        -.484483       .265505  -1.386729 -.644788 -.336993 -.482044    .059055    -1.825  .0953
BTHEIGH      -14.302843      9.067995   -.977575  .511219 -.291291 -.429477    .088788    -1.57   .1430
(Constant)    23.985926     22.133505                                                    1.084  .3017

------------------ Variables not in the Equation ------------------

Variable      Beta In  Partial  Tolerance  Min Toler          T  Sig T

BTSLOPE       .610371  .794742    .636046    .056923      4.141  .0020
TVOLUM      -1.449990 -.558150    .055590    .010204     -2.127  .0593
CHEIGH        .643310  .411453    .153471    .057227      1.428  .1839
CFINES        .170028  .126121    .206422    .035171       .402  .6961
ASPECT       -.199295 -.138404    .180938    .037685      -.442  .6679

End Block Number   6   All requested variables entered.
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Beginning Block Number  7.  Method:  Enter      BTSLOPE


Variable(s) Entered on Step Number  7..    BTSLOPE   BEACH TERRACE SLOPE


Multiple R           .92833                                           Analysis of Variance
R Square             .86179        R Square Change     .23696                           DF      Sum of Squares      Mean Square
Adjusted R Square    .76505        F Change          17.14551         Regression         7          1046.20457        149.45780
Standard Error      4.09609        Signif F Change     .0020          Residual          10           167.77988         16.77799

                                                                      F =       8.90797       Signif F =  .0013


------------------------------------ Variables in the Equation ------------------------------------

Variable              B          SE B        Beta     Correl Part Cor  Partial  Tolerance          T  Sig T

TIDAL         65.350973     60.670240     .149381   .267959  .126631  .322433    .718598       1.077  .3067
BFHEIGH       -5.290227      2.274444    -.572880 -.380700 -.273440 -.592513    .227823      -2.326  .0423
BFWIDTH        -.001302       .391398    -.001367 -.560107 -.000391 -.001052    .081869       -.003  .9974
BFSLOPE        3.772675      2.006048     .791233   .123677  .221091  .511151    .078079       1.881  .0894
BFVOLUM        -.349036       .172150    -.999039 -.644788 -.238357 -.539744    .056923      -2.028  .0701
BTHEIGH      -16.302710      5.792599   -1.114262   .511219 -.330864 -.664824    .088171      -2.814  .0183
BTSLOPE       10.195316      2.462213     .610371   .705327  .486786  .794742    .636046       4.141  .0020
(Constant)    20.953748     14.108581                                                           1.485  .1683


------------------ Variables not in the Equation ------------------

Variable      Beta In  Partial  Tolerance  Min Toler          T  Sig T

TVOLUM      -.512895 -.277564    .040476    .008413       -.867  .4086
CHEIGH       .374439  .383745    .145161    .054160       1.247  .2440
CFINES       .291877  .354528    .203906    .034308       1.137  .2847
ASPECT      -.396449 -.447545    .176127    .035365      -1.501  .1675


End Block Number   7   All requested variables entered.
```

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                                  * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

Beginning Block Number  8.  Method:  Enter      TVOLUM


End Block Number   8   Tolerance =     .010 Limits reached.
No variables entered for this block.





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Beginning Block Number 11.  Method:  Enter      ASPECT


Variable(s) Entered on Step Number 10..    ASPECT    ASPECT (BEARING PERPENDICULAR TO SHORE)


Multiple R           .96010                                        Analysis of Variance
R Square             .92180       R Square Change    .01914                          DF      Sum of Squares      Mean Square
Adjusted R Square    .81008       F Change          1.71324        Regression        10          1119.04754        111.90475
Standard Error      3.68272       Signif F Change    .2319         Residual           7            94.93691         13.56242

                                                                   F =       8.25109      Signif F =  .0052
```

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                                        * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

Beginning Block Number  9.  Method:  Enter      CHEIGH


Variable(s) Entered on Step Number  8..    CHEIGH    CLIFF HEIGHT


Multiple R           .93923                                              Analysis of Variance
R Square             .88215         R Square Change     .02035                                DF       Sum of Squares        Mean Square
Adjusted R Square    .77739         F Change           1.55422           Regression            8           1070.91185          133.86398
Standard Error      3.98710         Signif F Change     .2440            Residual              9            143.07259           15.89695

                                                                         F =       8.42073      Signif F =  .0022


------------------------------------ Variables in the Equation ------------------------------------

Variable            B         SE B        Beta    Correl Part Cor  Partial  Tolerance        T  Sig T

