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THE WEALDEN ENVIRONMENT: ANGLO-PARIS BASIN

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CONTENTS

The Wealden cyclothems in the Weald are distinct from other sedimentary cycles so far reported. Their re-interpretation is based on recent sedimentological studies of analogous modern environments.

The largely arenaceous lower part of each of the two megacyclothems in the Hastings Beds records the several environments of a growing and subsiding delta pile. Levee, crevasse and backswamp alluvium, pond-and-mere muds, channel sediments, shoreface sands, distributary mouth-bar and pro-delta deposits, etc., seem to be recognizable. The deltas advanced into lakes with fairly steady or falling water levels. Rates of deposition, up to 1 cm per 5 to 6 years, are suggested by certain of the fine-grained shoreface sands. 'Classical' rather than birdfoot types of delta seem to be represented. The exposed portions were surrounded by extensive shallow water platforms. No major breaks of underwater slope are detectable: large-scale foresets are probably absent.

The upper argillaceous parts of the megacyclothems, *together with the back-delta* (*northern*) *portions of the arenaceous members immediately beneath*, are now regarded as having been formed during times of rising lake level. The clays and their basal beds are transgressive delta-front and pro-delta lake-sediments, while the back-delta sands and silts below seem to have been valley-plug, levee and crevasse alluvium formed earlier behind the retreating coast in direct response to the rising base level. Alluvium also constitutes the more argillaceous parts of certain minor cyclothems of a different type. Extensive horsetail reedswamp grew offshore during times of retreat. The reeds were not able to establish themselves everywhere during periods of deltaic advance, owing to rapid silting, more frequent scour and the greater depth of suitable bottom sediments. Bigger plants as well as scattered horsetails grew on the surfaces of the deltas. Estuaries-of-inundation must have characterized these periods. The first major (Wadhurst) transgression advanced quickly, the reed beds in any one place lasting only a few years. Birdfoot deltas may have formed during its early stages for a short while.

Close lithological, faunal, floral and petrological similarities between the cyclothems show that the same changes of environment were repeated several times. Probably the major fluctuations of lake level were in part relative only, being due either to changes in the rate of subsidence or to repeated river diversions causing the periodic abandonment of deltas and their consequent inundation. But, at certain horizons, continuity of deposition between the Wealden of Sussex and that of northern France is indicated by the petrology of the detritus. Hence the long-term fluctuations in lake level were probably also due in part to distant movements of the sea back and forth across the Paris basin. These in turn would have influenced channel 'fixing' and abandonment in the English alluvial plain.

Short-term fluctuations of lake level were numerous. Some, near the base of the Wealden, may have been tidal in origin. Others took place mostly during times of deltaic advance.

Several lines of evidence suggest the existence of well-marked seasons.

Fundamental changes occurred during Weald Clay times, when the Wealden environments gradually coalesced and became transformed into a brackish arm of the advancing sea.

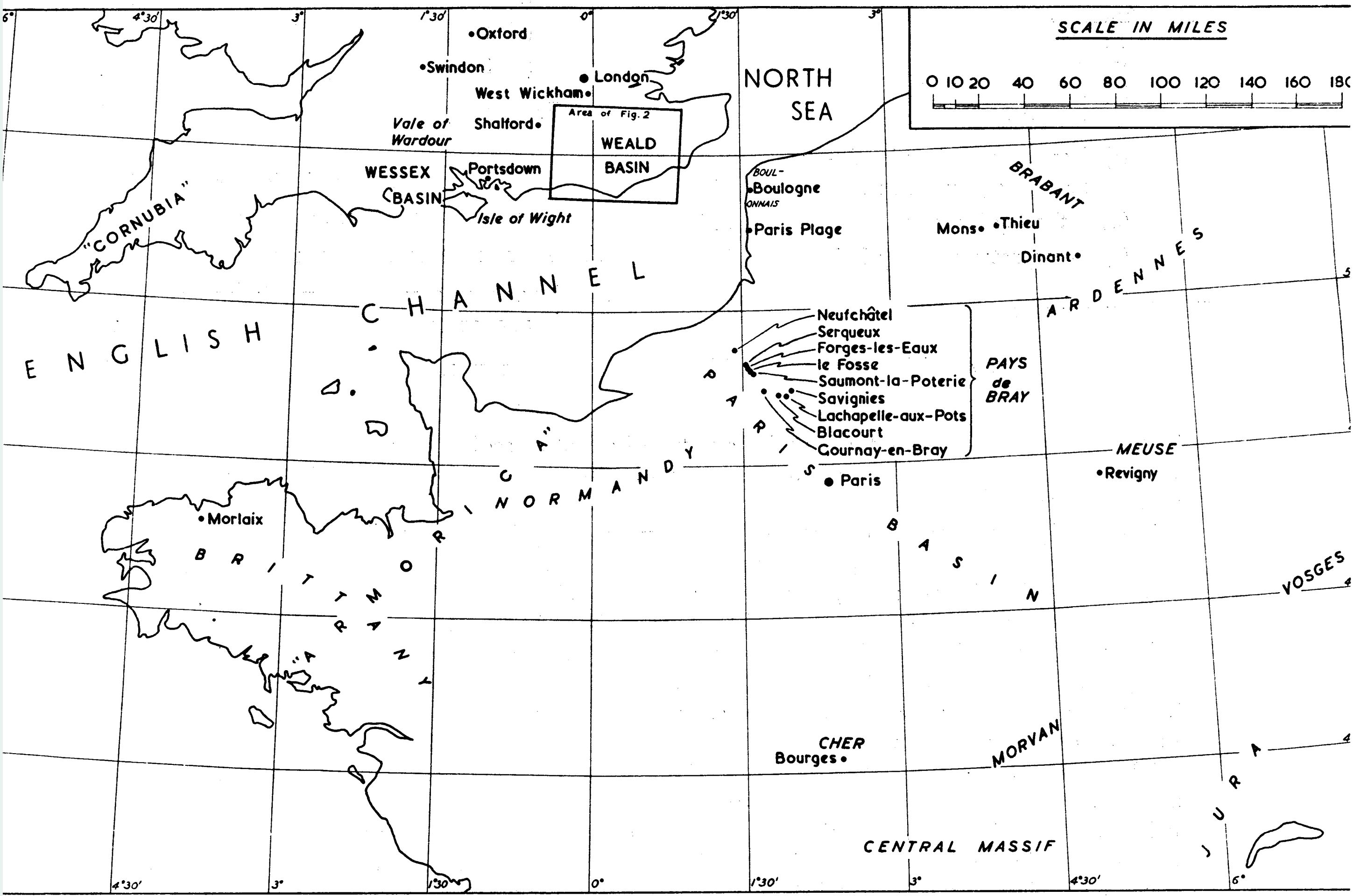

FIGURE 1. Districts and localities in western Europe mentioned in the text.

I. INTRODUCTION

During the past 100 years the Wealden of the Anglo-Paris basin (figure 1) has been variously described as 'alluvial', 'fluviatile', 'lacustrine', 'deltaic', or 'estuarine'. Recent work suggests that all these environments are represented, and that changes from one environment to another may have been controlled by movements of the sea on the Wealden margin (1955*a*, p. 278).*

The present paper examines the evidence for these conclusions. Particular attention is paid to the interpretation of the Wealden cyclothems and to searching for their causes.

II. Weald basin†

(*a*) *General*

The Wealden facies of the Anglo-Paris basin is best displayed and developed (up to more than 2000 ft.) in the Weald itself (see general locality maps, figures 1, 2). Broadly, it comprises a sandier and largely fresh-water series below (Hastings Beds) with a more argillaceous and brackish member above (Weald Clay).

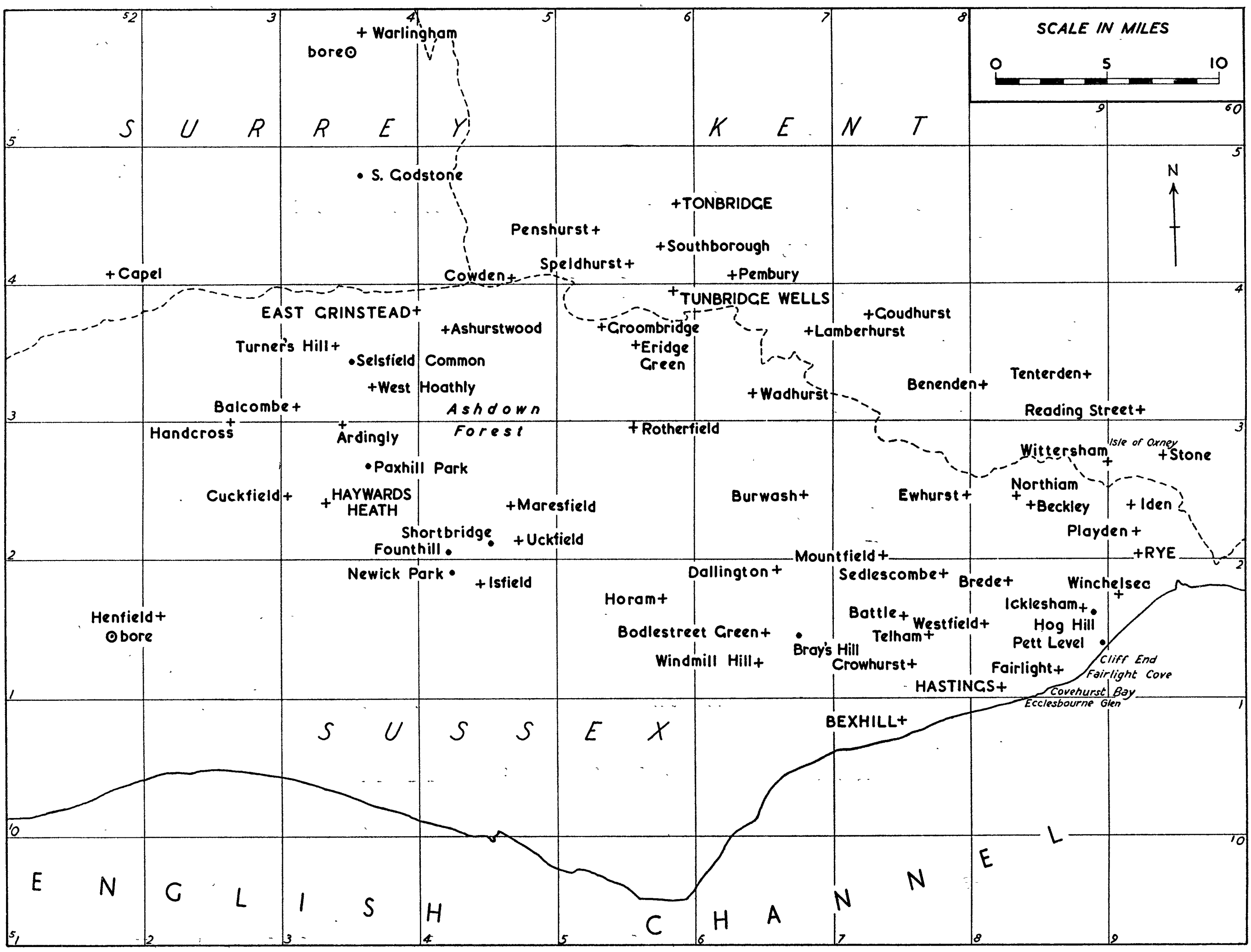

FIGURE 2. Places in the English Weald referred to in the text. Crosses mark parish churches.

The rocks present many puzzling features, all of which must be accommodated in any theory of their origin. Variability is their keynote. Thus while, for example, the commonest sediment in the Hastings Beds is fine silt, the strata vary rapidly from place to place

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* References with no name attached refer to the author's published work.

† A guide to the field evidence presented in this section is provided by reference 1959.

and horizon to horizon, ringing all the changes between conglomerate and pure clay, sorted and unsorted deposits. One common thread recurs continually: signs of shallow water and brief exposure (ripple marks, soil beds, desiccation cracks, pellet beds, footprints) are present in many lithological facies. Waterside and fen-forest vegetation was never far away. The famous Fairlight plants, for instance, must be very local: they are far too delicate to have travelled far. Further, stretches of shallow water and exposed sediment were sometimes extensive, for the non-swimming *Iguanodon* could get as far as the present Sussex coast (Beckles 1854; Tylor 1862; Topley 1875; Milner & Bull 1925; White 1928), 40 miles from the nearest margin of drier ground, and some of the suncracked horizons are widespread (p. 300).

The vertical succession is also puzzling. Indeed, the Hastings Beds (and to a lesser extent the Weald Clay) are remarkable in being dominated by a unique* type of sedimentary rhythm (1950). The 'standard' cyclothem may be summarized (figure 3) as:

– – – – (gradual passage or sharp break with erosion) – – – –

(viii) THICK DARK OSTRACOD CLAYS
Pyritous; *Viviparus*; bands of *Neomiodon* with scattered fish scales. Thin sandstones and siltstones. Seams of clay-ironstone nodules towards base.

(vii) THIN *NEOMIODON* SHELL BEDS
Gastropods rare. Clay-ironstone locally.

(vi) THIN DARK CLAY
Partings of aerial horsetail debris near base.

(v) *b* *EQUISETITES LYELLI* SOIL BED (WITH *PHYSA*)
At top of alternating series of

a THIN CROSS-LAMINATED LENTICULAR SANDSTONES, SILTSTONES AND CLAYS forming perfect passage from (iv) to (vi). Local bone beds.

(iv) THIN GRADED PEBBLE BED
Top rippled; interior rippled and/or current-bedded, with local suncracks. Oversteps all sedimentary structures and changes of facies below. Exotic pebbles dominant. Scattered debris of horsetails and other plants frequently forms parting at base.

– – – – sharp break with erosion – – – –

(iii) THICK SANDSTONE	ARGILLACEOUS SANDY SILTSTONES
In southern outcrops.	In northern outcrops.
Coarsens upwards; scattered pebbles, suncracks and roots (not horsetails) locally near top.	Replace top sandstones.
Local flat-bedded well-sorted silver-sands, large-scale cross-bedding, washout structures, etc.	Soil beds (including *E. lyelli*).

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* Since the above was written a cyclothem of the same type has been located in the Dakota formation (Lower Cretaceous) near Morrison, Colorado, during a visit kindly arranged by the Ohio Oil Company.

(ii) THICK LENTICULAR SILTSTONES AND SILTY CLAYS

In south forming, by gradual coarsening, a perfect passage upwards into (iii). *Unio*. Local soil beds (including *E. lyelli*).

In north contain more SANDSTONE, fining upwards into (iii).

(i) THICK SILTY CLAYS

Thickest in south. Locally red or red-mottled. Grade upwards into (ii).

Northwards partially replaced upwards by siltier and sandier beds.

