CHAPTER FOUR

METHODS

1. Surveying and Levelling

It was planned to use the results of pollen analyses, dendrochronology, etc. in attempts to deduce patterns of forest development, and associated changes in the coastal environment, particularly those resulting from changes in the local water table, due at least in part, to changes in sea level. It was therefore necessary to record the position of all exposures, auger holes, tree stumps, etc. very accurately, and to obtain precise levels for these features.

At Stolford (Chapter Five) and Borth (Chapter Six) in particular, where extensive forest exposures are present, and the positions of several hundred trees were precisely plotted, the mapping was greatly facilitated by the availability, at both sites, of aerial photographs, commissioned by the Department of Geography, U.C.W., Aberystwyth, for research programmes directed by Professor C. Kidson. Individual trees could in many instances be identified on these photographs, although the presence of surface mud or sand cover meant that only a small proportion of the forest bed was exposed at the time of the photography.

The positions of many sections, and stumps, etc. had therefore to be individually plotted, although it was usually possible to do this in relation to a fairly nearby feature, the large stumps serving as fixed points in plan, and as secondary bench marks, so that levelling of new features could be carried out without starting afresh each time from distant O.S. bench marks.

At Borth and Ynyslas, the very substantial timber groynes, at close intervals along the whole length of the forest exposure, provided a very useful framework for both the plotting of positions and the
levelling. The top of the end post of each of these groynes was
levelled from the bench marks on the main Borth-Ynyslas road, and all
the features recorded in the submerged forest exposures were sub-
sequently levelled from the nearest groyne. All levelling was carried
out with closing errors of less than 1 cm.

2. Auger Holes and Sections

All augering described in this work was carried out using gouge
augers manufactured by Eijkelkamp of Holland. These augers, 1 or 2 m
long, are of U-section, with sharpened edges and are made from an
extremely tough steel alloy, to withstand the high torque involved.

These augers are pushed or hammered down into the strata, and when
the required depth is reached, the T-handle is used to give the auger
one complete turn. This cuts out a complete cylinder of sediment,
which can then be withdrawn from the hole. These augers proved to be
the most satisfactory design for use in the very compacted peats, with
frequent wood, encountered in the submerged forest exposures. Only in
the very softest sediments was a problem encountered with the auger
failing to retain the sample when withdrawn from the hole. With this
type of auger, as opposed to the chambered type, the exposed half of
the sample is of course contaminated by the walls of the hole during
withdrawal. The portion of the sample protruding from the auger is
therefore cut away, with a knife, and samples for pollen and radio-
carbon analyses are taken from the part inside the auger. Pollen
samples are usually extracted by pushing 1 cm-diameter glass or plastic
tubes into the cut surface. It is found to be advantageous, in many
cases, to use plastic tubes with 1 mm holes drilled in the base, to allow
air to escape as the tube is pushed in, thus preventing air pressure
extruding the sample when the tube is removed. If a finger is placed
over the small hole, the partial vacuum produced assists in extraction of the sample. The tubes are immediately capped, and labelled, and the 1 mm holes are sealed with a small blob of plastic cement. Storage of the samples in the dark, for more than 5 years has proved perfectly satisfactory; no drying or other preservative measures being necessary.

At some sites, where larger samples were necessary, for either radiocarbon analyses or macroscopic plant identification, or because pollen concentration was low, pits were dug, and complete monoliths of peat etc. were removed.

In the case of the Clarach Bay submerged forest bed, which in places rests on gravel, which could not be penetrated by augers, a 3 m-deep hole was dug by a mechanical excavator, during the brief period around low water, when the site was uncovered by the tide. The stratigraphy was thus revealed far more plainly than would otherwise have been possible. This excavation was carried out as part of a research programme directed by Professor C. Kidson, and reported by Heyworth, Kidson and Wilks, 1985.

3. Pollen Extraction and Counting

In the case of normal sedge, Phragmites, etc. peats, 1 cc samples were taken from the storage tubes or the monoliths, and treated by the accepted methods (described by, e.g. Faegri and Iversen, 1975) that is; (a) disaggregation by hot 10% KOH solution; (b) sieving through 120 μm nylon mesh; (c) removal of cellulose by acetylation, using a hot mixture of 9 parts acetic anhydride and 1 part conc. sulphuric acid; (d) neutralization, followed by staining with basic fuchsin. The appropriate washing and centrifuging stages are of course also necessary; (e) the pollen extracts were stored in a 1:1 glycerol/water solution, in stoppered tubes. One drop of 10% ammonium hydroxide solution was added to each tube. No deterioration in samples kept in this way was
observed over periods of more than 6 years.

In many cases the acetylation stage was omitted, either because pollen concentrations were not greatly improved by it, or because it was wished to preserve other micro-fossils (such as desmids and Pediastrum) with cellulose walls, which would be destroyed by acetylation.