TIDAL       22.922164    68.160565     .052396  .267959  .038483  .111401    .539443     .336  .7444
BFHEIGH     -2.083692     3.393659    -.225643 -.380700 -.070261 -.200509    .096959    -.614  .5544
BFWIDTH       .099853      .389527     .104820 -.560107  .029334  .085137    .078317     .256  .8034
BFSLOPE      3.755254     1.952718     .787579  .123677  .220065  .539669    .078075    1.923  .0866
BFVOLUM      -.396226      .171791   -1.134111 -.644788 -.263933 -.609503    .054160   -2.306  .0465
BTHEIGH    -13.298377     6.131858    -.908921  .511219 -.248174 -.585858    .074552   -2.169  .0582
BTSLOPE      9.480413     2.464342     .567572  .705327  .440227  .788571    .601606    3.847  .0039
CHEIGH       3.493924     2.802580     .374439  .204525  .142661  .383745    .145161    1.247  .2440
(Constant)  -3.314494    23.822999                                                        -.139  .8924


------------------ Variables not in the Equation ------------------

Variable     Beta In  Partial  Tolerance  Min Toler        T  Sig T

TVOLUM     -.081715 -.036063    .022954    .004548     -.102  .9212
CFINES      .318106  .417179    .202695    .034174     1.298  .2303
ASPECT     -.341004 -.407978    .168693    .032244    -1.264  .2418


End Block Number   9   All requested variables entered.
```

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Beginning Block Number 10.  Method:  Enter      CFINES


Variable(s) Entered on Step Number  9..    CFINES    CLIFF FINES IN %


Multiple R            .95008                                              Analysis of Variance
R Square              .90266          R Square Change    .02051                              DF      Sum of Squares       Mean Square
Adjusted R Square     .79315          F Change          1.68568           Regression          9          1095.81192         121.75688
Standard Error       3.84338          Signif F Change    .2303            Residual            8           118.17253          14.77157

                                                                          F =        8.24265       Signif F =  .0034


------------------------------------ Variables in the Equation ------------------------------------

Variable               B          SE B          Beta     Correl Part Cor  Partial  Tolerance        T  Sig T

TIDAL          45.803822     68.026238       .104700   .267959  .074273  .231585    .503236      .673  .5197
BFHEIGH         1.337578      4.200650       .144847 -.380700  .035124  .111872    .058803      .318  .7583
BFWIDTH         -.343507       .507544     -.360596 -.560107 -.074657 -.232716    .042864     -.677  .5176
BFSLOPE          .985326      2.845129       .206650  .123677  .038202  .121535    .034174      .346  .7380
BFVOLUM         -.235371       .206815     -.673698 -.644788 -.125539 -.373286    .034724    -1.138  .2880
BTHEIGH       -12.135835      5.978265     -.829463  .511219 -.223924 -.583079    .072880    -2.030  .0769
BTSLOPE         9.759148      2.385194       .584259  .705327  .451331  .822586    .596732     4.092  .0035
CHEIGH          3.764972      2.709612       .403487  .204525  .153271  .440926    .144299     1.389  .2021
CFINES           .454402       .349988       .318106  .620054  .143217  .417179    .202695     1.298  .2303
(Constant)       .709564     23.172487                                                           .031  .9763


------------------ Variables not in the Equation ------------------

Variable     Beta In  Partial  Tolerance  Min Toler          T  Sig T

TVOLUM     -.496683 -.224275    .019847    .003309       -.609  .5618
ASPECT     -.336863 -.443424    .168669    .024344      -1.309  .2319


End Block Number  10   All requested variables entered.
```

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                                      * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
Beginning Block Number  8.  Method:  Enter      TVOLUM


