

## HOLOCENE SEA LEVEL CHANGES, CUMBERLAND COAST, NORTHWEST ENGLAND: EUSTATIC AND GLACIO-ISOSTATIC MOVEMENTS

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### ABSTRACT

Radiocarbon dates on materials from storm-eroded coastal sections plus other dates from peats and wood now below current high tide level are used to construct a preliminary history of relative sea level movement and to derive isostatic and eustatic components of the sea-level changes. Sea-level rose 22 m, relative to the land between 9,200 and 6,000 BP. No information is available for sea-level between 6,000 and 3,600 BP but it was probably slightly higher than present. The main Postglacial Beach along this stretch of coast, and the highest evidence of marine action, is ca. 5 m above average high spring tide level. Shells in this beach date from 2,300±BP which suggests that at least storm waves were reaching these elevations 3,000 years or so after the usually accepted age for the feature. Relative sea-level changes after 3,600 BP were complex and there is at least one soil forming interval recorded. The high coastal sand dunes backing this stretch of coast date from between 1,200 and 1,500 BP. The estimated glacio-isostatic recovery is ca. 18 m over the last 13,000 years. Computed eustatic curves indicate fluctuations in world sea-level in the last 5,000 years but these fluctuations could be caused by variations in storminess.

### INTRODUCTION

The aim of this paper is to present evidence for relative sea-level movements along the southern Cumberland coast, NW England (fig. 1) for the period 9,000 BP to the present and then to use these data to evaluate the local glacio-isostatic recovery of the region and the world-wide eustatic sea-level changes.

On Monday 27th February 1967, the southern coast of Cumberland experienced significant flooding of the lowlands

and major coastal erosion as the result of heavy rains (1.22 cm in 24 hours), and a southerly gale blowing from the direction of the incoming tide. The normal tide of 9.52 m was raised by 0.91 m (Lancashire River Authority, 1967) and conditions were described as "abnormal" and the worst for about 60 years. One result of the high tide, and accompanying wave erosion at heights well above normal spring tide level, was to cause considerable cutting into the dune systems that fringe part of the coast, exposing the stratigraphy. The coast was visited by Andrews in 1967/1968 and again in 1969/1970, and by King in 1969 and 1971. Materials collected at that time were processed by Stuiver at the Radiocarbon Laboratory, Yale University. Some of our dates have been reported in Radiocarbon 11 (Stuiver, 1969).

### REGIONAL SETTING - GLACIAL HISTORY

The coastal lowland of Cumberland is a narrow strip of land running around the previously glaciated massive of the Lake District (fig. 1). The area supported its own valley glacier system during the last glaciation and may have been completely inundated by an ice cap. The exact extent and thickness of the ice at this time is uncertain (West, 1968; Penny, 1964) but ice from the Lake District joined with Scottish ice in the Irish Sea basin (fig. 1) and flowed south possibly reaching as far as the coast of south Wales (West, 1968). Dates on marine shells suggest this readvance dates from around 25,000 BP (John, 1965; Worsley, 1970).

The thickness of ice over the southern Cumberland coast can be estimated from a formula developed by Nyé (1959). The formula has given reasonable fits for existing ice sheets (e.g. Hollin, 1962). Using a margin in the vicinity of south Wales the estimated maximum ice thickness over our study area is ca. 2,000 m. The amount of isostatic deflection caused by the ice load is in part controlled by the density of ice and displaced mantle material but it is also a function of the length of the crustal flexural parameter, (Walcott, 1970a and b; Brochie and Silvester, 1969). No values for this parameter have been obtained from Great

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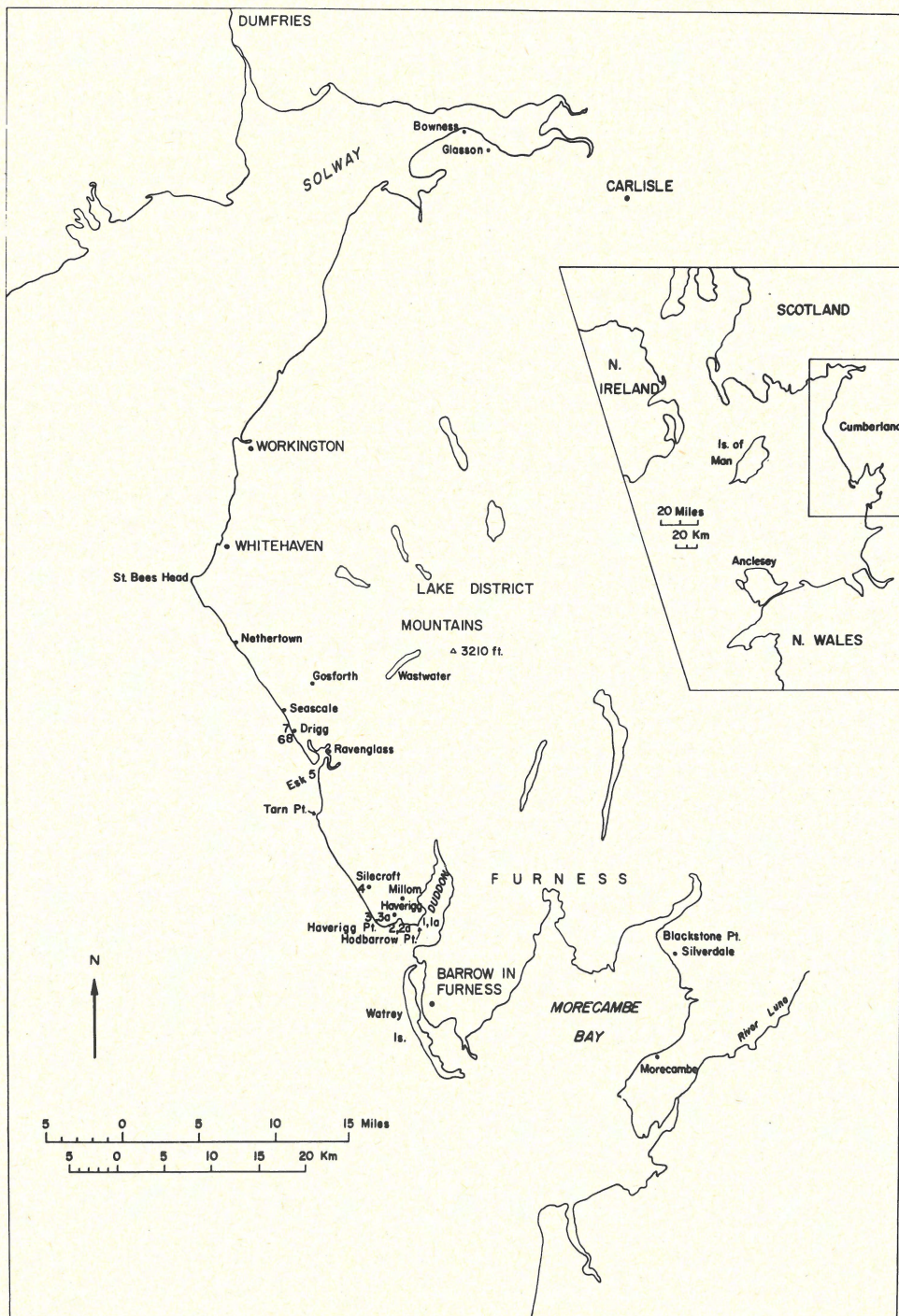


Fig. 1

Map of the south Cumberland coast and neighbouring region showing location of sites radiocarbon dated (3, 3a, etc. — see table 2). Insert map shows the Cumberland coast in its regional setting.