Many of the submerged forest peats were composed largely of wood debris, and the concentration of xylem was such that acetylation had little effect. In these cases the following oxidation procedure was used: (a) Following the KOH treatment and sieving described above, wash the residue and centrifuge, in a 15 ml tube. (b) Decant the water, and add 5 ml of 20% sodium hypochlorite solution. (c) Add 1 drop of hydrochloric acid. The resulting evolution of chlorine rapidly bleaches the woody debris. (d) As soon as the colour disappears decant the mixture into c. 20 ml of water in a beaker, to stop the reaction. If the colour does not disappear, a second drop of HCl may be added to the tube. In extreme cases, more sodium hypochlorite solution may be needed. Some experimentation is necessary with this procedure, as pollen grains can easily be oxidised, and this may occur differentially, some species having grains which are more susceptible than others.

This oxidation treatment also removed "black spheres" consisting of pyrite, which are often very troublesome in pollen preparations from peats formed in highly reducing conditions. Some of the black spheres may in fact be zygospores of Chlamydomonas or similar algae, with a coating of a manganese compound, presumably MnO₂ (Lewin, 1975). The oxidation is also very effective in destroying fungal spores and debris (chitin) which are unaffected by acetylation. Samples bleached in this way were always scanned before the addition of hypochlorite, in case diagnostic fungal spores, etc. were present (e.g. Ustulina ascospores, Figure 5.12).
Many of the samples from the submerged forest beds have a very high silt and clay content; some of the intercalated or underlying estuarine clays having only 1 or 2% organic material. It was necessary to extract pollen from these sediments, but it was found that the normal volume of 1 c.c. per sample was quite inadequate, due to the low pollen concentrations. In some cases sample volumes of up to 100 c.c. were needed to provide sufficient pollen.

A variety of extraction procedures was tried, including froth-flotation, various heavy liquids, and the normal hydrofluoric acid dissolution methods. The last proved to be entirely inadequate with the large samples involved, partly because of the considerable volume of HF needed, and the fact that very frequent stirring was required to allow the reaction to proceed at a reasonable rate, and partly because there was usually only a small silica content, most of the inorganic fraction being clay minerals, etc., which are attacked only very slowly by HF, or react to form insoluble or colloidal silicofluorides.

Some success was achieved using a modification of the method described by Frey (1955) using a mixture of bromoform and acetone, with a specific gravity of 1.8. With samples of 0.2 c.c., as described by Frey, the procedure worked well, the pollen grains rising to the surface, and the mineral particles sinking, during centrifugation. With larger samples, however, considerable difficulty was experienced in dehydrating them (bromoform is, of course, immiscible with water) and producing a uniform suspension in the acetone-bromoform mixture. The large volumes of bromoform required were expensive, and the noxious fumes were a further disadvantage.

A completely water-miscible heavy liquid is required for effective extraction, and the number of suitable liquids is small. Conc. $\text{H}_2\text{SO}_4$ has a suitable density, and is miscible with water, but is not easy to work with.
Kummel and Raup (1965) mentioned the use of saturated solutions of zinc bromide, ZnBr₂ and zinc chloride, ZnCl₂. The former has a slightly higher density than the latter, and is less viscous, but it is more expensive. The density obtainable with ZnCl₂ (about 2.0 gm per c.c.) is adequate for pollen flotation, and the viscosity is not sufficient to cause undue problems.

Björck, Persson and Kristersson (1978) compared the use of ZnCl₂ solution with that of HF in extracting pollen from mineralogenic sediments, and concluded that the ZnCl₂ method was clearly superior, both in terms of the concentration achieved and the preservation of the grains. The method they describe is not suitable for large samples (they suggest volumes of 1 to 3 c.c.) mainly because of the very large centrifuge tubes which would be required to accommodate the volume of ZnCl₂ solution needed to suspend the samples. If the proportion of sediment to solution is too great, the pollen grains cannot escape from the mineral layer and do not, therefore, rise to the surface.

The fairly recent availability, at a reasonable price, of 10 μm precision nylon mesh has enabled the direct separation of the pollen from clays by sieving, and a method was developed which combined this with the removal of larger particles by ZnCl₂ flotation. Clay particles are, of course, below 10 μm diameter, and they and other mineral grains of less than this size will pass through the sieve. Pollen grains are almost all greater than 10 μm diameter (the exceptions being mainly, Boraginaceae species such as Myosotis, which are seldom an important constituent of the pollen spectrum).

The procedure used was as follows:

(a) Test the sample for the presence of carbonates by adding dilute HCl. If appreciable effervescence occurs, it is
simpler to remove the carbonate with HCl, rather than by sieving or by gravity separation. If significant amounts of carbonate are indicated, excess dilute HCl should be added, and the sample stirred until it is disaggregated, and then left, with occasional stirring, until effervescence ceases, the mixture still being acid. Centrifuge, and decant the supernatant liquid.