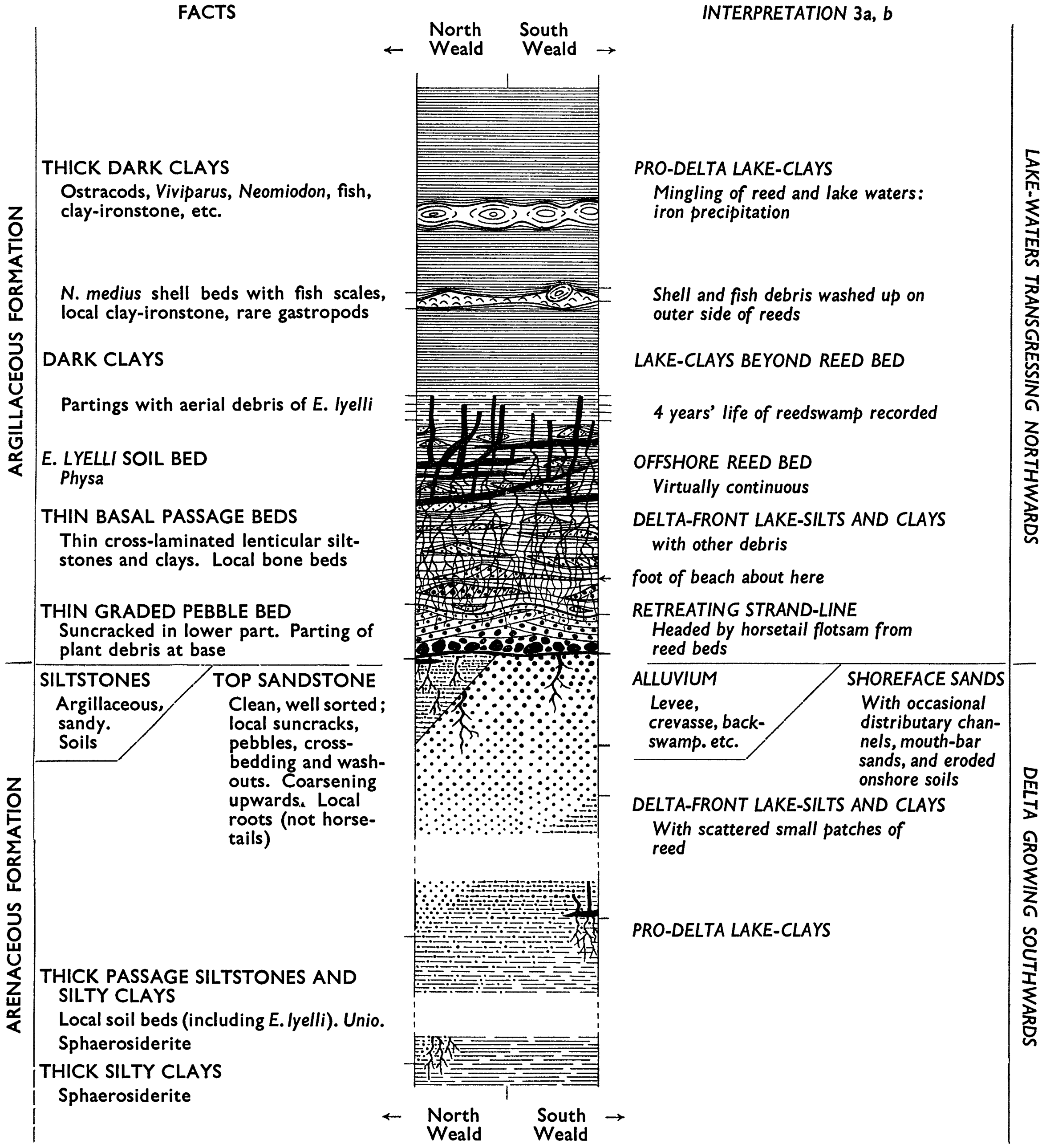

FIGURE 3. The 'standard' Hastings cyclothem. Labels on the right-hand side of the column refer to Interpretation 3*a* and *b* (pp. 318 to 333).

In some cyclothems certain of these beds may be missing, locally or regionally; in others they may be duplicated or repeated several times. It is a striking fact that, above the sharp break in the middle of the cyclothem, all horizons tend to become extensive and more homogeneous laterally. The thin beds (iv) to (vii) can be extraordinarily widespread, demanding such uniformity of conditions over great areas that they must surely be diachronous.

The Hastings Beds comprise two complete megacyclothems:

1 {Wadhurst Clay / Ashdown Beds 2 {Grinstead Clay / Lower Tunbridge Wells Sand;

and possibly part of a third

3 {lower Weald Clay / Upper Tunbridge Wells Sand,

but the stratigraphy at this level is imperfectly known.

Minor cyclothems of the same general type account for some of the small-scale variation within the megacyclothems (1959). This is true of the Wadhurst Clay (e.g. 1949*b*, figure 47), the Upper Tunbridge Wells Sand (e.g. cyclothem associated with the Balcombe Clay) and the middle and upper Weald Clay (e.g. 1948; Kirkaldy & Bull 1948). Every gradation exists between some of the larger and smaller cyclothems. In a general way the smallest tend to be the simplest, those only a few inches or feet thick often consisting merely of

(iii) CLAY

Silty at base, becoming less silty upwards. Local sandy washouts.

(ii) THIN PELLET-CONGLOMERATE

Locally-derived pellets of siltstone, sandstone or clay. Few or no exotic pebbles.

– – – – sharp break – – – –

(i) SANDSTONE

Coarsening upwards; well sorted; local cross-bedding.

At least one megacyclothem passes laterally into a minor cyclothem of this type (p. 303), but others seem to be fundamentally different (p. 298).

Topley (1875, p. 56) was well aware of the constant repetition '...we very frequently find rock-beds underlying clay, with the upper part of the rock coarse or containing pebbles. This occurs also at times even with the subordinate beds of each division, ..'. But unfortunately the example chosen, south-west of Winchelsea, which he thought lay well down in the Ashdown formation, actually represents the normal top (1959).

Exotic pebbles and coarse sand are rare in the Wealden, and form a negligible proportion by volume of the whole. Thus the graded conglomerates of the cyclothems are their most striking features, and indeed set them apart from other sedimentary cycles. For many years the pebble beds have seemed to be among the most important horizons in the Wealden, but their significance proved elusive. This was due in part to the misleading resemblances between the cyclothems and their classical counterparts in the Upper

Carboniferous. From such comparisons it is only too easy to ignore the conglomerates and assume that the soil beds represent plants growing on the delta surface, colonizing the alluvial topsets of a 'conventional' delta spreading into a continuously subsiding basin (1949*a*, p. 271). In this light the succeeding thick clays would obviously represent back-delta swamp and lake deposits.

But, though the Hastings cyclothems are in part clearly deltaic (laid down along the southern margin of the London–North Sea uplands), it must be remembered that the deltas spread into a large *fresh-water* lake. Consequently the horsetails were just as likely to have lived *offshore of the delta* as on the exposed surface of the delta itself. The clayey strata above the pebble beds would then represent transgressive delta-front and pro-delta lake deposits and, as will be seen, this provides the key to a new interpretation of the cyclothems.

(*b*) *Ashdown–Wadhurst megacyclothem*

(1) *Succession*

The detailed succession within a cycle is best illustrated by the widespread Ashdown–Wadhurst megacyclothem. This begins in the south-east Weald as a gradual change, by alternation and coarsening, from the grey silty clays (rich in drifted plant fragments, including *Equisetites lyelli*) and brightly mottled silty clays (unfossiliferous, sphaerosideritic) dominating the Fairlights, through pale ill-sorted silts and siltstones to the fine and medium sandstones of the upper Ashdowns.

At first the (Fairlight) succession shows practically no signs of exposure and very few of deposition in really shallow water. But when the mid-Ashdown silts and sands come in rootlet beds (1947*a*), footprint horizons, etc., begin to appear, though they always remain rare. The silts are sphaerosideritic, finely cross-laminated and lenticular on a small scale (see e.g. White 1928, pl. III A). They are poorly sorted, carrying a good deal of clay. Here and there wedges of mottled clay develop locally, and near the ill-defined Fairlight–Ashdown boundary there are puzzling washout-like structures, filled with fine sediment bedded parallel to the sides (Topley 1875, p. 47, figure 3; also White 1928, p. 39, figure 6). When these structures intersect (e.g. White 1928, p. 37) they simulate large-scale 'festoon'-bedding. Load casts, flute casts, contemporaneous slump folds and balls characterize certain localities (1959), and broken bands of siltstone are common where enclosed in clay: some of the disrupted rafts are typical 'pull-apart' structures with 'necked' margins. Good examples may be seen at Fairlight Cove where, in one instance, they lie at the feet of high foresets and the sandy balls and slumps are obviously due to slipping down these (see below; also 1959). Comparable structures also occur in the remaining argillaceous formations of the Hastings Beds and Weald Clay, though not usually associated with foresets. Articulated valves of *Unio* are sometimes found in the silts.

The upward transition from clay to sand in the south-east Weald is by no means smooth. Major reversals are common, and the mid-Ashdowns of the coastal section (Bexhill to Pett Level: 1959) show large foreset units piled on top of each other. A conglomeratic (bone bed) horizon occurs also (1959). Evidently the delta pile was composite. On average the major foresets slope south-westwards; whether true topsets are sandwiched between is not clear. One large unit exposed in the cliffs at Fairlight Cove is wedge-shaped

(White 1928, figure 5), and may be traced continuously from the Haddock's Steps fault (where the foresets are more than 30 ft. high) to a point $\frac{1}{4}$ mile north-eastwards where it wedges out (1959). The sandy foresets are rhythmically bedded and the hollow in which they lie, cut down nearly to the Fairlight Clay, is floored by pellet-conglomerate. Where the foresets pass into bottomset less-sorted siltstones and clays, slump structures (including sandstone balls) are common, and the 'pull-apart' load structures are best developed.

North-westwards across the Weald the upward transition to coarse sediment gradually comes in earlier, so that the lower Ashdown horizons seem to coarsen in that direction. (See, for example, the sandstones exposed in the Kent Water valley west of Cowden; Ashdown Forest, etc.)

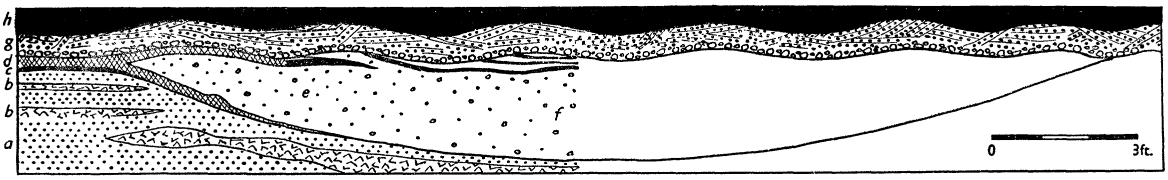

FIGURE 4. Plugged Ashdown distributary channel. Locality: east side of Goatley Farm, north of B 2165, $\frac{1}{2}$ mile south-west of Horns Cross, Northiam, Sussex.

h = Basal Wadhurst Passage Beds.
g = Top Ashdown Pebble Bed. Pebbles (up to 1 in.) chiefly quartz, including many only slightly abraded crystals.
f = Compact white sandstone with little or no carbonaceous plant material.
e = White, poorly cemented sandstone with scattered pebbles chiefly quartz (up to $\frac{1}{2}$ in.) and thin bands of finely comminuted carbonaceous woody matter ('sawdust').
d = Grey sandstone heavily laden with 'sawdust'.
c = Sandstone blackened with 'sawdust'.
b = Pellet breccias in top Ashdown sandstone with fragments (up to 3 in.) of fine sandstone and siltstone.
a = Coarse top Ashdown sandstone with scattered pebbles, chiefly quartz (up to $\frac{3}{4}$ in.), pellets of sandstone and siltstone, and 'sawdust'.

About 30 to 50 ft. from the top in the south-east Weald (Hastings, Battle, Mountfield, Ewhurst) there is a persistent band of shales or clays containing the tree-fern *Tempskya* (Topley 1875; White 1928). The fossils, which are silicified, are only slightly abraded and may have lived in the vicinity. Calcareous *Neomiodon*-beds occur at about the same level in the undercliff north-east of Rye. Above, the progressive upward coarsening continues over the whole central and south-east Weald, resulting in a variable thickness of fine or medium sandstone at the top (1949*a*, figure 1). Rarely, as in the extreme south and south-east, the coarser sandstones are sprinkled or seamed with pebbles (e.g. Wittersham, Rye, Icklesham, Fairlight, Burwash); or 'festoon' false-bedded (e.g. Lamberhurst); or false-bedded on a large scale with foresets more than 8 ft. high. (e.g. Dallington: 1947*b*, p. 78). Usually, however, the sandstones are well sorted and flat-bedded and do not contain sphaerosiderite. Finely comminuted plant remains become steadily commoner upwards: hence the glass-sands of Rotherfield, Crowhurst and Fairlight. Near the top rootlets, larger and sparser than those of *E. lyelli*, occur in the East Cliff, Hastings (White 1928,

p. 41)*; and at Brede (figure 5) and a few other places the plant debris is aggregated into regularly spaced partings (annual laminations?), each separated by an inch or two of relatively barren rock. The degree of sorting of both the unbedded and flat-bedded glass-sands is high for the Wealden, 80 % by weight of the particles (mostly quartz) often lying within the 0·25 to 0·50 mm grade (figure 9) (data from Boswell 1916, 1917). Types of cumulative curve obtained are commonly 's' and 't' of Doeglas (1946) and 'm' of Andel & Postma (1954). The advanced sorting is also shown by the heavy detritals. Moulds of *Neomiodon* valves are scattered here and there. Rare washouts occur in the sands; one example near Northiam (south-east Weald, figure 4) is 20 ft. wide, 2½ ft. deep and filled with poorly sorted sand, bedded concordantly to the channel sides and replete with exotic pebbles and locally derived pellets of sandstone (cf. that at Fairlight).