Britain but in the region covered by the Laurentide Ice Sheet a typical value is 200 km (Walcott, 1970b; Andrews, 1971). Shorter values have been obtained from pluvial Lake Bonneville. The length of the flexural parameter is a measure of how far a point on the surface is effected by loads up to some radius  $\alpha$ . Using a program developed by Brothie and Silvester (1969) and crustal flexural parameters of 50-200 km, and densities of 0.9 and 3.37 gm cm<sup>-3</sup> for ice and mantle materials, the estimated equilibrium isostatic depression would have been 400 to 500 m along the south Cumberland coast at the maximum of the glaciation.

The date of deglaciation of the south Cumberland coast is currently unknown. The probable date of deglaciation can be bracketed with moderate precision because of controls provided from areas to the south and north of the area. To the south a <sup>14</sup>C date of 16,830<sup>+970</sup><sub>-860</sub> BP led Saunders (1968) to suggest that ice was in the vicinity of the north Welsh coast at this time. An older date, however, of 18,990±300 BP (B-213) was obtained by Coope (in Thomas, 1971, p. 40) from the base of a kettle hole on the Isle of Man (fig. 1 - inset) due west of the south Cumberland coast and in direct line with ice moving from Scotland toward north Wales. One hundred kilometers to the north of the field area, deglaciation occurred prior to 12,290±250 BP (Q-816), a date from Redkirk Point, Dumfriesshire (Godwin and Switsur, 1966), on peat approximately 2 m below normal high water level. Regional syntheses on the pattern and timing of deglaciation (e.g. Sissons, 1967; Penny, 1964; and West, 1968) show the south coast of Cumberland lying on the distal side of the ice margin at the time of the Scottish Readvance. In view of these various dates we suggest that the south coast of Cumberland became ice free approximately 14,000 years ago with limits of ± 1,000 years.

One further aspect requires comment: the evidence for glacio-isostasy has long been recognized in Great Britain and elsewhere but less attention has been paid to the complementary crustal movements that result from loading the earth's continental margins by the Holocene sea level rise. In some areas the effect of hydro-isostatic loading has recently been judged to be very significant (Bloom, 1967; Higgins, 1965; Mörrer, 1969; Grant, 1970). The effect of the water load is to cause subsidence of the crust relative to an absolute datum. Examination of British Admiralty Chart 1826 indicates that depths in the Irish Sea between the Isle of Man and the Cumberland coast are shallow with a maximum depth of 40 m and most off-shore depths are in the vicinity of 25 m. The major problem in computing the point load for eustatic sea-level rise as it effects the south Cumberland coast is the radius over which the load should be averaged. Bloom (1967) and Grant (1970) used a radius of 50 km and obtained satisfactory comparisons with field data. With a radius of 50 km, the hydro-isostatic load on the south Cumberland coast, allowing for density differences between the sea water and the mantle rock, gives an effective load of only 3±2 m. This is a low value, comparable to the

Florida Everglades which Bloom (1967) judged to be a relatively stable coast.

## PREVIOUS WORK

Little detailed work on sea-level changes, and few published dates, are available for the south coast of Cumberland. There are, however, results published for adjoining areas relating to changes of sea-level in the post-glacial period. A review paper was published by Donner (1970) who describes land/sea-level changes in Scotland, and Churchill (1965) discussed the amount and form of crustal movement in Great Britain over the last 6,500 years.

Walker (1956) described the deposits at St. Bees, and (Walker, 1966-7) along the northern Cumberland coast (fig. 1). The latter work consists of a detailed study of the pollen stratigraphy of Bowness Common, Glasson Moss and Glasson Shore (fig. 1). He showed that sea-level in this area rose from -4 m in zone III (Table 1) to lay down deposits at

TABLE 1  
Dates assigned to the pollen boundaries used in Britain (from West, 1968).

Pollen Zone	Age (BP)
Zone VIIb	
Zone VIIa	5,000
Zone VI	7,000
Zone V	9,000
Zone IV	9,500
Zone III	10,500
Zone II	11,000
Zone I	12,000

+7.2 m O.D. in early zone VIIa, and +8.8 m later in this zone. The level of -3 m was not reached before the end of zone III. After the maximum transgression in zone VIIa sea-level fell again intermittently. On the northern Cumberland coast, in Bowness and Glasson Commons, the maximum transgression appears to have occurred about 7,000 BP, lasting to about 6,600 BP. Greater isostatic recovery in this northern area appears to have accelerated the start of the regression by as much as 650<sup>±4</sup> C years. Since zone VIIa, sea-level has fallen by about 4.5 m in the Bowness area. Walker suggests a linear decrease in the amount of sea-level lowering in a north-south direction from 3 m at Ravenglass to 2.7 m at the head of Morecambe Bay.

A date of 6,580±144 BP is quoted by Walker as the time of maximum transgression at the northern end of Morecambe Bay. Other dates for this area, which lies south of the area investigated in the present paper, give 5,734±129 BP and 5,865±155 BP. A date of 5,267±120 BP has been obtained at Helsington Moss. Walker concludes that a date of 6,000 BP is reasonable for the culmination of the transgression at the

southern end of the area considered in this paper, although it could have been 600 to 700  $^{14}\text{C}$  years earlier.

Gresswell (1958) mapped the raised shorelines of the Furness and Lyth areas. The maximum post-glacial transgression in this area reaches an elevation between 4.43 and 5.19 m. Silty clay underlies peat in the sheltered estuaries, but in the more exposed areas, drumlins have been cliffed up to 5.80 m. According to Oldfield (in Gresswell, 1958) the peat overlying the marine clays belongs to zone VIIa and VIIb, so the clays must be at latest early zone VIIa. There are also peat layers within the clay and these belong to the transition between zone VI and VIIa, and zone VIIb. Gresswell considers that the transgression is centered on zone VI-VIIa transition (table 1). He correlated the 4.58 m shorelines with the Hillhouse beach (5.18 m) which occurs a little further south and is higher owing to greater exposure. He thinks both belong to the so-called "25 ft" beach and that the isostatic rise is 0.3 to 0.6 m more in Furness than in southwest Lancashire.