(b) After the HCl treatment, or if no HCl treatment was necessary, add a sufficient volume of 10% KOH solution to suspend the sediment, and heat at 100°C for 10 to 20 minutes to disaggregate the colloidal organic fraction and release the pollen. Frequent stirring will be required. When disaggregated, dilute with twice the volume of filtered water and then sieve through 120 µm nylon mesh, to remove the larger particles. Wash through the mesh with more water, and collect the filtrate. Centrifuge the filtrate for 2 minutes at 2000 r.p.m. and decant the liquid.

The pollen can be stained at this stage, with basic fuchsin. The colour may change during the subsequent ZnCl₂ treatment, but will return to normal after washing.

(c) If there is a sand content, this will now be visible at the base of the sediment, and the pollen will all be in the upper clay or fine silt layer. If so, the pollen-rich layer can be carefully scooped off, and transferred to another tube. If no separate sand layer can be seen, then the whole of the residue must be used in the next stage.

(d) Sieve the residue through a 10 µm nylon sieve. If a large volume of sediment is involved it is advantageous to use a large (20 cm) diameter sieve, and to wash the clay through with water, passed through a 2 µm filter attached to a tap. Filtra-
tion through the 10 μm mesh can be very slow, and it may be speeded up by the addition of a detergent solution, or by using a nesting sieve with a base attached to a water-jet vacuum pump. A less-than-10 μm fraction can, of course, be simply washed down the sink. When the water passing through the sieve is completely clear, wash the material remaining on the sieve back into a centrifuge tube. Centrifuge at 2000 r.p.m. for two minutes, and decant the water. The residue will now consist only of particles of between 10 μm and 120 μm diameter.

(e) Add to the tube a solution of ZnCl₂, of Sp.Gr. 1.9 to 2.0 (prepared by dissolving 3 parts by weight ZnCl₂ in 1 part by weight of water, with the addition of a few drops of 20% HCl to ensure that the solution remains acid, thus preventing the precipitation of colloidal Zn(OH)₂). Stir and shake well to bring the residue into suspension. Centrifuge at 3000 r.p.m. for 5 to 10 minutes. The mineral particles will sink to the bottom and the pollen will rise to the top. A clear layer should be present between them. If it is not, repeat the centrifuging until the division between the two layers is distinct. Often, if little organic debris is present, the pollen layer on the surface is hardly visible.

(f) Decant the supernatant liquid into a second tube, being careful that the surface pollen layer does not remain attached to the wall of the first tube. Dilute the liquid with three times its own volume of distilled water, mix thoroughly, and centrifuge for five minutes at 2500 r.p.m. (the addition of a few drops of 20% HCl to the water will prevent the formation of colloidal Zn(OH)₂ at this stage). Decant the liquid into a beaker (the ZnCl₂ can be reclaimed). Wash the residue, or if a large amount of organic material remains, then:
(g) Add distilled water, shake to suspend the residue, and pour into a 10 μm sieve. Wash with a dilute detergent solution. This will remove the fine organic debris. Wash the residue to one side of the sieve with water, and then transfer it to a storage bottle with a 1:1 glycerol/water solution. The pollen is then ready to be mounted on a slide.

No further treatment (acetylation, etc.) is usually necessary, since, in these sediments, most of the organic particles with sizes between 10 μm and 120 μm are pollen and spores. If acetylation is required, it can be carried out immediately after the KOH stage.

Using the above scheme, with the appropriate sizes of centrifuge bottles, sieves, etc., samples of up to 100 c.c. have been processed, and reduced to c. 0.2 c.c. of pollen suspension, with c. 500 grains per drop. HF treatment of the same samples had suggested that they were almost completely barren.

Bates, Coxon and Gibbard (1978) suggest the use of sodium pyrophosphate (Na₄P₂O₇) as a deflocculating agent for clays in pollen extraction procedures, and describe how it may be used to keep clay particles in suspension during differential centrifugation, the pollen sinking to the bottom of the tube. They also mention its previous use in disaggregating samples prior to micro-sieving.

Na₄P₂O₇ treatment was included experimentally in the above schemes, immediately before the first 10 μm sieving. The clays did appear to be more easily taken into suspension, but the rate of sieving was not greatly speeded up, and as a water jet was needed to wash the sediment through the sieve, the Na₄P₂O₇ was quickly washed out and lost. The sieving did not appear to be significantly faster or more thorough than with dilute detergent solution.
In this application, unlike that of Bates, Coxon and Gibbèrd, minor floculation of the clay particles is not important. Unless the particles aggregate to 10 μm diameter they will eventually pass through the sieve.

Pollen counting

All pollen counting was carried out using temporary slides (1:1 glycerol/water) made from the stored pollen suspensions. This enabled the grains to be easily turned over if required, to assist in identification. No suggestion of swelling or disintegration of grains, such as occurred in glycerol jelly mounts, was observed.

The microscopes used were either Gillett and Sibert Conference or a Leitz Laborlux, both equipped with binocular heads, mechanical stages, and x25, x40 and x100 oil-immersion objectives. Phase-contrast viewing was also used when necessary.