End Block Number   8   Tolerance =     .010 Limits reached.
No variables entered for this block.
```

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Beginning Block Number 11.  Method:  Enter      ASPECT


Variable(s) Entered on Step Number 10..     ASPECT    ASPECT (BEARING PERPENDICULAR TO SHORE)


Multiple R           .96010                                          Analysis of Variance
R Square             .92180          R Square Change    .01914                          DF       Sum of Squares       Mean Square
Adjusted R Square    .81008          F Change          1.71324       Regression         10           1119.04754         111.90475
Standard Error      3.68272          Signif F Change    .2319        Residual            7             94.93691          13.56242

                                                                     F =       8.25109       Signif F =  .0052
```

```
Listwise Deletion of Missing Data

Equation Number 1    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter     ASPECT


Variable(s) Entered on Step Number  1..    ASPECT    ASPECT (BEARING PERPENDICULAR TO SHORE)


Multiple R           .20673                                            Analysis of Variance
R Square             .04274        R Square Change    .04274                               DF      Sum of Squares       Mean Square
Adjusted R Square    .03600        F Change          6.33991           Regression           1          1052.57654        1052.57654
Standard Error     12.88503        Signif F Change    .0129            Residual           142         23575.41006         166.02401

                                                                       F =       6.33991      Signif F =  .0129

------------------------------------ Variables in the Equation ------------------------------------

Variable              B         SE B       Beta   Correl Part Cor  Partial  Tolerance        T  Sig T

ASPECT          .074731      .029680    .206734  .206734  .206734  .206734   1.000000    2.518  .0129
(Constant)   -10.901327     9.594420                                                    -1.136  .2578

End Block Number   1   All requested variables entered.


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                                              Summary table
                                              -------------

Step   MultR    Rsq  AdjRsq    F(Eqn)  SigF   RsqCh     FCh SigCh      Variable  BetaIn  Correl
   1   .2067  .0427   .0360     6.340  .013   .0427   6.340  .013  In:  ASPECT     .2067   .2067    ASPECT (BEARING PERPENDICULAR


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```

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Equation Number 2    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      STRENGT


Variable(s) Entered on Step Number  1..    STRENGT   STRENGTH OF CLIFF FACIES


Multiple R             .02431                                             Analysis of Variance
R Square               .00059         R Square Change     .00059                             DF      Sum of Squares      Mean Square
Adjusted R Square    -.00645          F Change            .08394          Regression           1         14.55037         14.55037
Standard Error      13.16564          Signif F Change     .7724           Residual           142      24613.43622        173.33406

                                                                          F =        .08394       Signif F =  .7724


------------------------------------ Variables in the Equation ------------------------------------

Variable               B         SE B        Beta    Correl Part Cor  Partial  Tolerance         T  Sig T

STRENGT      3.24754E-05  1.1209E-04    .024307  .024307  .024307  .024307   1.000000      .290  .7724
(Constant)     12.898403    1.308238                                                       9.859  .0000


End Block Number   1   All requested variables entered.


                                       * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                                        Summary table
                                                        -------------

Step    MultR     Rsq  AdjRsq     F(Eqn)  SigF    RsqCh       FCh SigCh      Variable  BetaIn  Correl
   1    .0243   .0006  -.0064       .084  .772    .0006      .084  .772  In:  STRENGT    .0243   .0243   STRENGTH OF CLIFF FACIES


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```

```
Equation Number 3    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      PROTECT


Variable(s) Entered on Step Number  1..    PROTECT   PROTECTIVE FEATURES


Multiple R           .40710                                           Analysis of Variance
R Square             .16573          R Square Change    .16573                          DF      Sum of Squares       Mean Square
Adjusted R Square    .15985          F Change         28.20810        Regression         1          4081.52539        4081.52539
Standard Error     12.02886          Signif F Change    .0000         Residual         142         20546.46121         144.69339

                                                                      F =      28.20810       Signif F =  .0000

------------------------------------ Variables in the Equation ------------------------------------

Variable              B         SE B       Beta   Correl Part Cor  Partial  Tolerance        T  Sig T

PROTECT      -13.109298     2.468269   -.407096 -.407096 -.407096 -.407096   1.000000   -5.311  .0000
(Constant)    28.945263     3.146438                                                     9.199  .0000

End Block Number   1   All requested variables entered.


                            * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                                Summary table
                                                -------------

Step    MultR     Rsq  AdjRsq    F(Eqn)  SigF   RsqCh      FCh SigCh      Variable  BetaIn  Correl
   1    .4071   .1657   .1599    28.208  .000   .1657   28.208  .000  In: PROTECT   -.4071  -.4071    PROTECTIVE FEATURES