Oldfield (1960) studied the Lower Lonsdale area. He recorded wave cut notches on Silverdale Moss at heights of between 4.90 and 5.12 m and between 5.89 and 6.44 m at Blackstone Point. Pollen analysis gives a zone VIIa date to the maximum marine transgression, which left clay at 5.75 to 5.79 m. The higher level is due to greater tidal rise up the estuary where the clay was deposited. This clay was laid down about 5,800 to 6,000 BP or possibly a little earlier.

Jardine (1964, 1967) described the evidence from southwest Scotland. He concluded that the sea crossed the present coastline at about 8,000 BP and that the transgression lasted until 5,000 BP. Peats lie below and above the marine deposits. In the eastern Solway area sea level was 3 m above O.D. in 8,135 $\pm$ 150 BP. A piece of wood at 3.96 m in sedimentary strata in Wigtown Bay has been dated at 6,159 $\pm$ 120 BP. Nichols (1967) stated that the post-glacial shoreline formed in Dumfries (at  $\sim$ 7 m O.D.) in latezone VI and early zone VIIa between 8,100 and 6,600 BP. The zone VI-VIIa transition is dated about 7,000 BP. A level of 10.7 m is given for Machrihanish, on the Mull of Kintyre.

In northern Ireland, at Ballyhalbert, organic material under beach deposits is dated at 8,120 BP at a height of

1.83 m O.D., while the upper limit is given at +4.88 m O.D. at Cushendun with a date of 4,740 $\pm$ 110 BP.

Syngé and Stephens (1966) consider that the highest post-glacial beach is constant in age in the central glaciated area but that in the peripheral areas it gets progressively younger away from the central areas covered by ice in the last glaciation. McCann (1966) has shown, however, that it is not constant in height in western Scotland in that it declines in height from Loch Linnhe.

The conclusion to be drawn from this brief review of the literature suggest that the post-glacial transgression reached its maximum along the south Cumberland coast in the zone VI-VIIa transition, or at latest in zone VIIa. The radiocarbon dates given for this period range between about 6,000 and 6,600 BP. The maximum level of the transgression decline southward. The literature review indicates that the majority of evidence on sea-level changes has come from sheltered estuarine sites, and little information on changes is available on open coasts. Our study partly rectifies this bias.

#### RELATIVE SEA LEVEL, EUSTATIC AND ISOSTATIC MOVEMENTS ON THE SOUTH CUMBERLAND COAST

Detailed descriptions of the sites from which radiocarbon dates have been obtained, plus a description of other coastal sections, are listed in Appendix I to this paper and have appeared in part in Radiocarbon 11 (Stuiver, 1969). The eleven dates are listed on table 2. Appendix II contains faunal lists and comments on certain of the shell collections. The majority of dates from Great Britain concerning relative sea-level changes have been derived from peat or wood; few dates on marine shells have been attempted despite their obvious and proven success as reliable dating material in Fennoscandia, Spitsbergen, Greenland and coastal sites in North America (see in particular Geological Survey of Canada dating lists in Radiocarbon). Seven of our eleven dates are from collections of marine shells.

Two further dates are used; these were obtained 25 km southwest of Hodbarrow Point in Morecambe Bay (fig. 1)

TABLE 2  
Radio-carbon dates, for location see figure 1.

Site (Appendix 1)	Grid Reference	Material	Number	Date	Height OD (m)
1. Hodbarrow	SD182781	Shell	Y-2596	820 $\pm$ 80	8.75
1a. Hodbarrow	SD183781	Shell	Y-2308	550 $\pm$ 100	7.36
2. Haverigg	SD158782	Shell	Y-2597	2,120 $\pm$ 100	6.74
2a. Haverigg	SD158782	Charcoal	Y-2387	3,630 $\pm$ 160	6.90
3. Haverigg	SD157783	Shell	Y-2598	1,210 $\pm$ 100	
3a. Haverigg	SD157783	Shell	Gak-1829	1,530 $\pm$ 80	
4. Silecroft	SD120812	Shell	Y-2599	2,330 $\pm$ 100	8.72
5. Ravenglass		Wood	Y-2427	7,790 $\pm$ 160	-5.0
6. Drigg	SD043983	Peat	Y-2600	6,720 $\pm$ 120	0.41-0.73
7. Drigg	SD046986	Shell	Y-2601	Modern	
8. Drigg	SD046985	Wood	Y-2602	6,200 $\pm$ 140	6.60

and were reported by Shotton et al. (1970, as Birm-140 and 141). They are a similar distance away from Hodbarrow Point as the Drigg samples. Errors in assessing sea-level changes from data with this spread depend on: 1) the relationship between the sites and the regional system of isobases related to glacio-isostatic recovery, and 2) the amount of postglacial deformation. On both counts errors will not be large for our data. Walker (1966-1967) has estimated the gradient of the Main Postglacial beach to be of the order of  $0.03 \text{ m km}^{-1}$  (i.e. for deformation since 6,000 to 6,600 BP). The strike of the south and west Cumberland coast is probably not parallel to the isobases although detailed determinations for the coast are lacking. Regional isobase systems (Sissons, 1967) suggest that the coast intersects the isobase system at an angle of  $60^\circ$  or so. This reduces the distance between sites. The second point above is also a function of time and there will not be noticeable difference for sites younger than about 3,000 BP, a maximum difference of 1 m for sites < 6,500 BP and a maximum difference of 5 m for sites < 9,500 and > 6,500 BP is estimated.

Figure 2 shows two generalized stratigraphic sections for

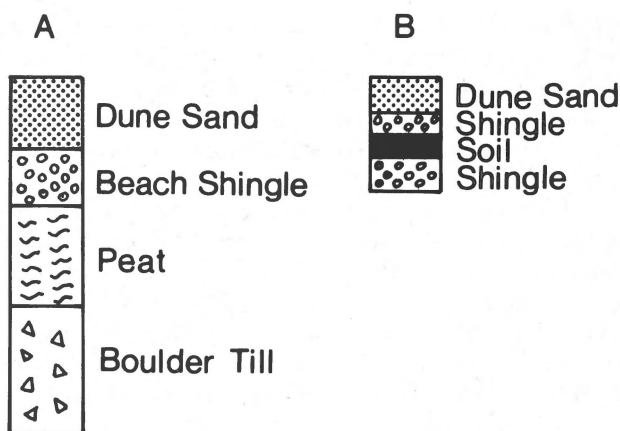


Fig. 2 Schematic stratigraphic sections from A: Drigg, and B: Haverigg.