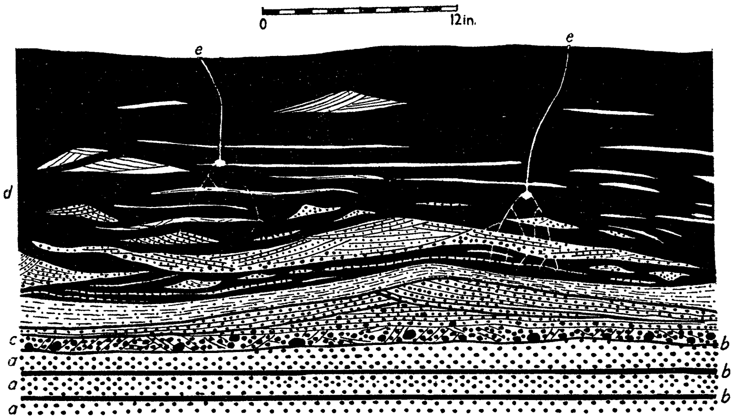

FIGURE 5. Depositional structures at the Ashdown–Wadhurst junction. Measured drawing. Locality: Hare Farm Lane, Brede, Sussex.

e = Rootlets, rhizomes (seen end-on) and stems of *E. lyelli*.
d = Basal Wadhurst Passage Beds. Clay shown black. Note lenticles ('biscuits'). Compare figures 10, 13.
c = Top Ashdown Pebble Bed.
b = Partings of comminuted plant debris.
a = Glauconitic top Ashdown sandstone.

N.B. The Brede Bone Bed (discontinuous runnel-fillings: 1949*a*, figure 1) does not appear in the part of the exposure drawn.

North and north-westwards, as already seen (1949*a*), the particle size and sorting of the topmost Ashdowns decline, the beds passing laterally into a few feet of clayey silt and fine silty sand overlying coarser sands (e.g. East Grinstead, Penshurst and Cowden (1959), Isle of Oxney (Barrow's Land), and Reading Street (Ramsden Farm)). The earlier trend (coarsening toward the north-west) is thus reversed. Near Tonbridge a local horsetail soil bed occurs in these strata (1947*a*, p. 304); near East Grinstead, suncracks (1949*a*, p. 270).

The top surface of the Ashdown is critical for any interpretation. It is marked by a sharp change to gravity-graded conglomerate: the Top Ashdown Pebble Bed. Locally, the surface on which the pebbles lie is strewn with small plant fragments (including *Equisetites lyelli*) and these may form a thin 'peaty' parting (Brede, Westfield, Sedlescombe, Burwash,

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* Almost certainly these remnants of eroded soils were originally more widespread, but have not often been preserved (see footnote on p. 299).

Playden). The pebbles in the conglomerate lie chiefly near the base, often flooring small runnels a few inches, occasionally a foot (e.g. Fairlight Place Farm), deep. Otherwise the surface on which it lies seems at first sight extraordinarily flat. Regional studies, however, show that it was broadly undulated into gentle swells and hollows. This topography was reconstructed by plotting the varying thickness of overlying Wadhurst sediment which had to accumulate before the horsetails could colonize it (1949*a*, figure 21, p. 301).

The pebble bed is only a few inches thick and oversteps all depositional structures below (false-bedding, washouts, etc.; see for example figure 4). Though so thin it is extraordinarily widespread, reflecting a common character of the minor horizons in the upper part of the cyclothem. Its matrix is everywhere similar to the sediments beneath and clearly churned up from them, being coarse sand in the south-east and fine clayey silt or sand in the north and north-west. Hence, a big size-discontinuity between pebbles and matrix develops northwards; and, though in the south-east Weald some of the pebbles will have been winnowed from the underlying beds, this was certainly not the case in the north-west (East Grinstead, Cowden, Penshurst) or along the north of the Isle of Oxney, where they are abundant and large, and form a surprising gravelly parting in an otherwise pebble-free succession of top Ashdown-lower Wadhurst silts, fine sands and clays. They look as if their *immediate* origin lay in the south, but originally of course they must have come from the north.

The pebbles (apart from abundant pellets of the underlying sediments) are almost entirely siliceous types, small fragments of plants (including *E. lyelli*) are common, scattered valves (casts) of *Neomiodon* are particularly notable in the Wittersham–Rye–Winchelsea district, and the bed is cross-laminated on a small scale. Imbrication of the pebbles is absent or poor. The top surface, normally without pebbles, is moulded into two sets of ripple marks mostly small (1949*a*, p. 269), but some of them (as at Hare Farm Lane, Brede) giants with wavelengths reaching 1 to 2 ft. The two sets intersect at right angles, leaving oval hollows between. Eroded asymmetrical (current) and roughly symmetrical (wave) ripples both occur, the latter more commonly. As recorded elsewhere (1949*a*, p. 269), the interior cross-laminations show that asymmetrical ripples always preceded the formation of symmetrical types (figure 7*D*). Occasionally, as at Fairlight, the ripple ridges are isolated, leaving the underlying sandstone bare where the troughs ought to be. On average, the crests strike north-west to south-east and north-east to south-west, their slip-faces sloping variously north or south and the second set normally showing the greater wavelength. The bed thus seems to have been deposited against a north-easterly or north-westerly trending coastline. Mapping of the margins of the bed suggests a north-west to south-east orientation (figure 6), flanking the south-easterly swing in the London platform (1954, text-figure 1). The water was shallow, for in one place at least where the passage beds are thin (possibly a sheltered bay) the horsetails colonized it (Ludley Hill, Beckley, Sussex: 1959), albeit through a thin covering of silt and clay; and the ripple-mark pattern strongly suggests agitation by cross-winds.

The basal Wadhurst sediments above are extraordinary. An immediate (and correct) impression on first seeing them is that, after Top Pebble Bed times, the source of coarser sediment became gradually (though irregularly) cut off, so that there was often not sufficient sand and silt to cover the floor between the ripples. The strata concerned comprise thin alternations of clay with oval or irregular lenses ('biscuits') and thin lenticular sheets of finely current-bedded sandstones and siltstones (figure 5). Some of the smaller lenses may be 'pull-apart' or other structures denoting contemporaneous movement, but their precise relation to the clays cannot always be ascertained at weathered outcrops. Many are, however, clearly short discontinuous ripples, recording the gradual break-up and disappearance of the pebbly facies. A high proportion of them are more or less symmetrically convex above and flat-bottomed or gently convex (forming load casts) below (figures 5, 7*A*, *B*; also Fitch 1930, figure 3). These undoubtedly represent isolated piles of coarser material swept up into broken sets of interfering oscillation ripple marks on an otherwise muddy floor during a period of rapidly increasing deficit of coarser materials. A few are markedly asymmetrical, proving, with the evidence of their cross-bedding, that the first type normally formed by modification of pre-existing current ripples. Most slip-faces and cross-laminations slope either roughly north or roughly south. Occasionally the upper surfaces of the smaller lenses are contoured with minute terraces (figure 7*A*).

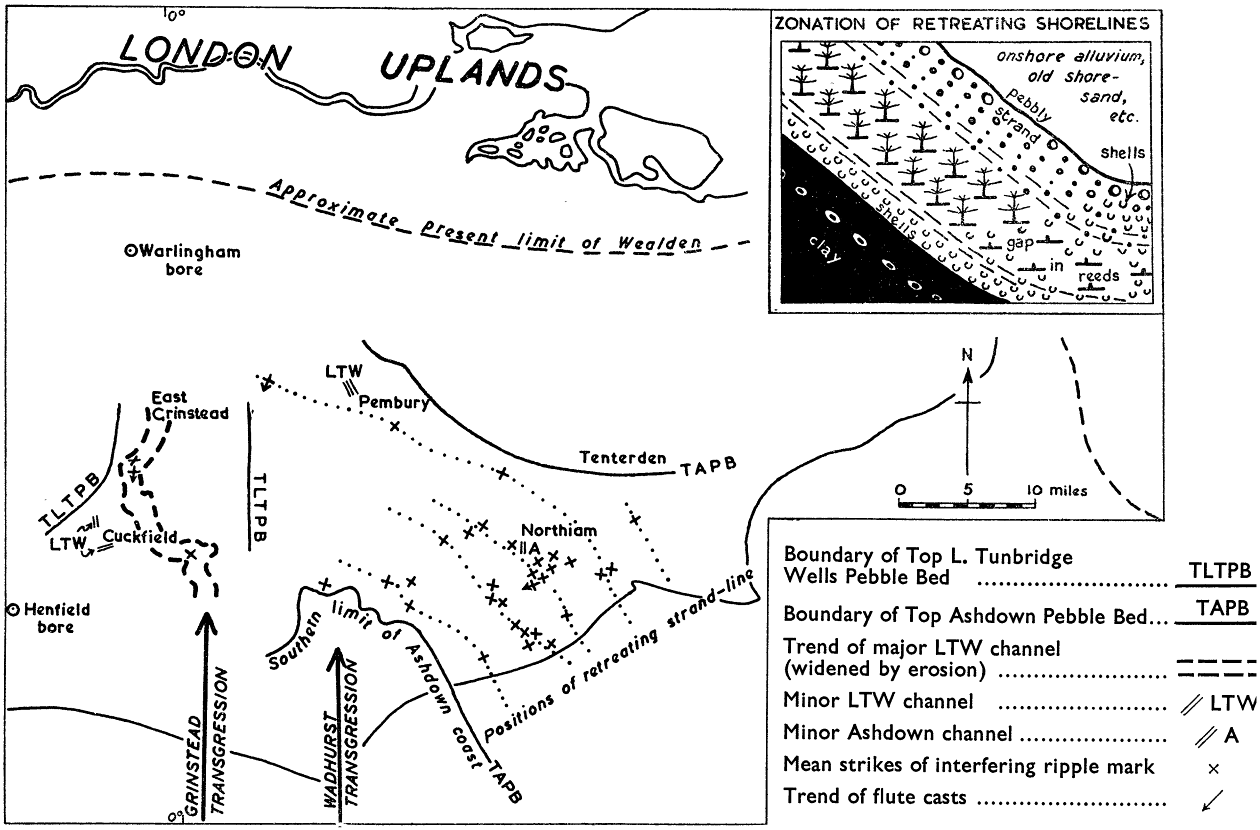

FIGURE 6. Orientation of Ashdown and Lower Tunbridge Wells distributary channels and retreating strand-lines during Wadhurst and Grinstead transgressions.

A = Ashdown, LTW = Lower Tunbridge Wells. Ripple strikes shown are local averages. The embayment in the southernmost Ashdown shore may represent the point of confluence of the deltas of the 'northern' and 'north-eastern' rivers.

Inset. Diagrammatic plan view of a retreating coast showing typical offshore zonation. During early Wadhurst times the major breach in the horsetail reeds (Wittersham–Iden–Rye–Winchelsea–Icklesham–Hastings district) was carved by the 'north-eastern' river; in Grinstead times it was made (e.g. around West Hoathly) by the 'northern' river.

Whether these indicate underwater erosion or actual exposure of the ripples is uncertain. A small proportion of lenticles are clearly small scour-and-fill structures (figure 7*C*: isolated 'flute casts' (Crowell 1955)). They are usually an inch or two across, several inches long, and often curved in plan with fine longitudinal ridges ('groove casts' of Shrock 1948). From below the ridged forms may be taken for poorly preserved horsetail rhizomes,

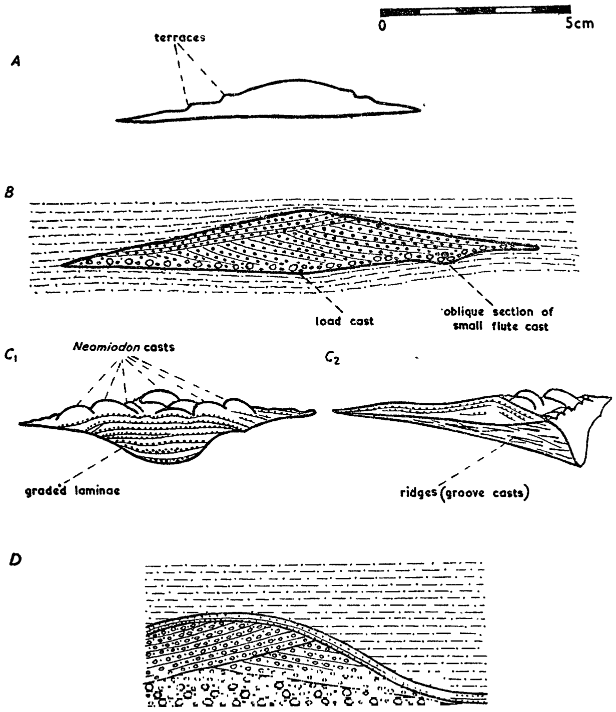

FIGURE 7. 'Retreat structures' formed in the delta-front zone (Basal Wadhurst Passage Beds) during the Wadhurst transgression.

A Terraced siltstone lenticle ('biscuit'). Locality: Cowden Cross, Cowden, Kent.

B Silty shale banked up unconformably against isolated sandstone ripple. Lower surface slightly deformed by load. Long axis of flute at 50° to ripple strike. Locality: Hare Farm Lane, Brede, Sussex.

C_1 Transverse section of typical scour-and-fill lenticle (= isolated flute cast). Note discordant graded laminae, and cap of *Neomiodon* shells (casts) washed off surrounding clay floor by weakening currents. Viewed north-eastwards, upstream and along axis of flute. Locality: near The Grove, Penshurst, Kent.

C_2 Longitudinal view of same 'biscuit' C_1 showing general form of upstream portion. Groove casts visible on lower surface; also laminations on polished longitudinal section of right-hand 'wing'.

D Basal Wadhurst siltstone banked against rippled upper surface of Top Ashdown Pebble Bed. Locality: Hare Farm Lane, Brede, Sussex.

but they are in no sense comparable with those reported from other formations by Linck (1956), Beasley (1914) and Cummins (1958), due to the dragging of horsetails along the bottom. The sandy fill is discordant to the channel sides and finely current-bedded or flat-bedded, sometimes with beautifully graded laminations. Occasionally it is topped by a little pile of *Neomiodon* shells (casts), clearly washed off the surrounding clay by weak currents and trapped on the rougher sand (figure 7*C*). Small flute casts may also occur on the lower surfaces of the ripple-lenticles (figure 7*B*). Their axes usually cross the ripple strike at high angles, and the groove casts and general form of the flutes show that minor currents frequently ran from north to south, i.e. down the shoreface slope.

The clay partings, silty at first, pass gradually upwards into pure clays and become steadily thicker. Near the base they may often be seen banked up unconformably against the ripples (figure 7*B*, *D*). The lenses, sandy or pebbly to begin with, are often crudely graded-bedded when coarse (figures 5, 7*B*), and of all shapes and sizes down to mere flakes. They and the sheets (up to several feet across at first) pass gradually upwards into siltstones, becoming smaller, less frequent and less graded. Finally, they disappear altogether. These changes take place in anything from a few inches (e.g. Ludley Hill, Beckley: 1949*a*, figure 21) to more than 15 ft. (e.g. around East Grinstead, Cowden, Penshurst) and form a perfect passage from the pebbly top of the Ashdown to the typical stiff clays of the Wadhurst. Rare burrows (vertical), scattered fragments of *Equisetites lyelli*, and single valves of *Neomiodon* occur throughout, but normally no gastropods or ostracods, and the whole is riddled with rootlets from the horsetail soil above. The *Neomiodon* valves are most abundant along the Wittersham–Rye–Winchelsea tract (several seams occur): significantly, *where the soil bed has been eroded.* Land-derived wood fades out rapidly. About the middle, a thin sandy bone bed (chiefly fish and reptilian fragments) is developed in the south-eastern Weald, cutting through the clays and lenses alike. Its course runs along the direction of the north-eastern river-inflow (1949*b*, figure 45) and parallel to the majority of flute casts.