                            * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

```
Equation Number 4    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      HTBEACH


Variable(s) Entered on Step Number  1..    HTBEACH   HEIGHT OF BEACH AT FOOT OF CLIFF


Multiple R           .16223                                          Analysis of Variance
R Square             .02632         R Square Change    .02632                             DF      Sum of Squares      Mean Square
Adjusted R Square    .01946         F Change          3.83823        Regression            1           648.17014        648.17014
Standard Error     12.99507         Signif F Change    .0521         Residual            142         23979.81646        168.87195

                                                                     F =        3.83823        Signif F =  .0521


------------------------------------ Variables in the Equation ------------------------------------

Variable              B         SE B       Beta    Correl Part Cor  Partial  Tolerance        T  Sig T

HTBEACH       -1.151399      .587706   -.162230 -.162230 -.162230 -.162230   1.000000   -1.959  .0521
(Constant)    17.795212     2.627616                                                     6.772  .0000


End Block Number   1   All requested variables entered.


                                  * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                                         Summary table
                                                         -------------

Step   MultR    Rsq  AdjRsq    F(Eqn)  SigF   RsqCh      FCh SigCh      Variable  BetaIn  Correl
   1   .1622  .0263   .0195     3.838  .052   .0263    3.838  .052  In:  HTBEACH   -.1622  -.1622    HEIGHT OF BEACH AT FOOT OF CL


                                  * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
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```
Equation Number 5    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      TIDAL


Variable(s) Entered on Step Number  1..    TIDAL     TIDAL COVERAGE %


Multiple R           .05163                                            Analysis of Variance
R Square             .00267         R Square Change     .00267                              DF      Sum of Squares      Mean Square
Adjusted R Square   -.00436         F Change            .37958         Regression            1            65.65769         65.65769
Standard Error     13.15196         Signif F Change     .5388          Residual            142         24562.32890        172.97415

                                                                       F =        .37958       Signif F =  .5388

------------------------------------ Variables in the Equation ------------------------------------

Variable             B         SE B        Beta   Correl Part Cor  Partial  Tolerance         T  Sig T

TIDAL         -.093388      .151578   -.051633 -.051633 -.051633 -.051633   1.000000     -.616  .5388
(Constant)   13.388450     1.188731                                                      11.263  .0000

End Block Number   1   All requested variables entered.


                                        * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                                                 Summary table
                                                                 -------------

Step    MultR     Rsq  AdjRsq     F(Eqn)  SigF   RsqCh       FCh SigCh       Variable  BetaIn  Correl
   1    .0516   .0027  -.0044       .380  .539   .0027      .380  .539  In:  TIDAL     -.0516  -.0516    TIDAL COVERAGE %


                                        * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
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```
Equation Number 6    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      BFWIDTH

Variable(s) Entered on Step Number  1..    BFWIDTH   BEACH FACE WIDTH

Multiple R            .28725                                        Analysis of Variance
R Square              .08251       R Square Change     .08251                          DF      Sum of Squares      Mean Square
Adjusted R Square     .07605       F Change          12.77016       Regression          1        2032.06712       2032.06712
Standard Error      12.61452       Signif F Change     .0005        Residual          142       22595.91948        159.12619

                                                                    F =       12.77016       Signif F =  .0005

------------------------------------ Variables in the Equation ------------------------------------

Variable              B         SE B       Beta   Correl Part Cor  Partial  Tolerance        T  Sig T

BFWIDTH         -.284430     .079593   -.287246 -.287246 -.287246 -.287246   1.000000   -3.574  .0005
(Constant)     21.375053    2.541844                                                      8.409  .0000

End Block Number   1   All requested variables entered.


                          * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                        Summary table
                                        -------------

Step   MultR    Rsq  AdjRsq   F(Eqn)  SigF   RsqCh     FCh SigCh      Variable  BetaIn  Correl
   1   .2872  .0825   .0760   12.770  .000   .0825   12.770  .000 In: BFWIDTH   -.2872  -.2872   BEACH FACE WIDTH


                          * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
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```
Equation Number 7    Dependent Variable..   RRATE    RECESSION RATE

Beginning Block Number  1.  Method:  Enter      BFSLOPE


Variable(s) Entered on Step Number  1..    BFSLOPE   BEACH FACE SLOPE


Multiple R           .06295                                                 Analysis of Variance
R Square             .00396          R Square Change     .00396                                    DF      Sum of Squares      Mean Square
Adjusted R Square   -.00305          F Change            .56489             Regression              1            97.58419         97.58419
Standard Error     13.14341          Signif F Change     .4535              Residual              142         24530.40241        172.74931

                                                                            F =        .56489       Signif F =  .4535


------------------------------------- Variables in the Equation -------------------------------------

Variable              B        SE B       Beta  Correl Part Cor  Partial  Tolerance        T  Sig T

BFSLOPE        -.395655     .526423  -.062947 -.062947 -.062947 -.062947   1.000000     -.752  .4535
(Constant)    16.111565    4.147683                                                     3.884  .0002


End Block Number   1   All requested variables entered.


                                      * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                                          Summary table
                                                          -------------

Step   MultR     Rsq   AdjRsq    F(Eqn)  SigF   RsqCh      FCh  SigCh   In:  Variable   BetaIn   Correl     BEACH FACE SLOPE