the Drigg section (A) and the stratigraphy at Haverigg (B) based on the descriptions in Appendix I. As may be seen for the radiocarbon dates these two sections cover the period

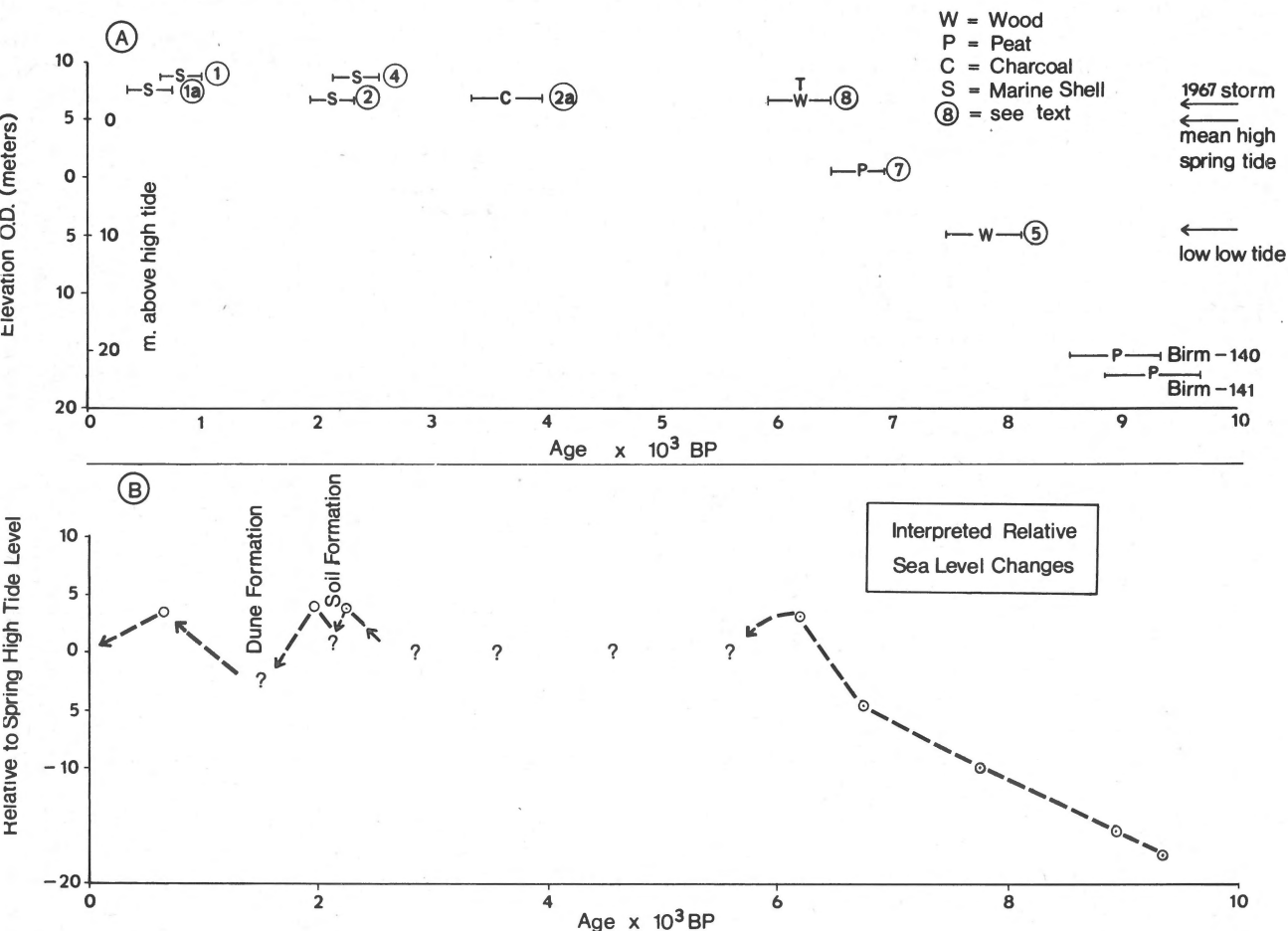


Fig. 3  
 A. Elevation of radiocarbon dated samples graphed against their age.  
 B. Inferred relative sea-level movements on the south Cumberland coast.  
 The zero elevation refers to high spring-tide level and not to Ordnance Datum.

8,000 to 6,000 and <3,600 years ago. Nowhere along this section of coast have we found materials that give an indication of sea-level for the intervening 2,000 years or so. Such evidence has been found by detailed coring of the estuarine deposits of the Duddon Estuary (Dr. M. Tooley, pers. comm. 1971) (fig. 1).

The elevation of the sites listed on table 2 and those relating to Birm-140 and 141 are plotted on fig. 3A. The dates are shown with horizontal bars equivalent to two standard deviations about the quoted age. Two elevation scales are used; the one on the outside of the *y* axis refers to elevation levelled to the British Ordnance Datum (O.D.) at Newlyn. Zero elevation is the height of the mean sea level at that site and variations throughout the U.K. are caused by variations in the geoid. The inner elevation scale refers to elevations relative to mean high spring tides along the Cumberland coast, which is a more realistic geological datum in terms of changes of depositional environments, especially in view of the large tides that effect the region. The figure illustrates that there was a relative sea-level rise and coastal submergence between about 9,200 and 6,000 BP, thereafter the dates from the high shingle ridge deposits lie between 6 and 9 m (O.D.) and date from <3,600 BP. However, fluctuations in relative sea-level are indicated by the presence of a soil profile overlying shingle at Haverigg and by the formation of the sand dunes. Our elevations of the raised shingle beach at Drigg and elsewhere are higher by 3 to 5 m than indicated by Walker (1966-1967).

Our interpretation of relative sea-level movements is given as fig. 3B. Note that our data provides a *minimum* estimate of sea-level position when based on peaty materials and it also provides a maximum estimate when based on marine shells. The elevation scale is measured relative to present mean high spring-tide level. Sea-level changes are shown as a line but this line should be considered the center of a confidence envelope with its boundaries determined by the uncertainties in elevation datum and in radiocarbon accuracy. The diagram shows that sea level rose ~22 m between 9,200 and 6,000 BP. This contrasts with an 8 m rise suggested by Donner (1970, fig. 3) for the marginal parts of Scotland; a similar value is given for central Scotland (Donner, 1970, fig. 2) although it should be less in this area due to greater glacio-isostatic recovery in this period (see Donner, 1970, fig. 6). The two peat samples from Drigg (samples 6 and 7, note wood from the peat was dated as sample 8) have been examined by Dr. M.C. Pearson for pollen. The analysis indicated the samples belong to zone VIIa (table 1). Sample 8 (highest sample) showed much alder, some hazel, oak, birch and pine. The presence of pollen of the sea pink *Armeria maritima* is of interest as it is now primarily located on sea coasts. A similar flora was observed in sample 6 from the lower foreshore as it contained much alder and hazel, and some oak, birch, elm and pine. Pearson (pers. comm.) suggests that the peat took at least 500 years to accumulate. The stratigraphy at Drigg shows that the peat mantled an undulating surface of mixed deposits, including clay till and flu-

vio-glacial deposits. Sea level rose high enough during this Holocene transgression to cover the peat and reached at least 7.33 m (O.D.) or about 3.66 m above the present high spring-tide level. The average rate of submergence between 9,200 and 6,000 BP was  $1 \text{ cm yr}^{-1}$ . As most eustatic sea-level curves indicate a rise of between 14 and 42 m since 9,200 BP it is apparent that the glacio-isostatic component on the south Cumberland coast is small.