The upper foot or so of the passage series, where structureless organic clay is becoming dominant, comprises the Brede Soil Bed (1941, 1947*a*, 1949*a*). This contains abundant fat rhizomes of *E. lyelli* and the lower parts of the vertical stems. Fibrous rootlets pass downwards for a yard or so at least. Remains of creatures that lived among the reeds may sometimes be found embedded in the top of the soil. Noteworthy are the gastropod *Physa* (1941, p. 371) and doubtful leafy liverworts. *Neomiodon* and *Viviparus* have only rarely been found. Pyrites is abundant.

On the upper surface of the soil the stems are twisted off or peter out (as if they had decayed) and are smothered by a foot or so of clay. This often shows delicate 'varving' in its lower part, due to regularly spaced partings of debris from the aerial shoots of the plants ('Fragment Beds': 1941 and 1947*a*) separated by 1 to 2 in. of relatively barren clay. Four 'varves' were the most ever seen (Burwash and Sedlescombe). If, as seems likely, they represent seasonal accumulations (1947*a*, p. 306), then the minimum lifetime of the reed beds is recorded at several places. The lack of disturbance of the laminae and few signs of channelling show that generally the reedswamp died quietly.

On top, the clay cap is surmounted by a constant seam of *Neomiodon* shells. *Physa* disappears and *Viviparus* only rarely occurs. The *Neomiodon* shells may be loose, in which case they are usually crushed, or they may be cemented with calcite or impure siderite. Occasionally small clay-ironstone nodules are developed, locally enclosing the shell bed. Signs of current action prove that the water in which the bivalves accumulated was still shallow, though probably deeper than in Soil Bed times. A little above, lies the lowest seam of Wadhurst clay-ironstone nodules (see, for example, 1949*b*, figure 46), famous in the past as a major source of Sussex iron.

The cycle closes with typical dark pyritous Wadhurst clays and shales, usually alternating rapidly with thin bands and lenses (including contemporaneously broken structures?) of calcareous sandstone and siltstone. The clays and shales carry enormous numbers of ostracods, and seams of *Neomiodon*, *Viviparus* and scattered *Unio*, and fish scales.

(2) *Petrology*

Detailed study of the sedimentary structures and mineralogy of the top Ashdown strata has shown (1949*a*, 1954) that the sandy part of the megacyclothem was built up by three main rivers converging on the Weald. One river entered at the north-east, one at the north-west, and one at the south-west. Each brought in sand grains of quartz, much clay, and grains of mica, black iron ores, zircon, rutile and tourmaline. Besides this detritus, each river also carried particles peculiar to itself, mostly rarer minerals.

From the north-eastern inflow came grains of glauconite, garnet and apatite, and a thin sprinkling of staurolite, kyanite and other minerals. Rare chloritoid also accompanied these, having recently been found at Wittersham where stilpnomelane was already known (1949*a*, p. 295). The north-western inflow, on the other hand, brought in quantities of chert pebbles, a few red-stained pebbles and rare grains of fluorspar. Subsequent work on the pebbles has revealed a wider range of types than suggested in the original report (1949*a*, p. 272). As will be shown in a later paper, these were derived from Old Red Sandstone, Lower Carboniferous (Viséan), Upper Jurassic and possibly other formations. From the south-western river came grains of staurolite, kyanite, sillimanite and other minerals, but no appreciable amounts of the 'characteristic' species of the other inflows previously mentioned.

The north-eastern river drained the North Sea–Ardennes uplands, the north-western river the western uplands of the London Platform, and the south-western river the distant highlands of Normandy and Brittany (1949*a*, figure 23; 1954, text-figure 2).

Through most of Wealden times the two streams from the northern land dominated the scene, for their characteristic minerals preponderate at several different horizons. Detritus from the south-western river, on the other hand, only rarely entered the Weald (1949*a*, p. 299), and this exclusively at times of maximum delta growth when arenaceous sediments seem to have extended all along the coast from Sussex to the Pays de Bray and Paris (pp. 339, 340).

(3) *Minor cyclothems*

Here and there, within the main mass of Wadhurst clay, the preceding faunal and floral facies are liable to recur. When they do *they are always in the same lithofacies*. Reappearance of coarse well-sorted sands brings specks of lignite and odd valves of *Neomiodon*; silts and less-sorted sands bring *Unio* and more fish debris; lenticular passage beds bring *Equisetites lyelli* soils on their clayier sides (1947*a*; Lock 1953); and dark pyritous clays mark the return of abundant ostracods, *Viviparus* and *Neomiodon*.

The close relation between lithology and fossils is well exemplified by the minor cyclothems in the Wadhurst Clay, for example that incorporating the Telham Bone Bed as its pebble bed (1949*b*, figure 47). The sandstone (Hog Hill) member of this also contains rolled bone and land-derived wood, and seems to have a wide distribution, perhaps even extending from the southern to the northern limit of outcrop (see, for example, *Geol. Surv.*, Sheet 287

(1950)). Over much of the Weald it begins about 15 to 30 ft. above the Wadhurst base and is seldom more than 3 to 10 ft. thick. But on a line from Stone south-westwards through Iden to Icklesham it swells to more than 20 ft. in places, locally cutting down this depth nearly to the Ashdown rocks (e.g. Hog Hill (>20 ft.), Winchelsea (>22 ft.: 1959), Iden (18 ft.: 1949*b*, p. 277, figure 46, H)) and digging away the Brede Soil Bed and basal Wadhurst ironstone.* Arrival of the Hog Hill Sands was clearly accompanied by local erosion of the clay floor; consequently they are thickest where the underlying lower Wadhurst is thinnest (e.g. Iden 2 ft. (917249†); Winchelsea $1\frac{1}{2}$ ft. (902169)). Owing to diagenetic changes, the original grain sizes and sorting cannot be estimated with any accuracy.‡ Following the overlying pebbly bone bed, significantly restricted to the southern part of the cyclothem (1949*b*, p. 276, figure 45) and containing rolled fragments of Wadhurst clay-ironstone (Teigh Farm, Stone: 1949*b*, p. 279), horsetail soils and thin shell beds are developed as at the Wadhurst base, and in passage strata of exactly similar lithology.

Near the top of the Wadhurst Clay the High Brooms *E. lyelli* Soil Bed is also 'tied' to the same lithofacies, though this represents a passage in the reverse direction (see below). At other horizons in the Wadhurst there are beds of sandstone (often calcareous 'Tilgate stone') unrelated to any known cyclothem.

(*c*) *Lower Tunbridge Wells–Grinstead megacyclothem*

The glimpse afforded by the Ashdown–Wadhurst megacyclothem is clearly not necessarily representative of Wealden or even Hastings times as a whole. The picture calls for more substance, and intensive stratigraphical and petrographical work has therefore been continued on similar lines at other horizons. Of these, the Lower Tunbridge Wells Sand–Grinstead Clay megacyclothem has proved sufficiently extensive and well enough exposed for comparative studies to be undertaken.

(1) *Succession*

The Lower Tunbridge Wells–Grinstead megacyclothem reproduces all the Ashdown–Wadhurst facies in the same order, so that very careful mapping is often necessary to distinguish between the two. Strictly, it begins as 'Fairlight'-type red or red-mottled silty clays in the upper Wadhurst Clay; but the red colour (seen, for example, at Mountfield, 1949*b*, p. 282) is not developed everywhere. The change to Lower Tunbridge Wells sands may be either gradual, taking place via clay and siltstone passage beds, or sharp with signs of erosion. When it is gradual, as at High Brooms (Southborough) and Pembury, the silty passage beds closely resemble their mid-Ashdown analogues in the south-east Weald. High Brooms and Pembury are also two of the relatively few localities where Lyell's horsetail is known to have colonized coarsening and shallowing sediments (High Brooms *E. lyelli* Soil Bed, Lock 1953), i.e. during an upward passage *from* clay *to*

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* This ironstone is directly overlain by the Hog Hill Sand at Winchelsea; at Iden it is absent.

† National Grid reference number.

‡ In these sandstones and the Telham Bone Bed there is frequently extensive replacement of the quartz grains by the calcite cement. The process has often gone so far that virtually no detrital shapes remain. Hence, the well-known 'sharpness' of the sands and sandstones (see, for example, plates 31 A, B, 32 A, C, Sweeting 1925). The trend is: sandstone → calcareous sandstone → sandy limestone → limestone. The fate of the removed silica is uncertain. Larger quartz and quartzose granules and pebbles are unaffected.

sand. Near Balcombe (200 to 300 yd. north of the lane-entrance to Pilstye Farm (311285)) the transition is again gradual. At East Grinstead on the other hand it is sharp, sandy foresets advancing directly across eroded Wadhurst clays (Topley 1875, p. 83, figure 13). Elsewhere too, contemporaneous pellet beds indicating erosion have been observed near the top of the Wadhurst Clay at Mountfield (bone bed: 1949*b*, p. 282) and Cuckfield (Michaelis, *in litt.*). Both beds contain pellets of greenish clay.

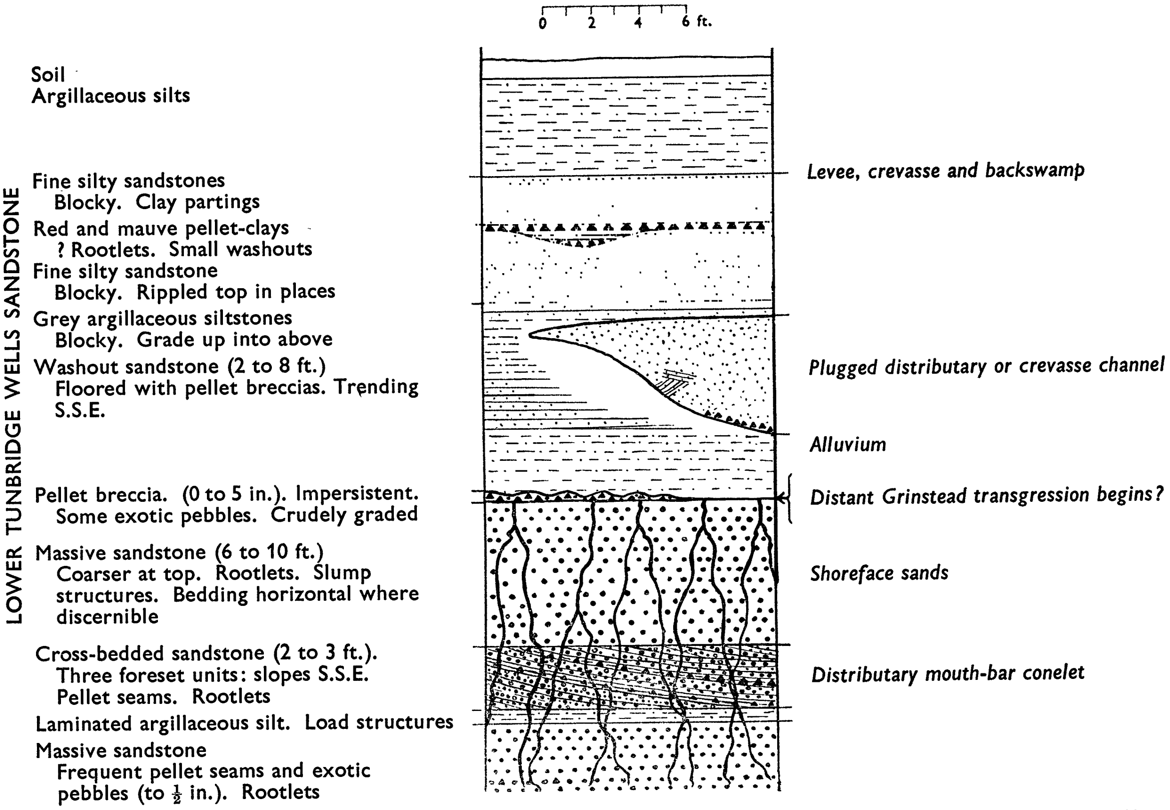

FIGURE 8. 'Grinstead' alluvium overlying Lower Tunbridge Wells shoreface and distributary mouth-bar sands. Locality: Pembury Wood, north of Hospital, Pembury, Kent. Generalized and diagrammatic. ▲▲▲ = clay-pellet seam.

Lenticular clays come and go through the Lower Tunbridge Wells formation, especially in its lower part. Some are associated with minor cyclothems of the simplest type (p. 288), having clay-pellet conglomerates devoid of exotic pebbles. One interesting section near Pembury (177264: 1959) shows a complete minor cyclothem in 25 ft. of strata, and includes two washouts (figure 8). Massive sandstone, forming the lower part of the quarry face, carries roots more than 3½ ft. long (diameters up to 2·5 mm) of a plant larger than *E. lyelli.* This bed is widely developed around Pembury Hospital. Similar roots, also stouter, less branched and sparser than those of Lyell's horsetail, penetrate the Lower Tunbridge Wells sandstones near East Grinstead (1947*a*, p. 310) and Groombridge (cf. top Ashdowns (p. 290)).