Identification of pollen and spores was carried out using the keys of Erdtman, Praglowshi and Nilsson (1963) and Moore and Webb (1978), together with a comprehensive collection of reference slides and photographs assembled by the author.

4. Dendrochronological sampling, ring-width measurements and matching

Most of the tree remains in the submerged forest beds are in a remarkably good state of preservation, and the species are easily identified. The trees are usually in their growth position, the stumps being firmly rooted in their original substrates. Many fallen trunks do occur, however, and isolated specimens of this kind were avoided in sampling since it is possible that they have been drifted to their present position either shortly after their death or by later
erosion of the forest bed. Where possible trees with the bark still intact were selected. Sampling was usually carried out by sawing complete discs, at least 10 cm thick from the stumps or trunks. Since the wood of these trees is usually extremely hard, a chain-saw is necessary, particularly in view of the short time available between tides (Plate 7) but great care was needed to avoid the ingress of sand and salt water into the mechanism.

The 10 cm-thick slices were allowed to dry out very gradually, in order to minimise the splitting and warping which would otherwise occur, and which is often inevitable with thinner slices. When dry, perhaps after several weeks, the wood was sawn into thinner slices using a bandsaw. This produced clean, flat faces, and it was frequently possible to measure the ring-widths without further preparation. Sanding of the surface was sometimes required, although this often gives a fluffy finish, which obscures the ring boundaries. A very useful tool in these circumstances was found to be an electric plane, but a very sharp handplane did, in some cases, produce an acceptable finish, although the problem of planing across the end grain of hard wood is notoriously difficult.

In the case of wet, relatively soft wood an alternative method of preparation was used. A thin slice was removed from the surface with a very sharp razor blade. This produced a clean cut through the vessels and fibres, and the ring boundaries were usually clearly exposed. Some of the wood specimens were too hard for this treatment, even when freshly collected.

As soon as possible after collection a note was made as to whether the centre of the tree and the bark were intact. It was sometimes necessary to measure the rings in the sapwood when wet, as considerable shrinking and disintegration may occur in this region when the wood is dried.
Plate 7  Collection of trunk section; fallen oak, Borth.
The ring widths were measured by three main methods. The simplest of these was by means of a x8 hand magnifier, with a built-in silvered scale (necessary for use on very dark oakwood) calibrated in tenths of a millimetre. This was perfectly adequate for wide rings. For narrow rings, a stainless steel ruler, calibrated in twentieths of a millimetre was used. The edge of this ruler was ground down at an acute angle, producing a very sharp edge, which could be laid flat on the surface of the section. The rings were examined using a stereomicroscope fitted with a x10, x20 or x 40 objective as required. It was possible to estimate ring widths to a greater accuracy than the calibrations, usually to within one-fiftieth of a millimetre.

A third method of ring width measurement was by means of the Kern PG2 Photogrammetric Plotter in the Department of Geography, U.C.W. Aberystwyth. Thin sections of wood (c. 5 mm) could be mounted directly in this instrument, and viewed by surface illumination. The floating mark could be moved from one ring boundary to the next, and on depressing a plunger the increments were recorded on punched tape, and the data could then be fed directly into the computer. The only disadvantages with this method were that the wood samples had to be completely flat-sided, and that they had to be perfectly clean, dry, and non-friable, to avoid contamination of the instrument.

The ring counts were carefully checked and coloured pins were inserted at every tenth ring, to minimise the possibility of mistakes. The ring widths were then plotted, either by hand, or automatically, as in the case of the figures in Appendix C. Two or more radii from each tree were usually measured, and checked against one another, to ensure that no rings had been missed, or duplicated. In some cases the measurements from the different radii were combined to give a single ring width graph for the tree. When attempting to match
two individual trees, the ring width plots, on tracing paper were superimposed and slid along until a good visual match was obtained. This, however, did not always produce a definite matching position and considerable ambiguity often remained. In many cases the matching position was obscured by the growth trend of the tree, i.e. the tendency to produce wider rings in its early years, since the total cross-sectional area added each year is relatively constant, whilst the circumference increases.

A computer programme devised by Baillie and Pilcher (1973) was used to produce a more objective determination of the best matching position. A slightly modified version of this programme is included here as Appendix A. The programme first removes the growth trend by converting the measured ring widths to indices, calculated by dividing each width by the average of a block of five ring widths (the ring itself and two on either side). The sets of indices for each tree are then compared at each position of overlap (defined here as the number of years the shorter chronology is moved from left to right along the longer) and a Student's t-values is calculated for each position, based not only on the agreement between increases and decreases in ring width, but on the magnitude of the variations.