   1   .0629   .0040   -.0031      .565  .454   .0040     .565   .454   In:  BFSLOPE    -.0629   -.0629     BEACH FACE SLOPE


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```
Equation Number 8    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      BFVOLUM


Variable(s) Entered on Step Number  1..    BFVOLUM   BEACH FACE VOLUME


                                                                  Analysis of Variance
Multiple R            .33851                                                       DF      Sum of Squares      Mean Square
R Square              .11459          R Square Change     .11459      Regression         1          2822.09959       2822.09959
Adjusted R Square     .10835          F Change          18.37752      Residual         142         21805.88700        153.56258
Standard Error      12.39204          Signif F Change     .0000
                                                                  F =       18.37752       Signif F =  .0000


------------------------------------ Variables in the Equation ------------------------------------

Variable              B         SE B       Beta    Correl Part Cor  Partial  Tolerance        T  Sig T

BFVOLUM         -.074520     .017383   -.338510 -.338510 -.338510 -.338510   1.000000    -4.287  .0000
(Constant)     17.702304    1.488803                                                     11.890  .0000


End Block Number   1   All requested variables entered.


                             * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                              Summary table
                                              -------------

Step   MultR     Rsq   AdjRsq    F(Eqn)  SigF   RsqCh      FCh SigCh      Variable  BetaIn  Correl
  1    .3385   .1146    .1084    18.378  .000   .1146   18.378  .000   In:  BFVOLUM  -.3385  -.3385     BEACH FACE VOLUME


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```
Equation Number 9    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      BTHEIGH


Variable(s) Entered on Step Number  1..    BTHEIGH   BEACH TERRACE HEIGHT


Multiple R            .21874                                          Analysis of Variance
R Square              .04785        R Square Change    .04785                             DF      Sum of Squares      Mean Square
Adjusted R Square     .04114        F Change          7.13549         Regression           1          1178.34333       1178.34333
Standard Error      12.85062        Signif F Change    .0084          Residual           142         23449.64327        165.13833

                                                                      F =       7.13549      Signif F =  .0084


------------------------------------ Variables in the Equation ------------------------------------

Variable              B         SE B       Beta    Correl Part Cor  Partial  Tolerance        T  Sig T

BTHEIGH       3.256269     1.219013    .218737  .218737  .218737  .218737   1.000000    2.671  .0084
(Constant)   11.938031     1.156546                                                     10.322  .0000


End Block Number   1   All requested variables entered.



                                   * * * * * * * * * * * * * * * * * * * * * * * * * * * * *



                                                     Summary table
                                                     -------------

Step    MultR     Rsq   AdjRsq     F(Eqn)  SigF    RsqCh      FCh SigCh     Variable  BetaIn  Correl
   1    .2187   .0478    .0411      7.135  .008    .0478     7.135  .008  In:  BTHEIGH    .2187   .2187     BEACH TERRACE HEIGHT



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```
Equation Number 10    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      BTSLOPE


Variable(s) Entered on Step Number  1..    BTSLOPE   BEACH TERRACE SLOPE


Multiple R            .07459                                          Analysis of Variance
R Square              .00556        R Square Change     .00556                           DF      Sum of Squares      Mean Square
Adjusted R Square   -.00144         F Change            .79448         Regression          1           137.02504        137.02504
Standard Error     13.13284         Signif F Change     .3743          Residual          142         24490.96155        172.47156

                                                                       F =        .79448       Signif F =  .3743


------------------------------------ Variables in the Equation ------------------------------------

Variable               B          SE B        Beta    Correl Part Cor  Partial  Tolerance         T  Sig T

BTSLOPE         2.705517      3.035352     .074591  .074591  .074591  .074591   1.000000       .891  .3743
(Constant)     10.463224      3.159294                                                        3.312  .0012


End Block Number    1   All requested variables entered.



                             * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                                Summary table
                                                -------------

Step    MultR     Rsq  AdjRsq     F(Eqn)  SigF   RsqCh      FCh SigCh      Variable  BetaIn   Correl
   1    .0746   .0056  -.0014       .794  .374   .0056      .794  .374  In:  BTSLOPE     .0746    .0746    BEACH TERRACE SLOPE



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Equation Number 11    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      BTVOLUM

Variable(s) Entered on Step Number  1..    BTVOLUM   BEACH TERRACE VOLUME

Multiple R           .04290                                     Analysis of Variance
R Square             .00184        R Square Change     .00184                       DF       Sum of Squares      Mean Square
Adjusted R Square   -.00519        F Change            .26180   Regression           1            45.32135         45.32135
Standard Error     13.15741        Signif F Change     .6097    Residual           142         24582.66525        173.11736

                                                                F =        .26180       Signif F =  .6097

------------------------------------ Variables in the Equation ------------------------------------

Variable              B        SE B       Beta     Correl Part Cor  Partial  Tolerance        T  Sig T

BTVOLUM        -.007392     .014448   -.042898 -.042898 -.042898 -.042898   1.000000     -.512  .6097
(Constant)    13.775882    1.709425                                                       8.059  .0000

End Block Number   1   All requested variables entered.


                                          * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                                            Summary table
                                                            -------------

Step    MultR     Rsq  AdjRsq    F(Eqn)  SigF   RsqCh      FCh SigCh      Variable  BetaIn  Correl
   1    .0429   .0018  -.0052      .262  .610   .0018     .262  .610  In:  BTVOLUM   -.0429  -.0429    BEACH TERRACE VOLUME
```

```
Equation Number 1    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      TIDAL