As in the Ashdowns, foreset beds are local in occurrence, and usually slope southwards. Good exposures sometimes reveal washout structures following them above, proving that on occasions the delta reached water level. This is exemplified by the Pembury section (figure 8), where the foresets of three conelets (sloping south-south-east and occasionally slumped at the base) are overlain first by massive (? shoreface) sandstones and (? alluvial) silts, and then by what appears to be a later extension of the distributary network itself: two sand-filled washouts. One of these, at the northern end of the pit, is 8 ft. deep and in part concordantly bedded; the other is smaller and shows some discordant bedding. Both washouts meander approximately south-eastwards, through ill-sorted silts and clays with pellet breccias, *in the same general direction as the foresets*. Actual cutting of the channels is shown by basal breccias of siltstone pellets, virtually identical with one accumulating today (1957) in the similar-sized Brede River ½ mile above Brede Bridge, and also flooring some of the alluvium there. No point-bar sequence, such as obliquely-bedded clays or silts, has yet been identified in the Pembury exposures. Washouts become most frequent in the upper part of the Lower Tunbridge Wells formation; the Pembury examples are probably very near the top. Several other channels are known in the Mid-Sussex district further west. Most trend between north-east to south-west and north-west to south-east (figure 6). The largest, 1 mile north of Cuckfield (307263), is a 'Thames' rather than a 'Brede', being 200 to 500 ft. across and running north and south (Michaelis, *in litt.*)

Towards the top the Lower Tunbridge Wells strata become predominantly sandy, and flat-bedded or practically unbedded sandstones extend over much of the outcrop. These are often silver-sands, well scattered with woody chips, in many places weathering out as rocky bluffs. Along the East Grinstead–Paxhill tract, the uppermost 7 to 15 ft. are locally suitable for building material. Beyond the western margin of the tract good building stone wedges out, passing laterally either into siltstone (transition well exposed from West Hoathly through Ardingly to Balcombe) or into thin- (? rhythmically) bedded argillaceous sandstone. Some of the latter shows typical 'festoon' false-bedding, i.e. numerous small channels or giant oscillation ripple troughs (up to several feet across and a foot or so deep) cutting into each other and filled with flaggy sandstone bedded *parallel* to the sides. Many of these peculiar little 'synclinal' washouts run roughly north to south, and at Turner's Hill they overlie a bed of suncracked ripples alined north-west to south-east (north side of B2110, 150 yd. south-west and south-east of church). As in the top Ashdowns, the sorting of the massive and flat-bedded facies is exceptionally good. Many samples show more than 80 % of the detrital grains lying between 0·25 and 0·50 mm (figure 9, data from Boswell 1916, 1917) and the same types of cumulative curve recur. Flecks, clumps and partings of plant debris occur in all facies, particularly in the finely laminated building stones capping the formation around West Hoathly. As in the top Ashdowns scattered pebbles and pebbly seams are rare, being again largely confined to the southern part of the distributary tract (see below), for example around Newick (Founthill).

The laminated building stones at West Hoathly show a well-developed rhythm (cf. top Ashdown rhythm (p. 290)). At Hook and Philpots quarries (figure 10 (localities 37 and 36 of 1959)) the units of repetition comprise groups of 9 to 13 laminations, each group ¾ to 1 in. in total thickness and separated by more strongly marked bedding planes. Detailed investigation is proceeding, but meanwhile it is tempting to connect them with an 11-year climatic cycle. Here and there the same 10 to 15 ft. of beds also show sporadic ripple marks picked out by thin partings of pale silty clay* or plant debris. Their crests usually strike between north-east

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* The clay-partings near the top of the formation all show sandy casts of fibrous rootlets coming down from the soil bed above (p. 305). Usually the rootlets are not preserved in the sandy courses between. This is general at many horizons in the Weald, and applies also to suncracks.

to south-west and east to west, the steeper slopes of the asymmetrical forms, and also the interior (small-scale 'festoon') cross-lamination of the symmetrical types, dipping variously north or south. An upper set, 8 to 9 in. below the top of the formation, is widely developed. It extends from Hook to Philpots, a distance of more than $\frac{1}{2}$ mile, and is covered by a suncracked parting of silty clay. Evidently an extensive area of sediment reached water level at this time. Perhaps the top sands were exposed more often than the evidence suggests, for suncracks will only have formed when they happened to have been smeared with a film of clay.

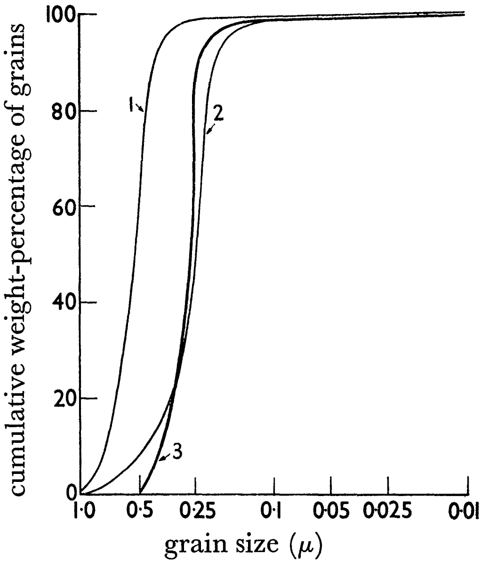

FIGURE 9. Ashdown and Lower Tunbridge Wells shoreface sands: typical particle size distributions. Data from Boswell (1916, 1917).

3. Top Lower Tunbridge Wells Sand. Locality: Ashurstwood, East Grinstead.

1, 2. Top Ashdown Sand near farthest-south shore of delta (see figure 6). Locality: Fairlight.

The sandstones are capped by a graded pebble bed identical in almost every way with the top Ashdown one. It is replete in pellets of the underlying strata, and pebbles from Upper Jurassic (Lydite Beds), Lower Carboniferous (Viséan only) and Old Red Sandstone formations. Fragments of aquatic and terrestrial plants (wood, *E. lyelli*, etc.) and animals (notably ganoid fish (*Lepidotus*), small long-snouted crocodiles (Pholidosaurids*) and plesiosaurs (? *Cimoliosaurus valdensis**)). Like its predecessor, the Top Lower Tunbridge Wells Pebble Bed possesses a matrix normally similar to the sediment underneath, with the result that changes in coarseness of the matrix do not necessarily reflect changes in the size of the pebbles (see, for example, the exposure on the west side of Paxhill Park (356272: locality 35 of 1959) where the pebbles, though large, are embedded in silty clay).

The surface on which the bed lies is similarly scoured and discordant to all sedimentary structures underneath. On average it is remarkably flat, and visible channels more than a foot deep or 2 yards across are rare. Sometimes the surface is marked by a thin parting of finely comminuted plant debris (with *E. lyelli*), the fragments often beautifully orientated north to south (perpendicular to the superincumbent ripple strikes); or it may have a skin of suncracked clay as at Hook Quarry, West Hoathly. There also, deeply bevelled

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* Kindly identified by Dr W. E. Swinton.

oscillation ripple marks have been observed (figure 11*G*). Doubtless the original surface was undulating on a broad scale, for in a general way the pebble bed is coarsest where the overlying (Grinstead) clay is thickest (cf. figure 30 in Reeves 1949 with figures 12 and 14), and suncracks do not occur everywhere.

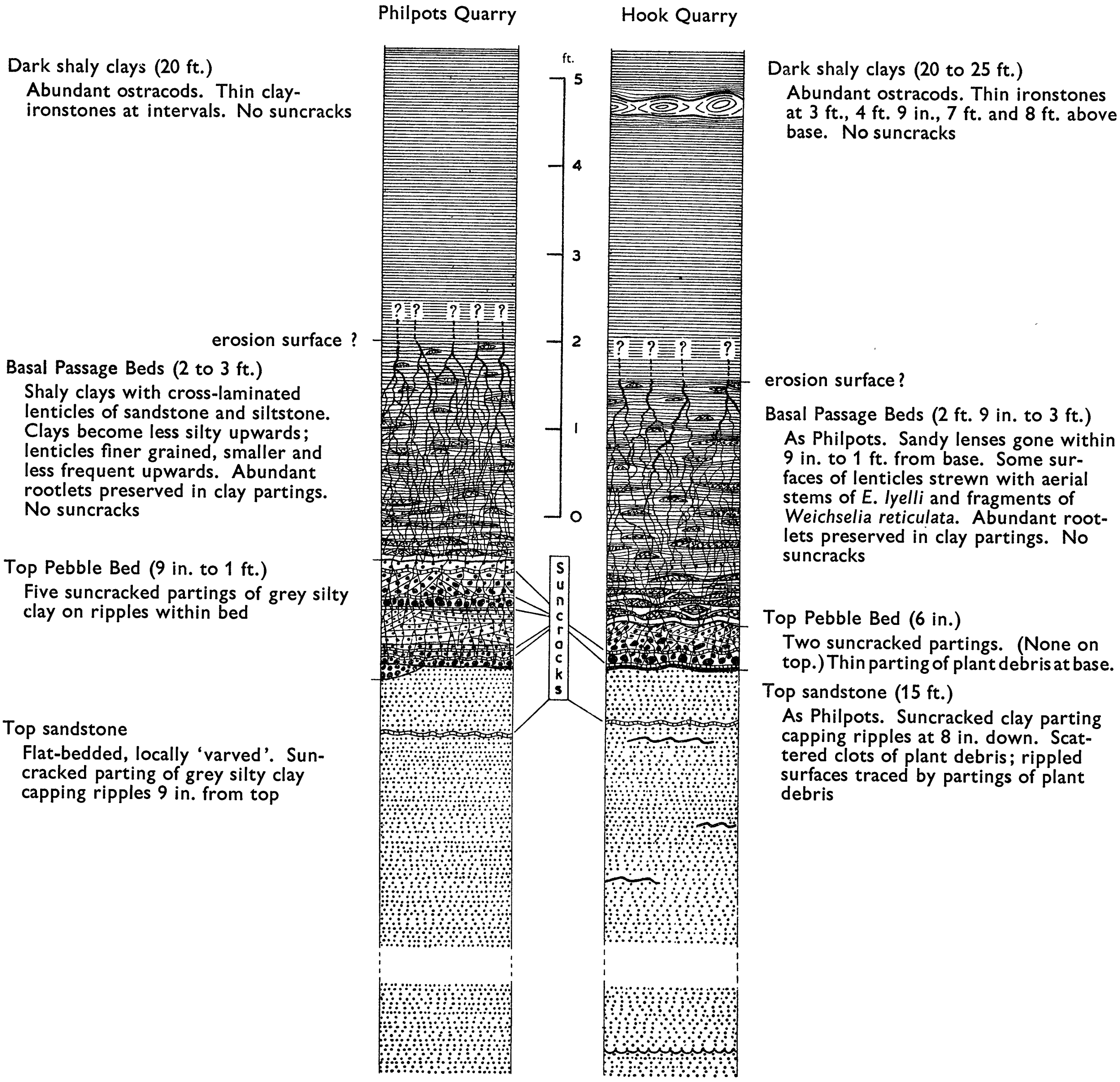

FIGURE 10. Lower Tunbridge Wells–Grinstead cyclothem at West Hoathly quarries. Compare with figure 13.

The interior of the bed is invariably cross-laminated on a small scale. Sometimes this was obviously due to successive generations of ripple marks (figure 11*F*). The interior ripples may be separated from one another by thin partings of pale silty clay, heavily suncracked right across or only in the troughs and penetrated by rootlets from the overlying soil bed. This is especially so along the East Grinstead–Paxhill belt, where the pebble bed reaches its maximum development. At Philpots five suncrack horizons are known in a thickness of 1 ft. (figure 10). The clay partings become steadily thicker upwards. On top the surface of the pebble bed is again rippled and thin trails are sometimes found, *but it is not suncracked and no further suncracks have been found in the clayey strata above.* This is significant because had the structures been formed they would certainly now be preserved. In the absence of ripple mark, pebble imbrication is always poor or absent.

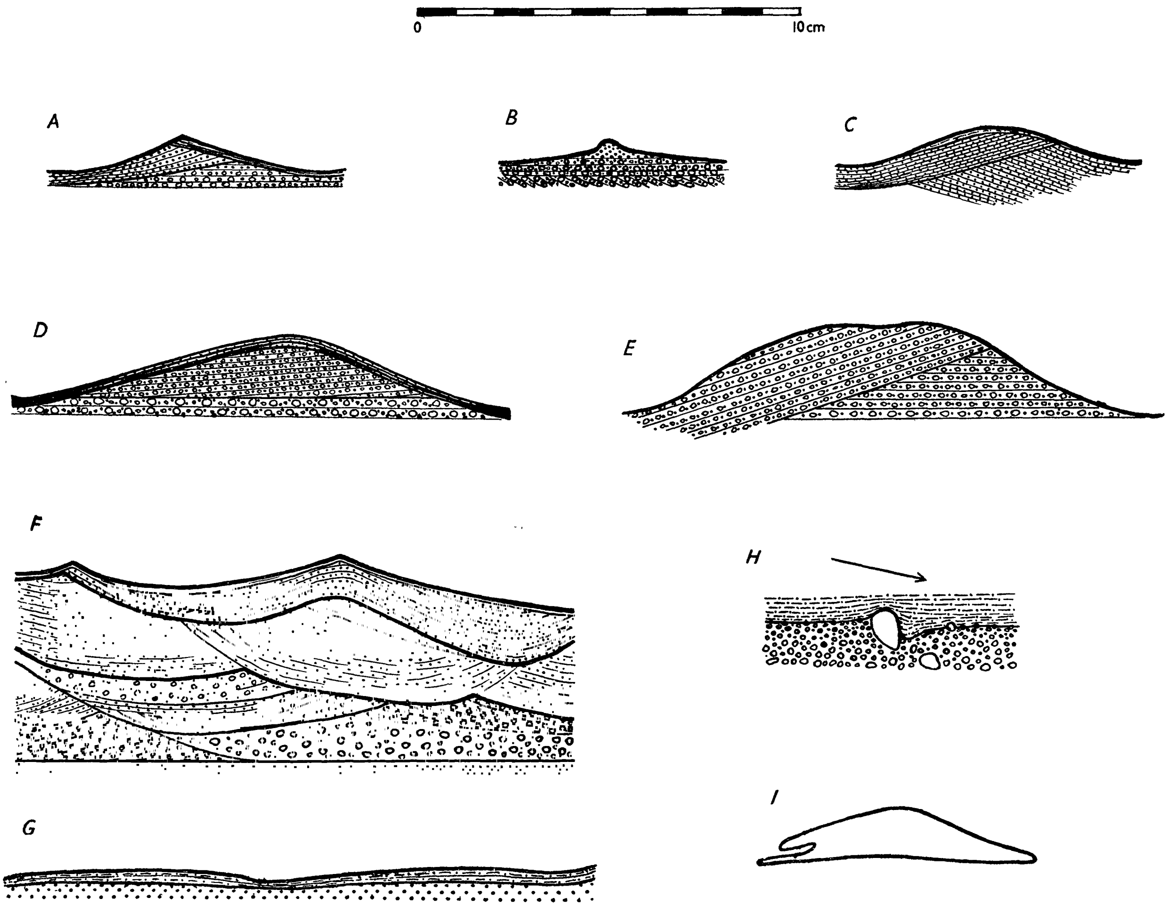

Figure 11. 'Retreat structures' formed in the shoreface and delta-front zones during the Grinstead transgression. Vertical sections perpendicular to crestlines. Locality: Hook Quarry, West Hoathly, Sussex.