Very good correlation at incorrect positions can of course occur by chance. This is clearly much more likely to happen when the overlap is short, so the fifteen year overlaps at either end of the series are ignored. It is generally agreed that correlations at overlaps of less than 70 to 100 years must be viewed with some suspicion. Baillie and Pilcher (op. cit.) suggest a t-value of 3.5 as the minimum which should be considered as an indication of a good match. At an overlap of more than 30 years this would imply a probability of less than 0.001 of the match occurring by chance. However, Pilcher et al (1984) have subsequently acknowledged that the t-values calculated by their programme cannot in
fact be converted into probabilities, since no allowance is made for autocorrelation of ring widths. This is a consequence of the "memory effect", whereby the growth of the tree in one year is influenced by that in previous years. Despite this drawback, however, the t-values produced are undoubtedly a very useful guide to the positions of good agreement. Values much higher than 3.5 were found in many cases, and there can be very little doubt that these suggested positions are correct.

**Determination of Organic Content by Volume**

The organic content of sediments was determined, in some cases, by the normal loss-on-ignition method, but in the examination of the transition from estuarine clay to peat (Ch. 8) it was necessary to find the percentage of organic material by volume. This was done by the following method.

1. Cubes of 2 x 2 x 2 cm were cut from the wet monolith and immediately weighed.

2. Each cube was then disaggregated by a water-jet and sieved through a 120 μm nylon mesh. The material passing through the sieve was examined under the microscope to ensure that the number of organic particles of less than 120 μm, being lost was not significant. This fraction had also been measured during the ZnCl₂ pollen extraction procedure (q.v.) and was found to be no more than 2% of the total volume.

3. The plant debris remaining on the sieve was allowed to drain for 2 mins., and then washed into a 25 cc measuring cylinder, using 10 cc. water from a pipette.

4. The organic content by volume was then calculated as in the following examples:-
(a) Depth of sample: 0-2 cm (peat)
Vol. of cube: 8 cc.
Wt. of wet cube: 12.25 g.
Density 1.53 g/cc.
Total vol. of water + organic debris: 21 cc.
Vol. of water added: 10 cc.
Vol. of organic debris: 11 cc.
% organic content by vol. = \( \frac{11}{8} \times 100 = 137\% \)

This figure of more than 100% is a measure of the degree of compaction of the peat. In the undissected monolith, the stems, etc. were flattened. After disaggregation and re-suspension, these had returned to their original tubular shape. The figures suggest that the peat has been compacted to \( \frac{11}{8} = 73\% \) of its original volume. The dry weight organic content is, however, c. 60%, so that the original would be greater than 11 cc., by the volume of the silt content, a total of c. 11.5 cc. It would have been possible to estimate the degree of compaction of the silt by re-suspension, but as the silt is, in comparison to the peat, compressible to only a small degree, it was not felt to be worthwhile in this instance. As a further check, the organic debris was dried at 100°C for 3 hrs and weighed.

Dry wt. organic debris: 1.33 g.
Density of dry organic debris, using wet (= living) volume

\( = \frac{1.33}{11} = 0.121 \text{g/cc.} \)

(b) Depth of sample: 20-22 cm (organic clayey silt)
Vol. of cube: 8 cc.
Wt. of wet cube: 16.78 g.
Density, 2.1 g/cc.
Total vol. of water + organic debris: 14.0 cc.
Vol. of water added: 10.0 cc.
Vol. of organic debris: 4.0 cc.
% organic content, by vol. = \( \frac{4.0}{8.0} \times 100 = 50\% \)

Dry wt. organic debris: 0.485 g.
Density of dry organic debris, using wet (= living) vol.

\( = \frac{0.485}{4} = 0.121 \text{g/cc.} \)

The full results from this monolith are given in Table 8.1.
CHAPTER THREE

GROWTH AND PRESERVATION

Having, in the previous two chapters, considered the distribution of the various types of submerged forest, and the nature of the closest present-day analogues, it is possible to discuss the ways in which these forests could have grown and been preserved. This will be done before proceeding to a more detailed description of individual sites, since this will enable the whole range of theoretical possibilities to be considered for each forest, rather than attempting to deduce their history on the basis of assumed causes and effects, from the often limited, and possibly misleading evidence seen at individual sites.

Two separate environments must be considered; firstly that which allowed the growth of forest trees and possibly brought about their death, and secondly that which caused them to be preserved throughout the following millennia. There were undoubtedly many coastal forests which flourished during the earlier Holocene, and which left no trace, whilst on the other hand many well preserved peats, etc., were formed in environments unsuitable for trees.

It is necessary to consider what degree of change is necessary in an environment to convert it from one in which trees could grow to one in which decay was sufficiently inhibited to allow the remarkably good state of preservation typical of submerged forests. Such a change could clearly come about as a result of a rapid rise in water-table but this could be brought about in various ways, and other factors may be involved. Changes in the water-table may be more or less direct responses to changes in sea level, or they may be entirely unrelated to them.