Variable(s) Entered on Step Number  1..    TIDAL     TIDAL COVERAGE IN %


Multiple R           .26796                                            Analysis of Variance
R Square             .07180          R Square Change     .07180                              DF      Sum of Squares      Mean Square
Adjusted R Square    .01379          F Change           1.23770        Regression             1            87.16668         87.16668
Standard Error      8.39203          Signif F Change     .2824         Residual              16          1126.81777         70.42611

                                                                       F =       1.23770       Signif F =  .2824


------------------------------------ Variables in the Equation ------------------------------------

Variable              B          SE B        Beta     Correl Part Cor  Partial  Tolerance         T  Sig T

TIDAL         117.226037  105.369688    .267959  .267959  .267959  .267959   1.000000      1.113  .2824
(Constant)      8.629775    4.922392                                                        1.753  .0987


End Block Number   1   All requested variables entered.


                              * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                                 Summary table
                                                 -------------

Step    MultR      Rsq   AdjRsq     F(Eqn)  SigF    RsqCh       FCh SigCh        Variable  BetaIn  Correl
   1    .2680    .0718    .0138      1.238  .282    .0718     1.238  .282   In:  TIDAL       .2680   .2680    TIDAL COVERAGE IN %


                              * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
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```
Equation Number 2    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      BFHEIGH


Variable(s) Entered on Step Number  1..    BFHEIGH   BEACH FACE HEIGHT


Multiple R           .38070                                        Analysis of Variance
R Square             .14493        R Square Change    .14493                           DF       Sum of Squares       Mean Square
Adjusted R Square    .09149        F Change          2.71197       Regression           1            175.94553         175.94553
Standard Error      8.05465        Signif F Change    .1191        Residual            16           1038.03892          64.87743

                                                                   F =       2.71197       Signif F =  .1191


------------------------------------ Variables in the Equation ------------------------------------

Variable              B          SE B       Beta   Correl Part Cor  Partial  Tolerance         T  Sig T

BFHEIGH       -3.515551      2.134770  -.380700 -.380700 -.380700 -.380700   1.000000    -1.647  .1191
(Constant)    29.366771      9.734100                                                     3.017  .0082

End Block Number   1   All requested variables entered.


                                        * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                                          Summary table
                                                          -------------

Step    MultR     Rsq   AdjRsq     F(Eqn)  SigF   RsqCh       FCh SigCh      Variable  BetaIn  Correl
   1    .3807   .1449    .0915      2.712  .119   .1449     2.712  .119  In:  BFHEIGH   -.3807  -.3807    BEACH FACE HEIGHT


                                        * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
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```
Equation Number 3    Dependent Variable..   RRATE    RECESSION RATE

Beginning Block Number  1.  Method:  Enter      BFWIDTH


Variable(s) Entered on Step Number  1..    BFWIDTH   BEACH FACE WIDTH


Multiple R            .56011                                          Analysis of Variance
R Square              .31372          R Square Change    .31372                          DF      Sum of Squares      Mean Square
Adjusted R Square     .27083          F Change          7.31411      Regression           1           380.85143        380.85143
Standard Error       7.21601          Signif F Change    .0156       Residual            16           833.13302         52.07081

                                                                     F =       7.31411       Signif F =  .0156


------------------------------------ Variables in the Equation -------------------------------------

Variable              B         SE B       Beta    Correl Part Cor  Partial  Tolerance         T  Sig T

BFWIDTH         -.533563     .197290   -.560107 -.560107 -.560107 -.560107   1.000000    -2.704  .0156
(Constant)     30.777749    6.559544                                                      4.692  .0002


End Block Number   1   All requested variables entered.



                            * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                                    Summary table
                                                    -------------

Step   MultR     Rsq   AdjRsq     F(Eqn)  SigF    RsqCh      FCh SigCh      Variable  BetaIn   Correl
   1   .5601   .3137    .2708      7.314  .016    .3137    7.314  .016  In:  BFWIDTH   -.5601   -.5601     BEACH FACE WIDTH


                            * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
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```
Equation Number 4    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      BFSLOPE


Variable(s) Entered on Step Number  1..    BFSLOPE   BEACH FACE SLOPE


Multiple R           .12368                                          Analysis of Variance
R Square             .01530        R Square Change    .01530                              DF      Sum of Squares      Mean Square
Adjusted R Square  -.04625         F Change           .24854         Regression            1            18.56913         18.56913
Standard Error     8.64369         Signif F Change    .6249          Residual             16          1195.41532         74.71346

                                                                     F =        .24854       Signif F =  .6249

------------------------------------ Variables in the Equation ------------------------------------

Variable              B        SE B       Beta   Correl Part Cor  Partial  Tolerance        T  Sig T

BFSLOPE         .589704    1.182872    .123677  .123677  .123677  .123677   1.000000     .499  .6249
(Constant)     8.933364    9.666960                                                      .924  .3692

End Block Number   1   All requested variables entered.


                                   * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                                 Summary table
                                                 -------------

Step    MultR     Rsq  AdjRsq     F(Eqn)  SigF    RsqCh       FCh SigCh     Variable   BetaIn   Correl
   1    .1237   .0153  -.0462       .249  .625    .0153      .249  .625  In: BFSLOPE     .1237    .1237    BEACH FACE SLOPE


                                   * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