A to *G*. Formation of symmetrical (oscillation) ripple marks just below strand-line (Top Lower Tunbridge Wells Pebble Bed): *A* = knife-edged type, derived from current ripple by asymmetrical deposition. *B* = compound type, from horizontal beds by erosion. *C* = rounded (eroded) type, from current ripple by erosion and asymmetrical deposition. *D* = rounded type, from current ripple by erosion and symmetrical deposition. *E* = 'giant' compound type, from erosion of 'giant' current ripple. For this drawing increase scale by $\frac{3}{2}$. *F* shows successive aggradational sequence: current ripples → primitive oscillation ripples → eroded oscillation ripples → primitive oscillation ripples. Hence small-scale 'festoon' bedding. *G* = flattened type, formed from horizontal beds by erosion and capped by silty clay.

H. Pebble protruding into Basal Grinstead Passage Beds from *sloping side of ripple* on upper surface of pebble bed. Arrow indicates local slope. Note 'scour shadow' filled with basal silt.

I. Sandy lenticle (an isolated ripple mark) slumped on to surrounding clay in delta-front Basal Grinstead Passage Beds.

All types of ripple mark are recognizable within or on top of the bed. The asymmetrical ripples are usually small (wavelengths about 3 in.) and arranged in long straight sets striking roughly east and west. Their slip-faces dip north more often than south, and north to south cross-ripples occur at intervals of a foot or so. Symmetrical or nearly symmetrical ripples have usually grown by erosion of asymmetrical types. They are more variable in character than the latter, and frequently comprise two intersecting sets resulting in a pattern of saucer-shaped or polygonal depressions between. The dominant set commonly strikes between north-east and south-west and east to west, its interior cross-lamination sloping north or south, more often the former. Every variety of near-symmetrical (oscillatory) ripple is known (figure 11 *A* to *G*), but knife-edged crests have never been observed on the *top* surface of the bed. Giant forms, with wavelengths up to 1½ ft., are common in the West Hoathly district (cf. the Top Ashdown Pebble Bed at Brede (p. 292)). They have knife-edged or rounded crests and coarse pebbly material may be segregated in their troughs. Some with rounded crests are sculptured into a coarse network of ridges as if by heavy rain. Bared pavements of the giants often show intersecting sets, the dominant one (straight rounded crests up to 9 ft. long) with a N.E.–S.W. to E.N.E.–W.S.W. strike. At localities where the pebble bed is thin the ripple ridges are sometimes completely separated from one another, lying isolated on the bare sandstone floor (Shortbridge: 1947*b*, p. 311; West Hoathly, etc.; cf. Ashdown pebble bed at Fairlight (p. 292)). Occasionally, ripples are seen which are breached by fan-shaped clusters of fine radiating ridges and furrows up to 6 in. long, formed as water drained away from the troughs during times of low lake-level —further proof of periodic exposure. Comminuted plant debris is often abundant in the ripple troughs.

As shown by figure 12, the pebble bed occurs over a wide area between East Grinstead and Haywards Heath in the north and south, and Balcombe and Ashdown Forest on the west and east.* Because of its smaller extent the boundaries are better known than those of the Top Ashdown Pebble Bed. Toward east and west it disappears altogether, the Grinstead Clay coming to lie directly on the sands beneath (Speldhurst, Eridge, Maresfield, Ardingly station, Balcombe, Turner's Hill). The disappearance is gradual, being clearly traceable at a number of localities. On the south-west of East Grinstead outskirts, for instance, the bed is well developed: several inches thick and containing exotic pebbles the size of traditional pigeons' eggs. By Hairley Farm, 1 mile south-westwards, big pebbles are rare, and in a roadside trench 2¼ miles further on (¾ mile south-west of Turner's Hill) they were absent altogether. Hereabouts the bed passes into ferruginous pellet-breccia, containing locally derived pebbles of pale sandstone, siltstone and clay, similar to the sediments underneath.

Again, in the rectangle formed by Selsfield Common, Balcombe, Ardingly and West Hoathly the pebble bed is seen to die out both north-north-westwards and south-westwards along the London road (B2028) in less than a mile. Thus at West Hoathly and Horn Combe (east side of B2028, ¾ mile north of Ardingly) it is fully developed and replete with

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* The pebble beds in the Newick Park–Isfield district are included on the map, but it is uncertain as yet whether they lie exactly on the horizon under consideration. Indeed Mr E. R. Michaelis suspects from detailed mapping that they are higher, probably lying (at an analogous position) in the Balcombe Clay minor cyclothem.

large pebbles, but in the pit $\frac{1}{4}$ mile south of Pearcelands (west side of B2028) it consists of no more than a single layer of scattered pebbles lying loosely in reworked sand. Opposite the White Hart Inn, a $\frac{1}{4}$ mile north of Pearcelands, and in the south lane-bank $\frac{1}{8}$ mile west of Ardingly Church, no large pebbles can be seen. Finally, in Balcombe parish the bed is usually absent altogether, or (less commonly) represented by either a thin seam of grit (e.g. $1\frac{1}{2}$ miles south of church, north of entrance to Pilstye Farm (311285), figure 13; see also 1947*b*, p. 76; 1959) or a contemporaneous pellet breccia like that at Turner's Hill (seen, for example, near the stream junction south of Cooper's Corner Farm (Michaelis *in litt.*) and in places at the entrance to Pilstye Farm (figure 13)). Obviously the water which spread the exotic pebbles also churned up the bottom for some miles beyond the gravel sheet. Further afield, the pebble bed being absent, the Grinstead Clay comes to lie directly on the Lower Tunbridge Wells Sand.

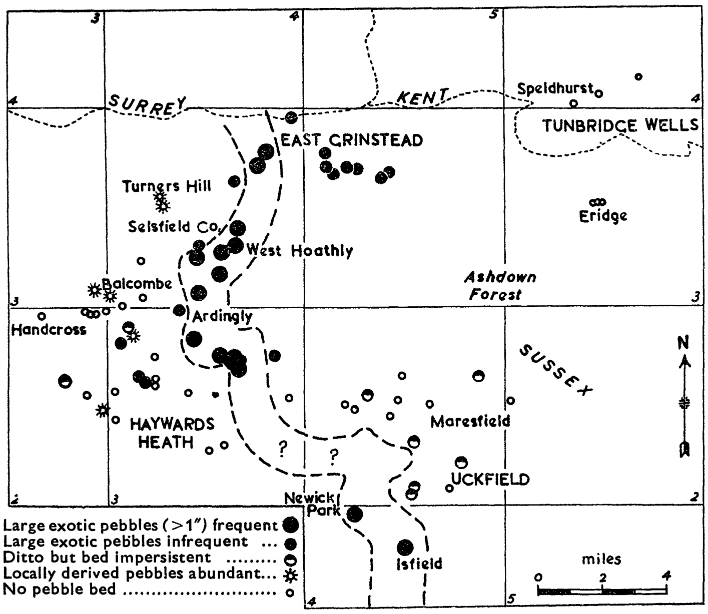

FIGURE 12. Areal distribution of the Top Lower Tunbridge Wells Pebble Bed (= a retreating strand-gravel). Note the large degraded north-south channel (dashed lines) greatly widened by erosion during the Grinstead inundation. See also footnote on p. 303. Compare with figure 2 in 1949*a*.

Evidently the pebbles spread across the area in either a north-to-south or a south-to-north direction (figures 6, 12). Detailed studies of their size and of the thickness of the deposit confirm this. The pebbles are biggest roughly in the longitude of West Hoathly and the bed is also thickest along this tract (figure 12). It may be significant that the best building stones underlie it here.

Following removal of some of the sand during formation of the final ripples, the blanket of finer detritus evidently came down gently, for pebbles embedded at the top of the conglomerate sometimes protrude edgewise into the silts and clays. Only those lying on the sloping sides of ripples may show asymmetrical 'scour shadows' (figure 11*H*); but such structures are very rare, and when occurring in ripple troughs or on flat beds they always take the form of *symmetrical* 'moats'. Thereafter, the supply of coarser material shut down rapidly, the little sand and silt arriving being usually swept up into two or more interfering sets of short isolated oscillation ripples (many beginning life as current ripples) and runnels on the otherwise muddy floor. Hence, immediately above the pebble bed come thin clays alternating with thin lenses and irregular sheets of graded sandstone and siltstone, recording the gradual disappearance of the pebbly type of lithology. These Basal Grinstead Passage Beds are everywhere riddled with rootlets of *E. lyelli*, but very few burrows, and are quite indistinguishable from those at the base of the Wadhurst Clay. As before, too, some of the 'biscuits' prove to be minute washouts (flute casts), others upstanding ripples. The flute casts often bear longitudinal ridges (groove casts) underneath and sometimes also 'knots' similar to those illustrated from the Lower Keuper by Cummins (1958, plate 2, figure 1). The set of longer ripples commonly strikes about E.N.E.–W.S.W. (roughly parallel to the ripple strike in the underlying pebble bed) and their foresets may

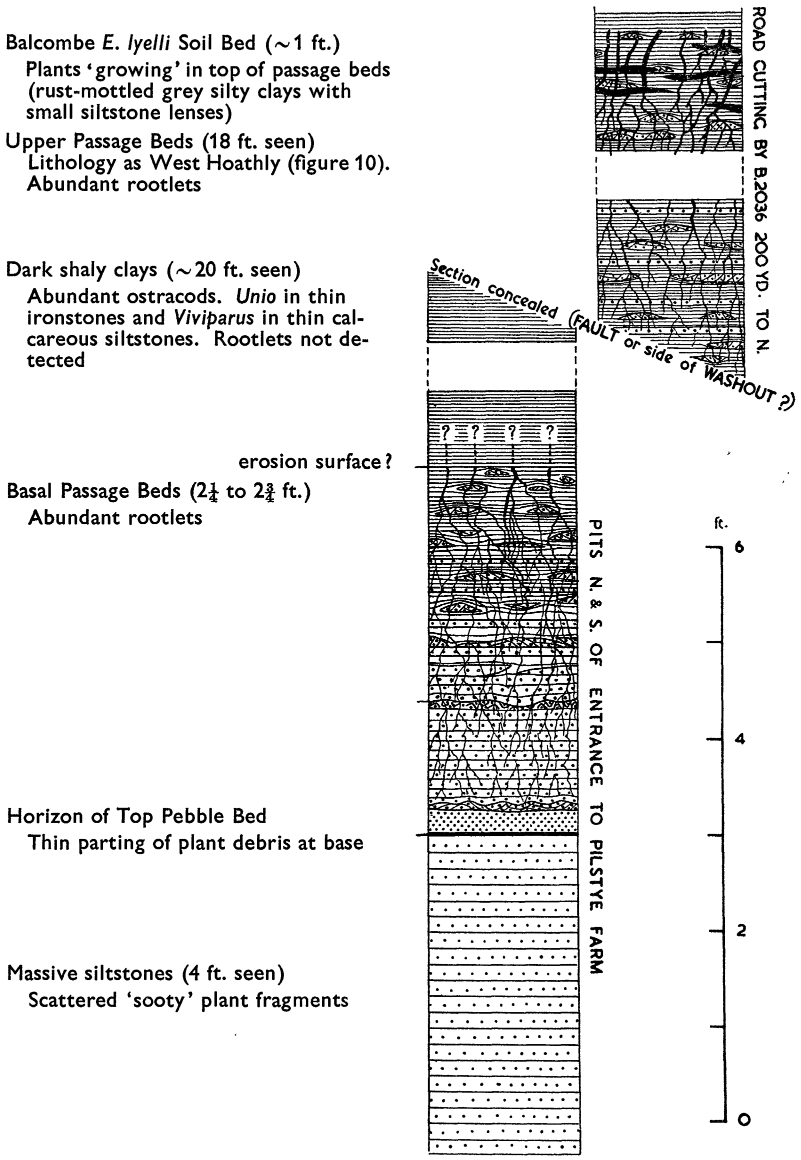

FIGURE 13. Lower Tunbridge Wells–Grinstead cyclothem near the entrance to Pilstye Farm, 1½ miles south of Balcombe, Sussex.

slope north or south. The axes of the flute casts usually cross the ripple strikes at high angles and the few which have been properly dissected show water movement from north to south. Slumping of the sandy ridges on to the clays accumulating round them is sometimes seen (figure 11 *I*), and contemporaneously broken structures may effect the siltstones. The lenticles and sheets are often strewn on top with horsetail debris. This comprises fragments of aerial stems (no cones) with some rootlets (bearing small tubers?), often crudely orientated parallel to the ripple strike. Land-derived wood, on the other hand, fades out rapidly. Scattered fragments of *Weichselia* fronds and odd pinnules are a feature of the West Hoathly quarries. Evidently the sediments were never exposed, for they are not suncracked.

The basal passage beds with their rootlets (less than 3 ft. thick) form a lithological transition to typical Grinstead clay, and obviously indicate waning water movement and sedimentary supply on a shallow bottom deepening gently towards a nearby horsetail reed bed. Near Balcombe (figure 13) they are followed by at least 20 ft. of dark ostracod clay, lacking rootlets. Then similar passage beds with rootlets reappear (more than 18 ft.), ending at the top, beneath the Upper Tunbridge Wells Sand, in the Balcombe *E. lyelli* Soil Bed (1947 *a*, p. 311). Clays with ostracods, *Viviparus*, *Neomiodon* and numerous small lenses of calcareous siltstone follow. As intimated elsewhere (1959), it is not absolutely clear whether one or two soils are represented. The two zones of rootlets may, for instance, both belong to the Balcombe soil, their absence from the clay parting being due to non-preservation. More probably, the lower zone of rootlets represents a separate and earlier soil, stripped of its rhizomes and stems before the clays were deposited. Sections elsewhere in the district do not help because they never clearly expose anything higher than the intervening clays. They do, however, reveal that the basal passage beds are always less than a yard thick and everywhere similarly riddled with rootlets (e.g. West Hoathly, figure 10).

Milner's discovery of sandstone pellets at the base of the clays following the lower passage beds and the relatively abrupt transitions seen at West Hoathly and elsewhere along the East Grinstead–West Hoathly–Paxhill tract (figure 10; also Milner 1923, p. 286 and figure 40) strongly suggest erosion in the district to the east and north-east of Balcombe. This may or may not be germane to the present problem however, for sandy 'balls' which are possibly not erosional in origin are known to occur in certain modern pro-delta clays (e.g. Mississippi: Scruton 1956, pp. 42, 43 (figure 11); Shepard 1956 *a*, pp. 2604 (plate V, figure 3) and 2605). More significant may be the apparent absence of rhizomes and stems higher up, for despite very detailed mapping neither Mr Michaelis nor the writer has ever seen any evidence of these organs in their positions of growth outside Balcombe parish. The tract in question coincides with the coarsest part of the pebble bed underneath (figure 12), and also with some of the thickest developments of the overlying Grinstead Clay. Hence, it may represent the site of a distributary channel or pass, along which current erosion was sometimes renewed temporarily. It would not be in the least surprising if, over the centre of the channel (e.g. around West Hoathly), only the lower rootlets remained, while on the western margin near Balcombe (where the underlying pebble bed vanishes) the soil was complete and uneroded. A similar thing had happened long before to the Brede Soil Bed, near Hastings (1947 *a*, p. 305, figure 55).