Forest beds may have been formed on advancing or retreating coastlines, although they can clearly be exposed in the intertidal area as submerged forests, only if an overall retreat has occurred since the trees grew. The relationships between varying rates of sea level change and sediment supply must therefore, also be considered, as follows;
(1) Rising sea level, retreating coastline (sediment supply low).
(2) Rising sea level, advancing coastline (sediment supply high).
(3) Static sea level, retreating coastline.
(4) Static sea level, advancing coastline.
(5) Falling sea level, retreating coastline.
(6) Falling sea level, advancing coastline.
(7) Oscillating sea level, in particular a fall interposed in period of overall rise.

Other possible combinations seem to be very unlikely to produce submerged forests.

Considering the above in more detail:

(1) Rising sea, retreating coast.

The normal consequence of a rise in sea level will be a retreat of the coastline, and during the period of rapid rise, during the earlier Holocene, this retreat would be brought about by the progressive submergence of the tree-covered topography of pre-Holocene sediments. If this were gradual, then the forest edge would retreat up-slope, as trees at the seaward edge were killed, either by increasing salinity, by waterlogging as the freshwater table rose, or by burial under a coastal barrier which was pushed inland by the rising sea.

Woodland might be replaced directly by salt marsh, as the latter moved inland, or a belt (of width determined by the degree of relief) could develop, in which the woodland was converted firstly to carr and then to fen. If sediment supply were sufficiently great, the boles of the dead trees (and any fallen trunks) could be buried by salt marsh silts and clays before they rotted away. Unburied trunks would decay much more quickly.

It must be noted here that it is, no doubt, possible for estuarine or brackish-water sediments to be lain down on top of organic beds, even on a
retreating coastline (Figure 3.1). This would be more likely to occur when sea level was rising than when it was static, since such sediments would only accumulate as a result of inundations. The result of the accumulation of deposits, under these conditions, would be the formation of a basal forest bed, following the undulations of the pre-Holocene deposits, the higher levels being the more recent, and covered by salt marsh clays and silts, by fen peat, or possibly by dune sand or storm beach shingle.

Closed basins in the pre-existing surface would become lagoons, and trees which were growing there would be similarly killed and preserved. Such basins might be flooded, well before the normal tidal levels reached them, by extreme tides. The water would not drain away, when the tide fell, and trees would be killed. Valleys draining to the sea could be blocked at their seaward end, by shingle etc., and subsequently behave as basins.

If, in recent times, continued retreat of the coastline exposed the beds to wave-attack, the overlying sediment could be stripped off and the submerged forest bed revealed.

It is difficult to imagine that trees would be preserved for long periods simply by being inundated by the sea. Such trees would be killed, and then exposed in an intertidal area, where they would be susceptible to wave-attack, and to alternate wetting and drying, and also to breakdown by fungi, bacteria, boring molluscs, etc. They would be far more likely to disintegrate than at a site with a freshwater table determined by the same sea level, since here the probability of stagnant, anaerobic conditions would be higher.

In the case of forest beds which now seem to be simply submerged, with no cover of later sediment, e.g. the North Sea "moorlog" (Godwin, 1943) and the woody peat found on the sea bed in Cardigan Bay, the tree remains would seem to have been incorporated into peat beds which were compacted before submergence; the trees are not simply a drowned forest.

(2) Rising sea, advancing coast.
Fig. 3.1 Sequence of events leading to the burial of peats by clays, etc., on a receding coastline, when erosion of the beds might be expected.

Fig. 3.2 Formation of peat beds at progressively higher levels, on an advancing coastline, during a period of rising sea level.

Fig. 3.3 Formation of intertidal forest bed, with no change in sea-level, as a result of retreat of the coastal barrier, and gravitational compaction.
Whilst, in the earlier part of the Holocene, when sea level rise was very rapid, almost all coastal areas would have undergone progressive submergence, it is likely that, as the rate of rise slowed somewhat, advance of the coastline could have occurred when the supply of sediment was sufficiently great. In this case, a salt marsh, or a storm beach or dune system would have moved seawards and, at the same time, risen with sea level. In the areas of slacks, fens or lagoons behind the coastal barrier, peat growth, impelled by the rising water table would be rapid. The peat-forming vegetation would, at any one time, be in a more or less horizontal plane, but the start of peat formation, at the seaward edge, would be progressively later as the coastline advanced, so that the base of the peat would slope upwards to the sea, forming a basin, infilled by peat (Figure 3.2).

The combination of an advancing, or even a stationary coastline, and rising sea level would clearly be one of a somewhat unstable equilibrium. In many instances, the position of the coastline would be largely determined by headlands, or other features of the pre-existing topography, so that there would be a considerable inertia in the system, which would eventually be overcome either by the steady rise of sea level, or by a catastrophic event, the position of the coastal barrier being suddenly moved to a new position of relative stability. This would probably be the fate of most advancing or stationary barriers when sea level rise was rapid. Over-topping or breaching of the barrier would allow flooding of the basin behind it, laying down silts and clays on top of the peat layers. Inlets or lagoons, etc., would therefore, be infilled by intercalated peats and clays, and the coastline would, in effect advance, even at times of rising sea level. A basal peat, following the floor of the basin might be found together with the horizontal peats (Figure 3.2).