The interpretation of sea-level events for the interval  $\leq 3,600$  BP is complex. Eustatic sea-level changes have been within  $\pm 1.5$  m of present (e.g. Schoff, Craigh and Stuver, 1970) or  $\pm 15\%$  of the present tidal range along the south Cumberland coast, these are small changes and effects could be attenuated by such factors as changes in the tidal range, periods of prolonged storminess and erosion of deposits representing slightly lower sea levels. The dates on marine shells from the raised shingle ridge representing the maximum elevation of the marine transgression are considerably younger than expected on the basis of the extant literature. Donner (1970), for example, infers a rapid marine regression which commenced about 6,000 BP while relative sea level had fallen by 5 m in the next 500 to 1000 years. Our data indicate that storm waves were reaching similar elevations to that obtained 6,200 years ago (Y-2602) during parts of the second and first millenia, as well as an earlier time.

The wave-eroded sections at Haverigg (Appendix I and fig. 2) indicate fluctuations in the local environment. The presence of a palaeosol overlying shingle suggests a period of lower sea level and/or quieter wave conditions. The palaeosol consists of a 5 cm black A horizon, followed by a light grey zone that probably represents podzolization which in turn overlies a B horizon. The 20 cm of soil sits on an indurated iron pan. The soil can be traced back under the dunes and represents a major stratigraphy break. The charcoal sample (2a) was collected from the top of the soil profile and was associated with fire-cracked rocks. The soil is in turn overlain by shingle and marine sands and the section is capped by extensive thicknesses of aeolian sands in the form of large dunes. Along the shore near Hodbarrow Point the 1967 storm had also cut into and exposed extensive shingle deposits. The period of soil formation is dated by samples 2 and 2a. The radiocarbon dates are, however, in reverse stratigraphic order. It is possible that the charcoal is the result of Neolithic man gathering drift wood and using this for firewood, and as a result the charcoal date could be too old, or the shell date may be somewhat too young because of contamination.

An analogous situation may exist in the Dundrom Dunes, Northern Ireland (Shepard, 1970) where paleosol within the dunes is recorded; Shepard (1970, p. 36) refers to it as a podzol. A date of 2,900 BP is given for charcoal from within sand and overlying the highest shingle deposits. The presence of thin podzols probably reflects colonization of the beach by coastal heath communities at a time of slightly lower sea level (fig. 3B). The period of soil formation was

followed by an interval of storm waves reaching elevations 3 to 5 m above present normal limits. It occurred between 2,000 and 2,500 BP and is correlative with a minor transgression recorded by *Sissons* (1967, fig. 82).

In Ireland at Downpatrick ( $54^{\circ}19'N$ ,  $5^{\circ}47'W$ ) *Smith et al.* (1971) dated organic material overlying an emerged beach at  $3160 \pm 95$  (UB-430A).

At Haverigg, large sand dunes occur on top of the shingle of this latter episode. At the moment the dunes are not actively accreting and large blow-outs suggest they are undergoing net mass loss. Shells are moderately prolific at the base of the dunes and are exposed at the base of some major blowouts. Dates on the shells (samples 3 and 3a, Appendix I and II and table 2) indicate a maximum age for the dunes of about  $1,000^{14}C$  years. The dunes of the south Cumberland coast thus appear to be correlative with the Younger Dunes of The Netherlands (*Jelgersma and Van Regteren Altena*, 1969). These authors also indicate that there is a correlation between active dune growth and marine regressions and that conversely periods of dune stability correlate with phases of the Dunkirk transgression ( $\sim 3,500$  BP). This might be related to a rise in the groundwater table in association with the sea-level rise. Fig. 3B tentatively suggests a marine regression related to the need to provide considerable foreshore areas for the development of the dunes. Finally, the two dates from Hodbarrow (Appendix I and II, table 2) indicate that high storm tides also occurred sometime after and may represent a phase of slightly higher relative sea level (fig. 3B).

The suggestion of slightly fluctuating relative sea levels within the last 3,500 years or so agree with evidence from some areas (e.g. The Netherlands - *Jelgersma and Van Regteren Altena*, 1969; Alaska - *Moore*, 1960 and *Hume*, 1965) but not with the evidence from others (e.g. *Bloom*, 1970); we need to be able to separate the eustatic and isostatic components, which together produce the resultant relative sea-level changes, before further interpretation can be made.

#### *Glacio-isostatic recovery and eustatic sea level changes*

Few attempts have been made to reconstruct the form of the glacio-isostatic recovery curve along the northern coasts of Great Britain although considerable attention has recently been focused on determining the patterns of postglacial crustal deformation based on an analysis of strandlines (see *Stephens*, 1968; *Sissons*, 1967; *Institute of British Geographers*, 1966). *Mörner* (1969) used the strandline diagram of *Stephens* (1968) to reconstruct glacio-isostatic recovery curves; *Andrews* (1970) discussed the form of the recovery based on *Sissons'* relative sea-level curve (*Sissons*, 1967); and *Sissons and Brooks* (1971) presented an isostatic uplift diagram for the Forth Valley, Scotland. In these cases the glacio-isostatic recovery is obtained from:

$$U_t = R_t - E_t \quad (1)$$

where  $U$  is the amount of isostatic uplift in time  $t$ ,  $R$  is the position of relative sea level at time  $t$  measured with respect to present sea-level datum and  $E$  is the position of eustatic sea level. In the case of *Mörner's* results  $\dot{U}_t$  was obtained by substituting into (1) the eustatic curve that he had developed from south Sweden and in the other example (*Andrews*, 1970) values for  $U_t$  were obtained by using *Shepard's* 1963 eustatic sea-level curve. Both these papers indicated a decelerating rate of recovery of the general form  $U_t = C(1 - e^{-kt})$  where  $C$  is the total amount of uplift since deglaciation and  $k$  is a decay constant. *Mörner* (1969) suggests that the irregularities in the uplift curves generated in his study, are the result of fairly subtle variations in ice and water loads. The apparent  $\frac{1}{2}$  life of the curves are 2,000 years (*Andrews*, 1970), 2,500-3,000 years for the curves drawn by *Mörner* (1969), and 2,500 years from the result of *Sissons and Brooks* (1971).