Following the demise of the soil (or the earlier, if two soils), the arenaceous detritus rapidly became finer in grain and shorter in supply until it finally ceased altogether. Hereabouts, the base of the overlying clays is often marked by a line of clay-ironstone nodules (cf. the base of the Wadhurst Clay). The passage to dark Wadhurst-like pyritous clays with ostracods, *Neomiodon*, *Viviparus* and occasional *Unio* and siltstone lenses is thus achieved in exactly the same way as in the earlier cyclothem. Lenses representing patches, ripples and flute casts are common. At the Balcombe exposure (east of the road) horsetail-like flute casts bearing groove casts exactly similar to those in the Wadhurst (p. 294) are abundant. The only difference noted between the two cyclothems lies in the absence of a well-defined seam of *Neomiodon* shells just above the Balcombe *E. lyelli* Soil Bed (see also, Topley 1875, p. 86). Indeed, one can never be sure of distinguishing between them on lithological, petrological, faunal or floral evidence alone.

(2) *Petrology* (*Top Lower Tunbridge Wells Pebble Bed*)

The close similarity between the megacyclothems extends even to the intimate details of their petrology. This is probably best exemplified by comparison of their pebble beds which, as will be shown, are virtually identical in nearly all important features. The only really significant differences noted arose from changes in the source-areas of the detritus during the Ashdown–Lower Tunbridge Wells interval, a subject outside the scope of the present paper. Down in the basin itself almost exactly the same cycle of conditions was repeated. In the following account, only the petrological features bearing on this problem and suggesting a possible cause for it will be considered.

(i) *Pebbles.* Certain of the exotic pebbles have already been reported on from West Hoathly (Milner 1923; Kirkaldy 1947), good exposures having attracted geologists there for many years. The wider mapping of the bed now gives a fuller insight into its petrology.

More than 99 % of the pebbles derived from outside the basin are of siliceous rocks. The rest ($\sim$0·3 % at Paxhill) are phosphatic. The siliceous pebbles came from strata of Old Red Sandstone and Lower Carboniferous (Viséan) age, and nearly all the phosphatic pebbles from the Upper Kimeridgian or basal Portlandian Lydite Beds. In the coarsest facies chert predominates. Conspicuously red-stained pebbles comprise up to 10·5 % (increasing with pebble size), and in this group chert is almost negligible ($<$5 %). The figure is a minimum, however, for some pebbles with unstained rinds prove to have red cores. This suggests leaching before burial, a conclusion supported by the siliceous nature of most of the pebbles.

Many types of rock are represented and they include all those observed in the Top Ashdown Pebble Bed. The only significant difference lies in the increased proportions of red-stained and phosphatic pebbles. Evidently this was due to changes operating in the source-area, and will not be discussed here.

(ii) *Grain types.* The sandy matrix of the bed has been studied in the same manner as that of the Top Ashdown Pebble Bed (1949*a*, pp. 260–267).

The light sand grains (sp.gr. $<$2·9) are identical with those in the earlier horizon, and the account published thereon (1949*a*, pp. 273–274) applies equally to the present bed. The same is true of the heavy detritals, which even recur in the same order of frequency.

Table 1 illustrates this, showing how extraordinarily close most of the frequencies are to those in the earlier horizon. The similarity applies both to species and varieties within species, but only broad specific comparisons are extracted here. Garnet, apatite, staurolite, kyanite and sillimanite differ significantly, but this is apparently due to geographical accident, as will be seen later (p. 309).

The close accord between the beds is also true of (i) the overall variation in abundance of each species, (ii) the relation between this variation and mean abundance, (iii) the mean sorting indices, (iv) the mean shape indices, and (v) the inverse relationships observed between shape index and particle size within each horizon. Clearly conditions in the two pebble beds were identical as far as these petrographical matters were concerned, despite the lapse of time (represented by 200 ft. of strata) between them.

TABLE 1. HEAVY DETRITALS

	mean % in			
mineral	Top Ashdown Pebble Bed (1949*a*, pp. 312, 313)		Top Lower Tunbridge Wells Pebble Bed	
‘ubiquitous’ species				
black iron ores and leucoxene	39·6		34·1	
zircon	38·3		42·0	
rutile	9·5		8·5	
tourmaline	7·2		7·5	
anatase	2·1		4·8	
brookite	0·06		0·07	
‘characteristic’ species				
garnet	1·5		0·9	
apatite	0·3		0·2	
staurolite	0·8	0·92	0·4	0·42
kyanite	0·09		0·01	
sillimanite	0·03		0·01	
monazite	0·04		0·05	
chloritoid	<0·005*		<0·005	
ceylonite	0·01		<0·005	
? sphene ? epidote	0·03		0·01	
unknown	0·40		1·4	
mean zircon size index	64·1 μ		56·5 μ	
mean zircon shape index	4·1%		5·4%	

* See p. 296.

The total proportion of heavy grains is generally low (<0·1 % by weight), as in the Ashdown pebble bed. But abnormally high concentrations do occur at a few localities, notably along the western margin of the gravel sheet where it is beginning to peter out. There, naturally panned residues are sometimes found flooring the small runnels in which the bed lies (e.g. $\frac{1}{4}$ mile south of Pearcelands; Horn Combe, Ardingly).

(iii) *Grain size.* Mapping of the Top Lower Tunbridge Wells Pebble Bed has permitted detailed studies to be made of the areal distributions of the quantitative characters of the heavy sand grains. Particle size is fundamental to them all, exerting a strong controlling influence as in the Ashdown bed. The areal distribution of average particle size (expressed as the zircon size index (1949*a*, pp. 262, 311)) is shown in figure 14. Contour intervals represent significant differences for the probability level 0·05, as before. The contours form a meandering north to south pattern, revealing the last effective current directions and confirming the evidence of the pebbles and ripple marks. The outline of the distributary coming down from London is well defined, showing that as the northerly-moving transgression crept up it the liberated sand was (like the pebbles) never spread really wide afield. This contrasts markedly with the situation in the Top Ashdown Pebble Bed further east. On that horizon the size-patterns of pebbles and matrix cross at right angles (1949*a*, figures 2, 4; and 1954, text-figure 1), proving that the receding Ashdown coastline ran *athwart* the converging distributary pattern.

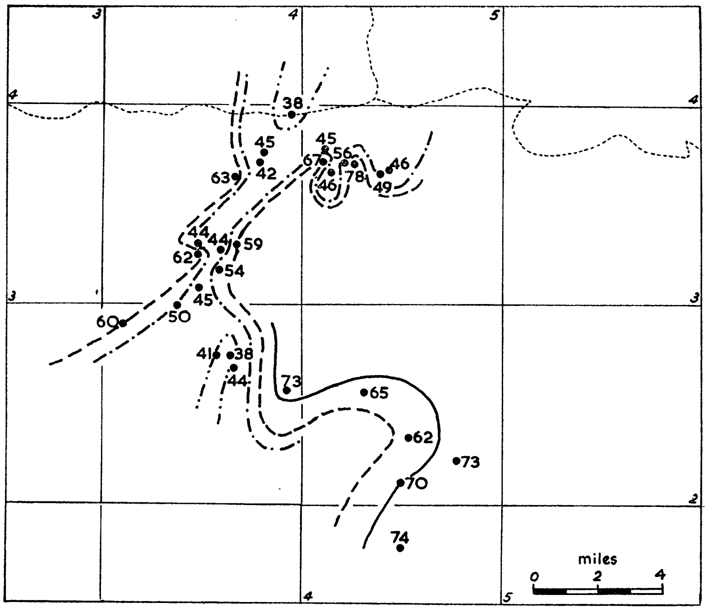

FIGURE 14. Top Lower Tunbridge Wells Pebble Bed. Areal distribution of the zircon size index, with tentative 'contours'. 40μ —··—, 50μ —·—, 60μ — —, 70μ —. Compare with figure 4 in 1949*a*.

The average particle size of zircon (56·5μ) in the present bed is significantly different from that in the earlier horizon (64·1μ), although the variation in size from place to place is about what would have been expected for an Ashdown facies of similar coarseness. This is consistent with the closer proximity of the district both to the London inflow and to the rear area of the delta, where only ill-sorted alluvial silt and fine sand would be available to mix with the sandy distributary gravel. The most distant exposures of the Ashdown bed are quite 30 miles further south-east from the inferred position of the distributary pass or estuary at West Wickham (1954, p. 504), and consequently received much greater contributions of coarse sand from the south-western and north-eastern inflows. But, if the average size of zircon in the Ashdown bed is calculated for the *north-western half of its area* (i.e. between East Grinstead and Tonbridge, north-west of 'CD' in figure 2, 1949*a*), which was much less under the influence of the north-eastern and south-western rivers and little further from West Wickham than the present horizon, we obtain a figure (53·4μ) close to that of the Top Lower Tunbridge Wells Pebble Bed. The main differences between the horizons appear to be due largely to their different geographical positions.

(iv) *Areal distribution.* But what of these two remaining streams that had also supplied detritus long before? If they still operated in Tunbridge Wells times their 'characteristic' minerals must have been more diluted with London Platform detritus than was ever usual in the Ashdown pebble bed. This has already been noted (see table 1, p. 308). Inspection of the contoured distribution maps for garnet, apatite and staurolite (figures 15 to 17), and comparison with their analogues from the earlier bed (1949*a*, figures 7 to 9), bring

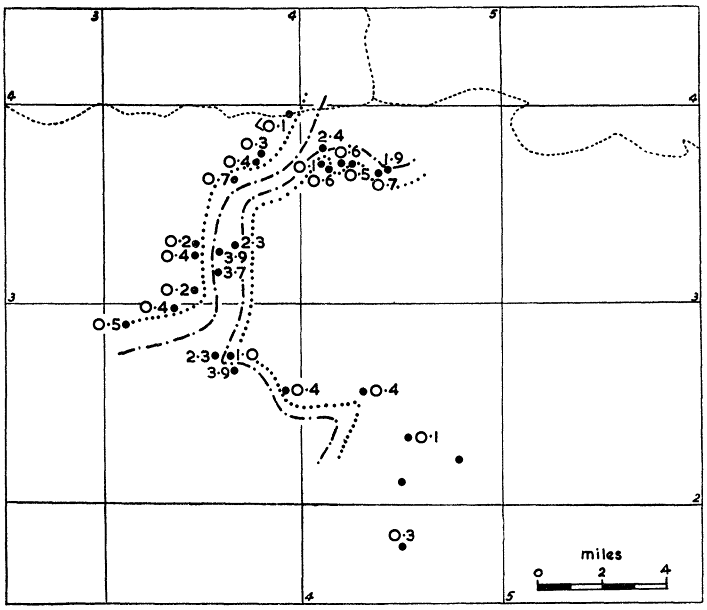

FIGURE 15. Top Lower Tunbridge Wells Pebble Bed. Areal distribution of garnet-percentage in the detrital heavy suite, with tentative isopleths. 0·5 % . . . , 2·0 % —·—. Localities with no figure attached yielded 0 %. Compare with figure 7 in 1949*a*.

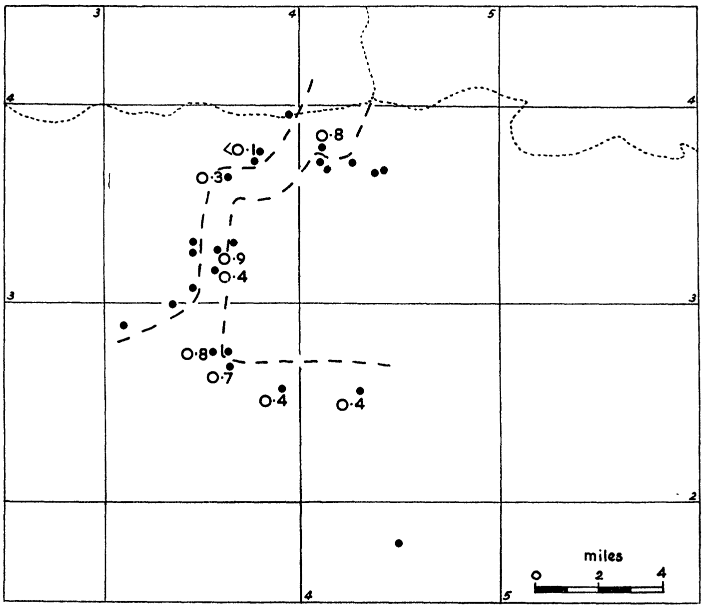

FIGURE 16. Top Lower Tunbridge Wells Pebble Bed. Areal distribution of apatite-percentage in the detrital heavy suite, with tentative isopleths. Data incomplete. Localities with no figure attached yielded 0 %. Limit of area with > 0·1 % — —. Compare with figure 8 in 1949*a*.

out the same point. So also does the extreme rarity of kyanite, sillimanite and other 'restricted' minerals of the Ashdown horizon, for these are now far too scarce even to reveal anything significant about their distributions.

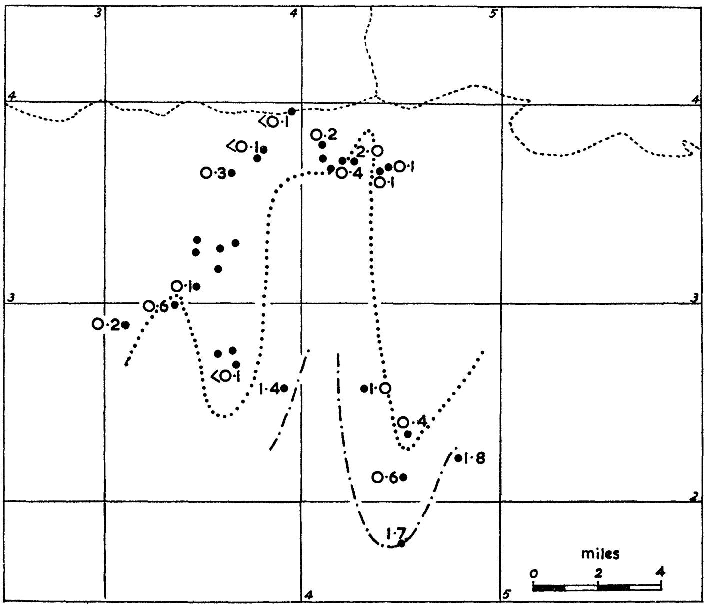

FIGURE 17. Top Lower Tunbridge Wells Pebble Bed. Areal distribution of staurolite-percentage in the detrital heavy suite, with tentative isopleths. 0·5 % . . ., 1·7 % —·—. Localities with no figure attached yielded 0 %. Compare with figure 9 in 1949*a*.