Conditions suitable for trees would be unlikely in this situation, except at the landward edge of the basin, where a raised bog might also develop, and the trees in this position would be less susceptible to subsequent exhumation by the sea, and exposure in the form of submerged forests. This
exposure could, of course, occur only if the advance of the coastline were subsequently reversed. Many potential submerged forest beds are now preserved as buried forests, well inland.

The growth of trees might have been possible near to the coastal barrier during relatively brief intervals, and their remains could be preserved in the intercalated peats. The trees growing on the earlier surface immediately before tidal effects were felt, might also be preserved, at the base of the peat and clay infill.

(3) Static sea level, retreating coast

With no rise in sea level, there would be no consequent rise in the fresh water table in coastal areas, and peat growth above the general surface would occur only by the development of raised bogs. Trees would not as a rule, therefore, be killed and preserved by the development of fen peat round them. Lagoons, etc., would be gradually infilled, however, and trees could then grow on the resulting bog surface and be subsequently overwhelmed and preserved in Sphagnum peat. These trees could, without any change in sea level, be buried by a retreating storm beach, or by dunes, which could cause a considerable degree of compaction of the peats (see below, this Chapter) so that when the barrier was pushed back still further, leaving the peats on its seaward side, the trees would be at a level below that of high tides (Figure 3.3).

Trees which grew on mineral soils could similarly be preserved by Sphagnum peat spreading onto them from an adjacent bog, or by burial under a coastal barrier, and could also be subsequently exposed as submerged forest beds, although, as the extent of compaction would be much less than with a peat substrate, the forest bed would be virtually at its original level, and be reached only by highest tides.

The storm beach, pushed inland by the sea, is very likely to block the mouth of a river, and cause ponding-up of drainage water. This could kill trees by waterlogging, and preserve them, without any rise in sea level, and
the coastal barrier could subsequently pass over them, exposing them as a submerged forest on the foreshore. Catastrophic breaching or overtopping of the storm beach could have a similar result, either through a rising water table, or the increase in salinity. Godwin (1943) cites the example of a site in the Norfolk Broads, many miles from the sea via the meandering river channel, but close to it in a straight line, where breaching of the coastal barrier flooded an area hitherto completely isolated from the influence of the sea. The depth of flooding which would, under natural circumstances occur, appears however to be somewhat exaggerated, since it is based on the supposition that the amplitude of the tidal wave will be diminished as it passes up-river, so that the water level inland will be near to mean sea level, but this does not take into account the gradient needed to allow the escape of drainage water to the sea. This gradient varies, of course with the state of the tide, and the determination of the “average” sea level which controls the level of the river in its tidal reaches is very complex; depending on the tidal range, the form of the river channel and of its mouth, the volume of freshwater discharge, etc.

In the Somerset Levels, the lowest areas, which are well inland, are virtually at the water-table, that is, at river level, at a height of c. 2.1 m O.D. The surface level of the coastal clay belt (see Kidson and Heyworth, 1973 and 1976) is at c. 6 m O.D. However, the low inland level is only maintained by an elaborate system of sluices and pumping stations, and has been gradually lowered over the centuries (Williams, 1970) as increased drainage has caused the underlying peat to shrink, lowering the surface, and requiring even greater effort to avoid flooding. If artificial drainage were to stop, then the water-table in the inland area would rise to probably 4 or 5 m O.D., and eventually peat would grow up to this level also. If Godwin's hypothesis were correct, then the flow in the river would consist only of the same water moving upstream at high tide and downstream at low tide, with the gradient being reversed, and no net outflow. It follows that, only in areas
with a very small tidal range can the inland river level approximate to that of mean sea level. Nevertheless, it is still quite possible for breaching of the coastal barrier, in the situation described, to produce dramatic effects on the inland vegetation, since extreme tides can be well above the freshwater level.

Consideration of the above points shows that there are many ways in which a buried forest bed could be formed at a time of static sea level, and could later be exposed on the beach as a submerged forest bed, giving the impression that a rise in sea level had been responsible.

(4) Sea level static, coast advancing

There are two main ways in which the coastline can advance when sea level is static. Firstly a coastal barrier can build out in a seaward direction, as e.g. the dunes on the South Lancashire coast (Ainsdale, etc.) or the shingle complexes of Bridgwater Bay, Somerset (Kidson, 1960). In these and similar cases the landward dunes or ridges become fixed and vegetated, and seaward extension requires new material to be brought in from elsewhere; the earlier barriers do not themselves move seawards, and the whole complex becomes wider. Low-lying areas of slacks or lagoons behind the coastal barrier will be infilled by peat, and buried forest beds may be preserved there, to be exhumed during a later retreat of the coastline, and exposed as a submerged forest. This area of peat formation will not, however, move seaward as the coastline advances, since it is bounded by the earlier barrier.