On the basis of the glacio-isostatic recovery curve from Scotland, *Andrews* (1970) prepared a Shoreline Relation (SR) diagram that can be used to draw relative, isostatic and eustatic curves given information about the height and age of one point. The chosen value was the height of relative sea level at 7,000 BP taken from fig. 3B. The resulting curves are illustrated as fig. 4. *Shepard's* 1963 curve is an integral part

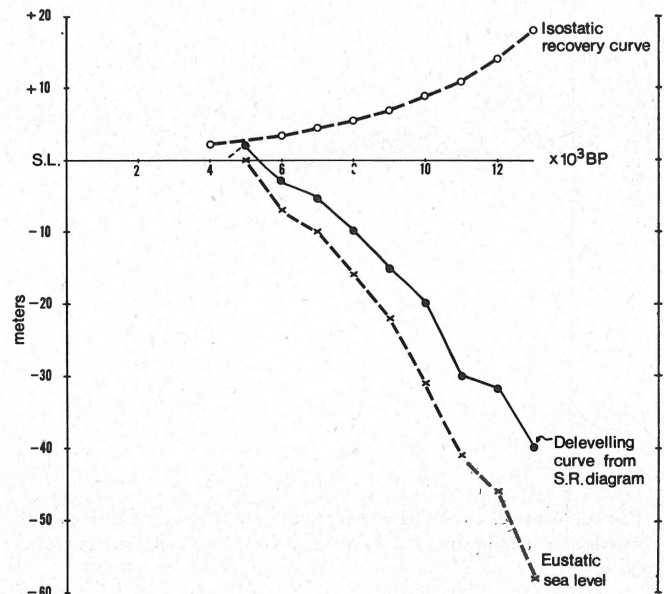


Fig. 4

Relative sea-level curve for the south Cumberland coast based on elevation of sea level 7,000 BP and using the shoreline relation diagram in *Andrews* (1970, fig. 4). The isostatic recovery curve for the coast is also illustrated for the last 13,000 BP.

of the development of this particular SR diagram and hence the eustatic sea-level curve is not independently generated. What is important is the agreement between the delevelling curve of fig. 4 and the interpreted relative sea-level curve for

the period  $> 5,000$  BP (fig. 3B). Note for example a relative sea level on both diagrams of  $-12$  m at  $8,000$  BP and  $-17$  m for  $9,000$  BP. The two diagrams differ over the position of sea-level between  $6,000$  and  $5,000$  BP. The isostatic recovery curve is a smoothly decelerating curve with an apparent half-life of  $2,000$  years. In the last  $13,000$  years there has been  $18$  m of rebound. In the last  $6,500$  years there has been  $4$  m of recovery, which accords well with Churchill's 1965 estimate of  $4.6$  m from Silverdale Moss (fig. 1).

In fig. 4 we have treated  $E_t$  as a known quantity in order to obtain  $U_t$ . However, it would be useful if there were methods by which  $E_t$  could be estimated with only  $R_t$  known. The mathematics of such a method were presented and discussed by Thompson (in Schofield, 1964) and used to reconstruct a eustatic sea-level curve from relative sea-level data taken from 10 Norwegian sites. A program for the solution of both Thompson's iterative methods was developed by L.D. Williams, University of Colorado. Input for the program consisted of the position of relative sea level for 5 sites from northern Great Britain, namely those published by Sissons (1967), Stephens (1968), Donner (1970) and the curve from fig. 3B of this paper. Positions were interpolated in 500 year intervals from  $10,000$  BP to the present. The two solutions for eustatic sea level are

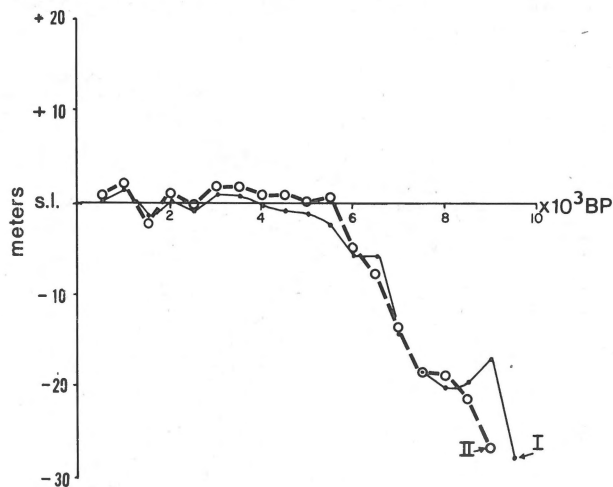


Fig. 5  
Eustatic sea-level curves based on relative sea-level curves from Great Britain and Thompson's (in Schofield, 1964) mathematical solutions.

graphed as fig. 5. Number I is based on a general convergence and II uses the south Cumberland curve as a datum (for more detailed discussion see the paper by Schofield, 1964). Both curves (fig. 5) indicate a rapid rise of sea level after  $10,000$  BP with present sea level being reached by about  $5,500$  BP. Curve I suggests that a regression of sea level occurred between  $8,000$  and  $8,500$  BP; this could be associated with the Cockburn/Cochrane phase of the Laurentide

Ice Sheet (Andrews and Ives, 1972). Three small transgressions are indicated after  $5,000$  BP with dates of ca.  $3200$ ,  $2000$  and  $900$  BP.

In view of the controversy of the position of sea level during the last  $5,000$  years fig. 5 indicates sea level *could* have been up to  $3$  m higher than at present. We do not wish to be, nor can we be, dogmatic about this issue as the arguments center about fluctuations of  $1$  to  $3$  m and these are within the range of chance tidal surges and other non-periodic events. Certainly, sea level was very close to present by  $5,000$  BP and there is evidence that effective sea level has been slightly higher than present during the last  $5,000$  BP together with small regressions and transgressions.

The regression  $\sim 900$  BP coincides with beginning of the last Neoglacial phase of ice build-up. Similarly, the regressions of  $2,500$  and  $1,500$  BP correlate with the North American Neoglacial sequence. More detailed results of sea-level changes should emerge from detailed corings from the estuaries in the area (these have been undertaken by Dr. M.J. Tooley, University of Durham, pers. comm., 1971).