```
Equation Number 5    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      BFVOLUM

Variable(s) Entered on Step Number  1..    BFVOLUM   BEACH FACE VOLUM

Multiple R           .64479                                          Analysis of Variance
R Square             .41575          R Square Change    .41575                             DF      Sum of Squares      Mean Square
Adjusted R Square    .37924          F Change         11.38560       Regression             1           504.71573        504.71573
Standard Error      6.65802          Signif F Change    .0039        Residual              16           709.26872         44.32929

                                                                     F =       11.38560       Signif F =  .0039

------------------------------------ Variables in the Equation ------------------------------------

Variable              B         SE B       Beta   Correl Part Cor  Partial  Tolerance         T  Sig T

BFVOLUM       -.225270      .066761  -.644788 -.644788 -.644788 -.644788   1.000000    -3.374  .0039
(Constant)   27.861507     4.496155                                                      6.197  .0000

End Block Number   1   All requested variables entered.


                                    * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                                        Summary table
                                                        -------------

Step   MultR     Rsq  AdjRsq    F(Eqn)  SigF   RsqCh      FCh SigCh       Variable  BetaIn  Correl
   1   .6448   .4158   .3792    11.386  .004   .4158   11.386  .004  In:  BFVOLUM   -.6448  -.6448    BEACH FACE VOLUM


                                    * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

```
Equation Number 6    Dependent Variable..   RRATE    RECESSION RATE

Beginning Block Number  1.  Method:  Enter      BTHEIGH


Variable(s) Entered on Step Number  1..    BTHEIGH   BEACH TERRACE HEIGH


Multiple R            .51122                                         Analysis of Variance
R Square              .26135        R Square Change    .26135                              DF      Sum of Squares       Mean Square
Adjusted R Square     .21518        F Change          5.66100        Regression             1           317.26902         317.26902
Standard Error       7.48630        Signif F Change    .0301         Residual              16           896.71542          56.04471

                                                                     F =        5.66100       Signif F =  .0301

------------------------------------ Variables in the Equation ------------------------------------

Variable               B         SE B        Beta   Correl Part Cor  Partial  Tolerance        T  Sig T

BTHEIGH         7.479624     3.143643     .511219  .511219  .511219  .511219   1.000000    2.379  .0301
(Constant)     12.314734     1.850927                                                       6.653  .0000

End Block Number   1   All requested variables entered.


                                      * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                                        Summary table
                                                        -------------

Step   MultR     Rsq   AdjRsq    F(Eqn)  SigF   RsqCh      FCh  SigCh      Variable  BetaIn  Correl
   1   .5112   .2613   .2152     5.661  .030   .2613    5.661   .030  In:  BTHEIGH    .5112   .5112    BEACH TERRACE HEIGH


                                      * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

```
Equation Number 7    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      BTSLOPE


Variable(s) Entered on Step Number  1..    BTSLOPE   BEACH TERRACE SLOPE


Multiple R           .70533                                                  Analysis of Variance
R Square             .49749          R Square Change     .49749                                     DF      Sum of Squares       Mean Square
Adjusted R Square    .46608          F Change          15.83996              Regression              1           603.94124         603.94124
Standard Error      6.17476          Signif F Change     .0011               Residual               16           610.04321          38.12770

                                                                             F =       15.83996       Signif F =  .0011

------------------------------------ Variables in the Equation ------------------------------------

Variable              B         SE B       Beta    Correl Part Cor  Partial  Tolerance         T  Sig T

BTSLOPE       11.781410     2.960194    .705327  .705327  .705327  .705327   1.000000     3.980  .0011
(Constant)     3.957508     2.835887                                                      1.396  .1819

End Block Number   1   All requested variables entered.


                             * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                                Summary table
                                                -------------

Step    MultR     Rsq  AdjRsq    F(Eqn)  SigF    RsqCh      FCh SigCh      Variable  BetaIn   Correl
   1    .7053   .4975   .4661    15.840  .001    .4975   15.840  .001  In: BTSLOPE     .7053    .7053     BEACH TERRACE SLOPE