The second way in which the coastline can advance is by the development of an increasingly extensive salt marsh in front of the earlier storm beach. Good examples of this type of development are seen in Morecambe Bay, Lancashire. The tidal cover of the landward areas of the salt marsh becomes less and less frequent, and eventually trees may colonise the marsh, probably spreading from the fens or mosses present in the inlets of the earlier coastline. Slight changes in the tidal regime or in the positions of drainage channels in the
marsh could render these areas unsuitable for trees, which might be killed and preserved by increased accumulation of salt marsh clays and silts around them. It is also possible that a new barrier could develop at the outer edge of the marsh, resulting in the ponding up of freshwater, and the conversion of the salt marsh to fen or carr. A subsequent small rise in sea level would suffice to bring the resulting peats to a position where they might be exposed as submerged forest bed.

There is, of course, no sharp dividing line between an imperceptibly rising sea level and a very slowly rising one, and the pattern of development described above could occur during a period of slow rise, which if continued, could perhaps, because of the diminution of sediment supply, submerge the previously emerged areas. Regressions and transgressions could result from the same rate of rise.

(5) Sea level falling, coast retreating.

It is possible, in a high energy environment, for a retreat of the coastline to occur even if sea level is falling. With an imperceptibly slow rate of fall, this retreat could go on for long periods; with a rapid rate of fall the period would be limited, since wave energy would be dissipated in the increasingly shallow sea.

As sea level fell, areas previously occupied by fen or bog would, as a result of the falling water table become suitable for tree growth. The margin of the woodland would then move towards the sea. If at the same time, a coastal barrier were being pushed inland, it is probable the trees would be buried by shingle or by dune sand, and even that the woodland itself would be subjected to wave-attack, roots and branches being incorporated in contemporaneous storm beach material. This phenomenon has been noted at a number of sites and is worthy of particular attention, since there are very few present day sites in Britain where mature trees are found near to an active storm beach.
(6) Falling sea level, advancing coastline.

This is obviously a more likely combination than the previous one. A falling sea level, would in general, allow salt marsh vegetation to colonise areas of the beach slope, which previously experienced too great a degree of submergence, whilst the landward edge of the salt marsh would also move towards the sea, followed by a fresh water zone, and probably woodland. Trees would colonise areas at progressively lower levels, reversing the pattern of rapid sea level rise, when the woodland margin was pushed back up the earlier slopes. However, there is an important difference between the two situations, since the falling sea would not preserve the woodland in its wake. Trees which grew on areas previously below high tide level would not be preserved when they died; they would simply decay and disappear as in any other normal forest. If woodland spreading down a beach slope were preserved it would show a very characteristic pattern, in that the lower trees would be more recent than the higher, unlike the general rule for the vast majority of sea level related organic deposits from the Holocene, that is; the higher the bed the more recently it was formed.

There seems no obvious way, however, in which trees in this situation would be preserved. Even if living trees were found to be growing on a Holocene salt marsh deposit, it would be difficult to prove that this was not simply the result of local changes in the coastline. It is therefore unlikely that evidence of this pattern of colonization, as a result of falling sea level, will be found. If a subsequent rise in sea level occurred, then some trees would be preserved.

(7) Oscillating sea level; fall interposed in general rise.

If the fall in sea level (described under 6) were followed by a rise, then the lowest point reached by the trees as they colonised the beach slope, would very soon be rendered unsuitable for trees once more, as the water-table rose. Higher trees would be killed and preserved by continuing sea level rise, exactly as during the formation of the basal peat (as described under 1).
At such sites the preserved evidence of a fall followed by a rise would, therefore, be a sloping forest bed equivalent to the basal peat, but resting on the earlier salt marsh clays or silts, rather than the pre-Holocene deposits. Other substrates uncovered by the falling sea would, of course, also be available for colonization by trees. The most recent trees would, again, be the highest. At the lower limit of the bed, marking the turning point in sea level, from fall to rise, there would be a zone without trees, or with only very short-lived specimens, since the period during which this level was free from marine influence would be short. The effects of sea level changes on the ages of the trees is discussed further in Chapter Eight.

It has been implicit in the work of several authors, e.g. Tooley (1974), that a rise in relative sea level will bring about a transgression, whilst a fall of sea level will cause a regression.

This may not always be the case, so that an oscillation in sea-level could occur, whilst the coastline was continuously advancing or retreating, the behaviour during the rising and falling phases and intermediate stands being as described above, under 1 to 6.

If, for example, the rise-fall-rise sequence occurred at a site with abundant sediment supply, the advance of the coastline might be continuous throughout, especially if the rate of rise were only moderate. In this case, low-lying areas would be formed behind the coastal barrier, when sea-level began to rise once more. Extensive lagoons could be developed in this way, and these would be likely to undergo rapid infilling by peats, driven by the rise in water level.