The eustatic sea-level curves of fig. 4 and 5 are sufficiently similar in view of the several error sources that we conclude that the glacio-isostatic recovery curve of fig. 4 is a reasonable approximation. The  $18$  m of recovery in the last  $13,000$  years represents only  $\sim 5\%$  of the estimated equilibrium deflection under the ice load. A striated, wave cut, bedrock platform at Hodbarrow Point (Appendix I) about  $2$  m above present storm wave action is probably interglacial in age implying that crustal recovery is nearly complete.

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#### APPENDIX I

##### THE SITES AND SAMPLES COLLECTED ON THE SOUTH CUMBERLAND COAST

The area from which samples were collected extends from Hodbarrow Point (SD183780) in the south to Drigg in the north, although the coast was examined as far north as Nethertown (SD980070). There are no solid outcrops on the coast between Hodbarrow Point, where Carboniferous limestone outcrops, and St. Bees Head, north of Seascales, where the St. Bees sandstone forms high cliffs. The intervening coast is backed by drift cliffs, estuarine deposits and sand dunes. The sites from which samples have been dated are listed in table 2.

Hodbarrow Point is a small limestone promontory in the Duddon Estuary; the limestone is overlain by till at the Point. There is a wave-cut platform at 7.35 m O.D. and a higher irregular limestone surface ranges up to 14.3 m O.D. There are striations on this surface with a bearing of S40°W. The preservation of the striations indicate that the sea has not reached this elevation since the ice marked the surface.

The dated sample consisted of shells from a 1 to 1.5 m thick beach deposit lying on the lower platform. The irregularity of the limestone platform suggests a brief incursion of the sea to about 8.70 to 8.85 m O.D. The shingle resting on the lower platform is well rounded, set in sand and includes shells; it passes up into sand. A sample of the shingle was analysed for roundness, a mean value of Cailleux's roundness index being 442, with a large standard deviation of 147. This suggests that the stones have only briefly been rounded by the sea.

Two dates are available for shells (Appendix I and II) from this site. Y-2596 gives a date of 820±80 BP, the elevation of the sample being 8.74 m O.D. The other sample, Y-2388, gives a date of 550±100 BP, the elevation being about 7.4 m. The first sample came from a site with a south-westerly exposure whereas the second was collected from the more sheltered eastern side of the promontory. The dates are comparable and indicate that these deposits are much younger than the maximum post-glacial transgression, despite their considerable elevations.

The maximum elevation of the deposits is about 8.85 m O.D. which is about 4.58 m above the high spring-tide level. The site is not very exposed to the waves but it is possible that the shingle might have been thrown to this elevation by extreme storm waves, perhaps acting under surge conditions with an abnormally high water level. It does seem anomalous, however, that the more exposed site records the older date implying that the shells here were not disturbed in the later storm. The elevation of the shells at 8.75 m O.D. is higher than that given by Oldfield for the Blackstone Point wave cut notch at about 6 m which he considers to represent the post-glacial maximum transgression. The Hodbarrow deposits show no sign of disturbance by waves at present, despite several severe storms in the area in the recent past.

The next site to the north is at Haverigg (fig. 1) which is 3 km west of Hadbarrow and nearer to the entrance of the Duddon Estuary being only about 2 km from the open sea at Haverigg Point. The beach is wide and sandy and is backed by dunes. At the top of the beach a layer of shingle, covered by shell-bearing dark sand, was exposed by the 1967 storm waves. At other positions a well-developed palaeosol overlies the shingle. The top of the shingle was at 6.74 m O.D. where shell sample 2 was collected. The upper limit of the palaeosol was at 6.90 m O.D. This palaeosol contained the charcoal, sample Y-2387, which was dated 3,630±160 BP, whereas the shells in the sand (Y-2387) gave a date of 2,120±100 BP.

A large number of shells are found amongst the dunes, and two samples of these have been dated. The dates agree fairly closely being (Y-2598) 1,210±100 BP and (Gak-1829)

1,530±80 BP. The dunes, therefore, formed in the millenium between 2120 and 1210 BP. The sand was probably derived from the shore as sea level fell. Immediately behind the dunes, trenches expose a reddish clay till.

The precise date of the formation of the shingle at the top of the beach is not clear. If the shell date 2120 BP is accurate the shingle must have collected before this as the shells overlie the shingle. The level of the shingle is slightly variable, ranging between 6.38 m and 7.48 m O.D. where exposures are available. This is between 2.64 m and 3.73 m above mean high water spring tide. The shingle was probably thrown above this level by storm waves, so that it is likely that it accumulated when sea level was about 3 m higher than it is now.

#### Sample 4:

Between Haverigg Point and the Esk Estuary at Ravenglass (fig. 1) the coast is low and faces the open Irish sea. It is backed by low drift cliffs in places but elsewhere, as at Silecroft, the back of the beach consisted of an old storm beach. At Silecroft a sample of shells was collected at a height of 8.72 m O.D. which is 4.9 m above the mean high spring-tide level and 4.12 m above a recent (1969) high tide line of seaweed. The shells were collected from a layer of shingle, mixed with sand, which forms an old storm beach above the present upper shingle beach. The crest of the ridge rises above the ground to landward of it where no shells were found despite good exposures in an open trench and an old brick pit. The trench revealed pure clay with no shells and very few stones, possibly being material accumulating in the shelter of the storm beach. Behind the flattish clay surface the ground was undulating and it does not appear to have been under the sea. The few stones in the brick pit exposure were much more angular than those on the beach at present, where they are exceptionally well rounded. A similar shell-bearing raised shingle storm-beach ridge was located 10 km further north at Tarn Bay (SD080906), with similarly very well rounded beach pebbles. The date of the Silecroft shell sample (Y-2599) is 2,300±100 BP, which correlates well with the Haverigg shells collected in a similar storm ridge. Part of the difference in height between the Silecroft and Haverigg sites (1.98 m) is due to the exposed nature of the Silecroft site. It has a steep shingle slope on the upper beach, compared with the sandy, gently-sloping beach at Haverigg, which is also partly sheltered owing to its estuarine position. The difference of exposure could account for at least 1 m. The highest line of seaweed at Silecroft is 5.18 m O.D. while the upper beach at Haverigg is at 4.27 m O.D.