                             * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

```
Equation Number 8    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      TVOLUM


Variable(s) Entered on Step Number  1..    TVOLUM    TOTAL VOLUME


Multiple R           .50196                                              Analysis of Variance
R Square             .25197         R Square Change    .25197                                DF      Sum of Squares       Mean Square
Adjusted R Square    .20521         F Change          5.38942            Regression           1           305.88370         305.88370
Standard Error      7.53368         Signif F Change    .0338             Residual            16           908.10075          56.75630

                                                                         F =       5.38942       Signif F =  .0338


------------------------------------ Variables in the Equation ------------------------------------

Variable              B        SE B       Beta   Correl Part Cor  Partial  Tolerance        T  Sig T

TVOLUM        -.362240     .156036  -.501963 -.501963 -.501963 -.501963   1.000000   -2.322  .0338
(Constant)   38.920763   11.031713                                                     3.528  .0028


End Block Number   1   All requested variables entered.


                                   * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                                      Summary table
                                                      -------------

Step   MultR     Rsq  AdjRsq    F(Eqn)  SigF    RsqCh     FCh SigCh      Variable   BetaIn   Correl
   1   .5020   .2520   .2052     5.389  .034    .2520   5.389  .034  In: TVOLUM     -.5020   -.5020    TOTAL VOLUME


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Equation Number 9    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      CHEIGH


Variable(s) Entered on Step Number  1..    CHEIGH    CLIFF HEIGHT


Multiple R            .20452                                       Analysis of Variance
R Square              .04183      R Square Change     .04183                           DF      Sum of Squares      Mean Square
Adjusted R Square   -.01806       F Change            .69850       Regression            1           50.78134         50.78134
Standard Error      8.52644       Signif F Change     .4156        Residual             16         1163.20310         72.70019

                                                                   F =        .69850       Signif F =  .4156

------------------------------------ Variables in the Equation ------------------------------------

Variable             B         SE B       Beta    Correl Part Cor  Partial  Tolerance        T  Sig T

CHEIGH        1.908435     2.283459    .204525  .204525  .204525  .204525   1.000000     .836  .4156
(Constant)    7.272391     7.884640                                                      .922  .3700

End Block Number   1   All requested variables entered.


                         * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                           Summary table
                                           -------------

Step    MultR     Rsq  AdjRsq     F(Eqn)  SigF   RsqCh      FCh SigCh     Variable  BetaIn  Correl
   1    .2045   .0418  -.0181       .699  .416   .0418     .699  .416  In:  CHEIGH    .2045   .2045    CLIFF HEIGHT


                         * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

```
Equation Number 10    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      CFINES


Variable(s) Entered on Step Number  1..    CFINES    CLIFF FINES IN %


Multiple R           .62005                                             Analysis of Variance
R Square             .38447         R Square Change    .38447                             DF      Sum of Squares       Mean Square
Adjusted R Square    .34600         F Change          9.99371          Regression            1          466.73628         466.73628
Standard Error      6.83396         Signif F Change    .0061           Residual             16          747.24816          46.70301

                                                                        F =        9.99371       Signif F =  .0061


------------------------------------ Variables in the Equation ------------------------------------

Variable              B          SE B       Beta   Correl Part Cor  Partial  Tolerance        T  Sig T

CFINES           .885722      .280178    .620054  .620054  .620054  .620054   1.000000    3.161  .0061
(Constant)      4.738015     3.245313                                                     1.460  .1637


End Block Number   1   All requested variables entered.



                          * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                          Summary table
                                          -------------

Step    MultR     Rsq  AdjRsq     F(Eqn)  SigF   RsqCh      FCh SigCh      Variable  BetaIn  Correl
   1    .6201   .3845   .3460      9.994  .006   .3845    9.994  .006  In:  CFINES     .6201   .6201    CLIFF FINES IN %


                          * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

```
Equation Number 11    Dependent Variable..   RRATE   RECESSION RATE

Beginning Block Number  1.  Method:  Enter      ASPECT


Variable(s) Entered on Step Number  1..    ASPECT    ASPECT (BEARING PERPENDICULAR TO SHORE)


Multiple R            .04813                                      Analysis of Variance
R Square              .00232       R Square Change    .00232                           DF      Sum of Squares       Mean Square
Adjusted R Square    -.06004       F Change           .03715      Regression            1             2.81240           2.81240
Standard Error       8.70047       Signif F Change    .8496       Residual             16          1211.17205          75.69825

                                                                  F =        .03715       Signif F =  .8496


------------------------------------ Variables in the Equation ------------------------------------

Variable              B         SE B       Beta     Correl Part Cor  Partial  Tolerance        T  Sig T

ASPECT         .018135      .094087    .048132  .048132  .048132  .048132   1.000000     .193  .8496
(Constant)    8.008367    29.312109                                                       .273  .7882

End Block Number   1   All requested variables entered.


                                         * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                                                    Summary table
                                                    -------------

Step   MultR     Rsq  AdjRsq    F(Eqn)  SigF   RsqCh      FCh SigCh      Variable  BetaIn  Correl
   1   .0481   .0023  -.0600      .037  .850   .0023     .037  .850  In:  ASPECT       .0481   .0481    ASPECT (BEARING PERPENDICULAR
```