At Ravenglass, *in situ* wood was collected at low tide and dated at 7,790±160 (Y-2427) The most extensive stratigraphic section was examined 5 km north of the Esk Estuary at Drigg (fig. 1). At this site fluvio-glacial sands and gravels outcrop and there are extensive peat deposits both on the foreshore and in the lower part of the cliff section where they are associated at one point with raised beach deposits. The dates of the peat and included logs of wood may be

compared with the date of wood from the submerged forest at Ravenglass. The latter sample (Y-2427) yielded a date of 7,790±160 BP. The foreshore sample at Drigg (Y-2600), collected from peat outcropping between 0.41 and 0.73 m O.D. was dated 6,720±120 years BP and the wood sample from the cliff at the back of the beach (Y-2602) at 6.60 m O.D. was dated 6,200±140 BP. The other material from this site that was dated were shells found in and under the cliff, but not *in situ*. These shells proved to be modern (Y-2601). The Drigg dates agree closely with others obtained for the maximum postglacial transgression, for which there is also evidence at this site, as the upper past level immediately underlies a shingle beach deposit. This deposit ranges between 6.60 m and 7.33 m O.D. This upper level of the peat is undulating and it must have covered an uneven surface. On the foreshore it overlies a clay till while in the cliffs it rests on sands and pebbly deposits. It is separated into layers by sandy partings with very angular stones in its upper part. In places where the beach shingle is lacking, the peat passes up into sand which then merges into the dunes that now cap this part of the coastal section and extend some distance inland.

Immediately to the north of the peat outcrop the cliff is formed of sands, muddy sand and layers of pebbles, which dip down under the peat. The cliff reaches a height of 15.25 m O.D. The deposits appear to be largely fluvioglacial in origin and form the undulating surface on which the peat accumulated and later wind-blown sand to form the dunes. The sands dip steeply south at angles of 33°, 20° and 11°. They were of various colours, pink, passing through buff and into dark brown pebbly sand and then up into less steeply dipping grey sand, with some layers of stones. The variations in colour suggest that the streams depositing the sand had access to different source materials, which would be possible in a complex ice front with superimposed or adjacent ice stream fed from areas with different source rocks. The deposits dipped down steeply under the peat. A steeply dipping junction separated these coarser strata sand to the north. The whole sequence of strata are outwash deposits and not raised beach sediments.

The roundness of the pebbles was recorded to compare with the marine eroded pebbles at Hodbarrow. A mean roundness of 299 showed a very significant difference in roundness from Hoddbarrow pebbles ( $t=5.037$ ,  $df\ 98$ , significantly different at 0.001). A sample of the sand has also been analysed mechanically. It has a mean  $\phi$  size of 2.08, sorting 0.545, skewness -0.0148 and kurtosis 1.13 (Inman graphic  $\phi$  measures). The sorting is higher than that in beach sands, while the skewness does not have so high a negative value as is common in beach sands. Subsequent electron microscope examination of quartz grains from this deposit confirmed that the material was not beach sand as it showed clear evidence of glacial texturing.

Two kilometers further north at Seascale (SD037007) there is another extensive exposure of drift deposits. They appear to be glacial and fluvioglacial rather than marine. At the north end the section consists of two layers of sandy-

clayey till, with rounded pebbles, the lower layer being pinker than the upper, which is grey. At the south end there are alternating layers of sand and lenses of pebbles set in a sandy matrix extending over a vertical distance of 3 m. The pebbles are crudely stratified and the sand shows varying dips, mostly to the south, indicating deposition by turbulent streams. Between these two outcrops are two stretches of well stratified deposits, consisting of layers of dark brown sand about 15 cm thick between horizontal layers of large, very well rounded stones, many 10 to 15 cm in length. Some of the layers consist of only one line of stones, others are about one metre thick. The outcrops extend laterally over a width of 15 to 30 m. At southern end of the southern stratified outcrop the well rounded stones and stratified sands end abruptly against a deposit of unstratified stoney gravel with clay, contain only fairly small stones, which has the appearance of till.

A possible interpretation of the stratified deposits is that they represent the fill of a meandering subglacial stream, which flowed through stagnating ice. The section exposes two cuts across the filled up channel. The stratified rounded stones and sandy layers are the only possible marine deposits in the part of the coast. They contain no shells, however, and a fluvioglacial origin appear more likely in view of the stratigraphical relations described. Mechanical analysis of the sand provided results somewhat similar to the Drigg sample, although the mean size was larger. (Mean 0.97 $\phi$ , sorting 0.41, skewness -0.02, kurtosis 1.22). The results again show a larger sorting and smaller skewness than is usually associated with a beach sand. The stratigraphical relationship also provide strong evidence for the non-marine origin of these deposits.

The coast was also visited at Nethertown (SD988073) north of Seascale, where till cliffs are cut in drumlines. The sandy till contains well-rounded small stones. There is no evidence of raised coastal features in this area, nor were marine deposits located inland. There are plenty of sand and gravel features inland, but they all appear to be of fluvioglacial origin. One example is the esker near Gosforth (SD674019), which showed very well developed current bedding, with minor faulting picked out by thin indurated layers of sand. Many coal fragments were included in the coarser pebbly layers amongst the current bedded sand and clayey sand. Thus the only evidence of higher sea level in post-glacial time is seen in the immediate vicinity of the coast.

## APPENDIX II

### MOLLUSCA FROM CUMBERLAND RAISED BEACHES

Hodbarrow

(Sample 1)

*Littorina Littoralis* (Linne)

*Hygromia striolata* (C. Pfeiffer) Terrestrial

*Mytilus edulis* (Linne)

*Cerastoderma edule* (Linne)

*Venerupis* sp.

*Macoma balthica* (Linne)

Mammalian rib

This is a shallow water marine fauna (excepting *Hygromia* and the rib) probably produced in a rocky shore strand line.

Haverigg

- (Sample 2) *Mytilus edulis* (Linne)  
*Arctica islandica* (Linne)  
*Acanthocardia echinata* (Linne)  
*Cerastoderma edule* (Linne)  
*Macoma balthica* (Linne)  
*Maetra corallina* (Linne)  
*Pholadidae* gen. indet.  
 (small fragment only)

Haverigg Dunes

- (Sample 3) *Littorina littorea* (Linne)  
*Buccinum undatum* (Linne)  
*Mytilus edulis* (Linne)  
*Arctica islandica* (Linne)  
*Ostrea edulis* (Linne)  
*Acanthocardia echinata* (Linne)  
*Cerastoderma edule* (Linne)  
*Ensis* cf. *siliqua* (Linne)

Silecroft

- (Sample 4) *Buccinum undatum* (Linne)  
*Mytilus edulis* (Linne)  
*Ostrea edulis* (Linne)  
*Arctica islandica* (Linne)  
*Acanthocardia echinata* (Linne)  
*Cerastoderma edule* (Linne)  
*Macoma balthica* (Linne)  
*Maetra corallina* (Linne)

Samples 2,3 and 4 represent a fauna of low intertidal marine bivalves which mainly prefer a soft bottom. Most forms have thick shells which are able to survive in active conglomerates.

Drigg Cliff

- (Sample 7) *Neptunea antiqua* (Linne)  
*Buccinum undatum* (Linne)  
*Ostrea edulis* (Linne)

This restricted fauna suggests the presence of an oyster bed just below the intertidal zone or at least a stable shelly bottom.

Shells identified and notes on environment by Adrian J. Rundle.

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