(v) *Covariation between frequency and particle size.* Garnet, apatite and staurolite are very regularly distributed in patterns closely resembling that of particle size (cf. figures 15 to 17, with figure 14). The commoner minerals, on the other hand, are dispersed haphazardly. Again, this is a faithful copy of late Ashdown petrography.

Statistical analysis confirms that the relationships between frequency and particle size are very close. Two sharply distinct types of relation are revealed: (1) a curvilinear relationship for garnet and apatite, both of which are most abundant in facies of moderate coarseness (zircon size indices 40 to 60μ), and (2) an apparently linear relationship for staurolite which becomes steadily commoner up the grain size scale. Figure 18*A* to *C* illustrates this. Evidently the particle sizes available for final deposition differed greatly between the two groups. By analogy with the earlier bed it may be concluded that they came from different sources, by way of different river systems. Garnet and apatite presumably travelled in the north-eastern inflow, staurolite came from the south (= Ashdown south-west), and zircon, rutile, black iron ores and tourmaline came from all quarters. But these conclusions cannot be checked solely by reference to the Tunbridge Wells pebble bed alone.* The number of samples obtained (28) is too small to allow, for example, the recognition (within facies of equal coarseness) of opposing lateral changes in the frequencies of garnet and apatite on the one hand, and in those of staurolite on the other, as was done for the Ashdown pebble bed (1949*a*, p. 290 and table XII). Since therefore an argument

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* Nevertheless, if the pebble beds about Isfield are actually on the Top Lower Tunbridge Wells horizon (but see footnote, p. 303), a southerly (= Ashdown 'south-westerly') origin for the staurolite is strongly indicated by its areal distribution.

by analogy cannot be avoided, the onus of showing that the Ashdown and Tunbridge Wells horizons are *closely similar in every other respect* must be accepted. Two further aspects of the critical particle size/frequency relationships will therefore be examined.

First, the *intensities* of the relationships between particle size and frequency in the two horizons are virtually identical (table 2). When the difference for staurolite is examined statistically with the *z*-test, the probability of its being fortuitous proves to be high ($P > 0{\cdot}05$). There is thus every reason to suspect that the two values are really estimates of the same figure.

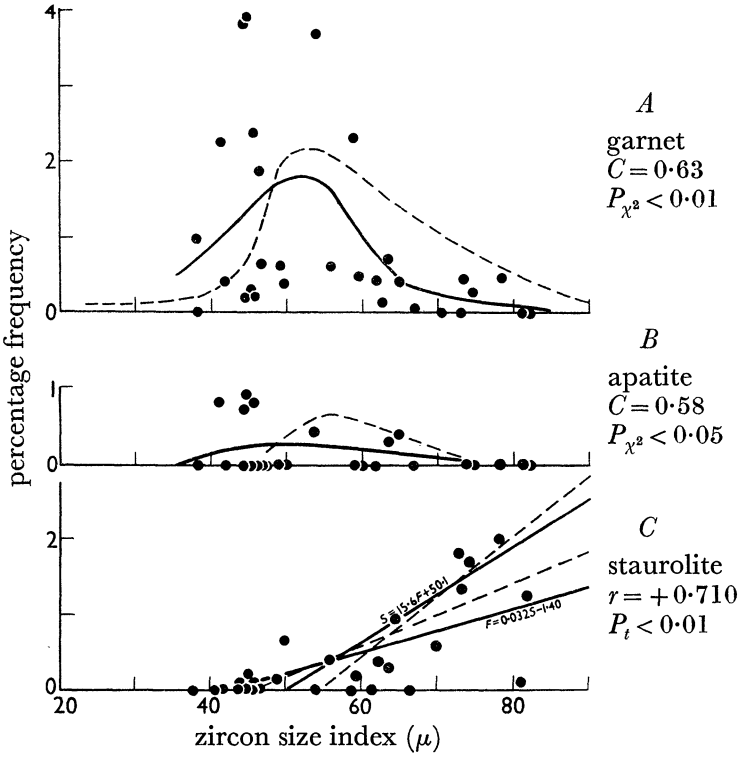

FIGURE 18. Top Lower Tunbridge Wells Pebble Bed. Scatter diagrams and regression lines showing the relationship between the coarseness of the sediment (measured as the zircon size index (S)) and the percentage-frequency (F) of *A* garnet, *B* apatite, *C* staurolite. — curve for the regression of mineral frequency on size. The corresponding regression curves (— —) from the Top Ashdown Pebble Bed are also inserted for comparison. Compare figures 17 and 18 in 1949*a*. C = coefficient of contingency.

Secondly, the exact *forms* of the three relations are surprisingly similar in the two horizons. This is shown graphically by figure 18*A* to *C*, on which the regression lines from the corresponding Ashdown scatter-diagrams (figures 17, 18 of 1949*a*) have been inserted. While the shapes of the curves differ only slightly, it will be noted that those from the Tunbridge Wells horizons are displaced towards lower precentages owing to the smaller average frequencies of the three minerals. The displacement may be expressed algebraically in the case of staurolite by the difference in the constants of the regression equations (table 3).

(*d*) *Other cyclothems*

A third megacyclothem may begin with the locally red or red-mottled top of the Grinstead Clay (seen, for example, $1\frac{1}{4}$ miles south-east of Ardingly: 1959) and end in the lower part of the Weald Clay. But insufficient is known about the detailed stratigraphy of the Upper Tunbridge Wells Sand and lower Weald Clay to be sure. Indeed, since the Weald Clay becomes brackish upwards (1955*a*) sedimentary conditions must at times have changed drastically. This is shown by the detrital petrology, which becomes quite different from anything known before. High tourmaline contents (e.g. 28 % at Clock House, Capel (1948, p. 236); 30 % at South Godstone, Surrey; 35 % at Slinfold, Horsham), low zircon and rutile, and appreciable quantities of hitherto rare or absent detritals (e.g. hornblende (Davies 1916, p. 56; Ferguson 1926, p. 413), cassiterite and dumortierite (Groves 1931, p. 66), and biotite) seem to be characteristic of the sands in the Weald Clay.

TABLE 2

	horizon		
	Top Lower Tunbridge Wells Pebble Bed		Top Ashdown Pebble Bed
detrital mineral	intensity	significance	intensity (1949*a*, pp. 292–293)
garnet	$C = 0{\cdot}63$	$P_{\chi^2} < 0{\cdot}01$	$C = 0{\cdot}60$
apatite	$C = 0{\cdot}58$	$P_{\chi^2} < 0{\cdot}05$	$C = 0{\cdot}60$
staurolite	$r = +0{\cdot}710$	$P_t < 0{\cdot}01$	$r = +0{\cdot}715$

TABLE 3

	horizon	
equations for regression of	Top Lower Tunbridge Wells Pebble Bed	Top Ashdown Pebble Bed
particle size (S) on staurolite frequency (F)	$S = 15{\cdot}6F + 50{\cdot}1$	$S = 12{\cdot}4F + 54{\cdot}3$
staurolite frequency (F) on particle size (S)	$F = 0{\cdot}032S - 1{\cdot}40$	$F = 0{\cdot}041S - 1{\cdot}85$

Yet minor cyclothems of the same general character as those in the Hastings Beds do undoubtedly exist at certain horizons in the Weald Clay. In two of them (Clock House, Beds 1 to 3 and 8 to 11 of Kirkaldy & Bull 1948, p. 80) the coarser tops of the sandy members are asymmetrically ripple marked and suncracked, and in the lower one (Beds 1 to 3) the horsetail soil bed and silty passage-clays lie at the top of and follow on the sandstone, respectively.*

(*e*) *Interpretation of cyclothems*

Broadly, there can be no doubt that part at least of each Hastings cyclothem records the life history of a delta or delta-complex spreading into non-marine waters. Some of the minor cyclothems, such as that within the Wadhurst Clay, seem to represent smaller deltas constructed by single streams, for they are local in occurrence and petrologically simple in constitution. The widespread and petrologically complex Ashdown–Wadhurst megacyclothem, on the other hand, signifies a subsidence-pile of confluent deltas built up by at least two major streams, being composed therefore of multi-source sediments.

But when one attempts to be more precise than this, interpretation of the cycles runs into difficulties. While it is possible to recognize the sediments broadly as 'deltaic', it is not so easy to answer such questions as: What did the deltas actually look like at various stages in their histories? What are the exact relations, in time and space, of the recurrent faunal,

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* In a third, the Horsham Stone cyclothem, Miss F. H. J. Terrell has recently found an *E. lyelli* soil bed at Theale Farm, Slinfold, near Horsham.

floral and lithological facies of each cycle? These queries reveal the main core of the problem: *What type of delta do the cyclothems represent?* In plan, river deltas of today vary between the 'classical' or Nile type, and the 'birdfoot' or Mississippi type. Intermediate stages occur, the differences being controlled by water depth, currents, salinity, topography and lithology of the foundation, particle size distribution of the detritus available, load and its seasonal variations, and the frequency of flooding: in short, largely by the balance between deposition, erosion, subsidence and fluctuation in base level over geological time. These distinctions are mainly sedimentological, and it should therefore be possible, in principle, to reconstruct the succession of geographical conditions from detailed sedimentary studies of the Wealden cyclothems.

This is attempted below. Three interpretations are examined in detail. Interpretation 1 treats the pebble beds, passage beds, soil beds and argillaceous formations as on-delta sediments, laid down in shoals, marshes, meres, levees, channels, etc. Steady subsidence is assumed throughout. In Interpretation 2 only the pebble beds, passage strata and soil beds are claimed to be on-delta deposits: the thick clay formations are considered as transgressive lake sediments. This explanation closely resembles that normally given for Coal Measures cyclothems. In Interpretation 3 *all* the strata mentioned—pebble beds, passage beds, soil beds and clays alike—are rejected as on-delta deposits. They are concluded to be transgressive delta-front and pro-delta sediments lying on erosion surfaces of transgression at the bases of the pebble beds. Subsidence continued throughout each cyclothem. For the moment no assumptions are made regarding the relative roles of fluctuation in subsidence, absolute changes of lake level, etc., in causing the periodic transgressions and regressions.

Much of the discussion hinges on the peculiar 'biscuit' lithology of the passage beds which usher in each major clay formation. This is essentially a succession of isolated ripples, piles, thin lenticular sheets and runnels of sand separated by thin partings of clay. Modern work on recent sediments suggests that similar lithologies form in environments where the supply of sand and silt is deficient and/or the arenaceous/argillaceous boundary fluctuates markedly.* Examples, the first two culminating like the Wealden in soil horizons, are:

(1) *Intertidal environments.* E.g. where salt-marsh muds build out over shoreface sands (see Häntzschel 1936, 1939; Van Straaten 1954, pl. I).

(2) *Delta-top environment.* Where backswamp and levee deposits build out over delta-front sands (see Scruton 1956, figure 7 and pp. 30–35; Shepard 1956*a*, pp. 2602–3 (plate VI, figures 1, 2)).

(3) *Delta-front environment.* Along inner margins of pro-delta clay zones (see Scruton 1956, figure 8 (p. 36); Moore & Scruton 1957, figures 2, 3, 4, 7, 12; Shepard 1956*a*, plate VI, figure 3).

Superimposed on this distinctive lithology, of course, each group of Wealden passage beds shows an upward gradation from coarser to finer sediment, from asymmetrical towards symmetrical ripples, and from high frequencies of exposure to none at all. This seems to eliminate intertidal environments altogether, quite apart from the remaining geological evidence.

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* Instances abound in the British geological column at least as far back as the Cambrian (e.g. lower *Lingula*-Flags of Porth Ceiriad, near St Tudwals, Caernarvonshire.

(1) *Interpretation* 1

In a former publication (1949*a*) the Ashdown–Wadhurst cyclothem was tentatively interpreted as representing a conventional deltaic complex, rather like that of Yorkshire Upper Estuarine times (Black 1929), spreading into a non-marine lake or inland sea. The deltas subsided steadily throughout their history. Sedimentation was at a maximum in the front of the delta, where it outpaced subsidence, and reached a minimum in the back-delta area, where subsidence exceeded it.

According to this view (figure 19*A*), the Fairlight clays and silts represent pro-delta bottomsets, and the Ashdown silts and sands the transition to foresets and shore sands, culminating, when these came to wave base, in the formation of the Top Ashdown Pebble Bed by winnowing in the shallow water at the delta front. Thus the pebble bed could be held to correspond with the 'couronnement horizontal de cailloux' of de Lapparent. As the delta front moved forward, levees formed along the flanks of the underwater trenches made by the more vigorous currents (1949*a*, figure 21), gradually confining the waters to definite distributary channels. Sedimentation became slower and the topset detritus between (spread only during times of flood) rapidly finer in grain. Concomitantly, unilateral current movement gave way to gentle oscillation of the water, though this was of course often reversed temporarily by floods during the early stages. The puzzling Basal Wadhurst Passage Beds and succeeding clays were thus held to represent an assortment of on-delta deposits formed partly in levee and backswamp and partly in ponds and lakes during a period of diminishing sand supply and steadily increasing clay supply. They may be compared, apart from their pebble bed, with the marsh and levee deposits of certain modern deltas (e.g. Mississippi levees: Shepard 1956*a*, plate VI, figure 2, and p. 2602. Rhône levees: Kruit 1955, pp. 369, 376 and 400. Mississippi marshes: Scruton 1956, figure 7 and pp. 30–35; Shepard 1956*a*, plate VI, figure 1, and pp. 2602–3). The ponds were thought to have been fringed with horsetail reed communities, *Neomiodon* lived further out and, in the deepest water with its anaerobic muds, there were abundant *Viviparus* and ostracods. Conditions closely analogous to these may be seen in the Rhône delta today. The étang lakes (for example, the large Étang de Vaccarès) are normally bordered by reeds, with brackish *Cardium* flourishing in great numbers further out.

Distributaries ran between the Wadhurst ponds and lakes, conducting the coarser detritus to the southern margin of the delta, where it spread along the Ashdown shore. Base level was fairly steady and subsidence slow. Hence, serious floods were infrequent and crevassing was practically unknown in the back-delta area. The coarser detritus remained in the distributaries, and only thin films of mud spread across the intervening depressions during rare overtopping of the levees. Individual channels operated for long periods before clogging up, and are now represented by the sandy courses in the lower Wadhurst Clay.

Eventually, as the delta advanced, subsidence in the older part gradually overhauled and finally outpaced sedimentation. The back-delta lakes and ponds consequently expanded and coalesced, a process possibly aided by wind erosion of their shores as in the Étang de Vaccarès today. This resulted in lateral migration of the three biofacies and establishment of the upward succession now observed: horsetail reed bed→*Neomiodon*

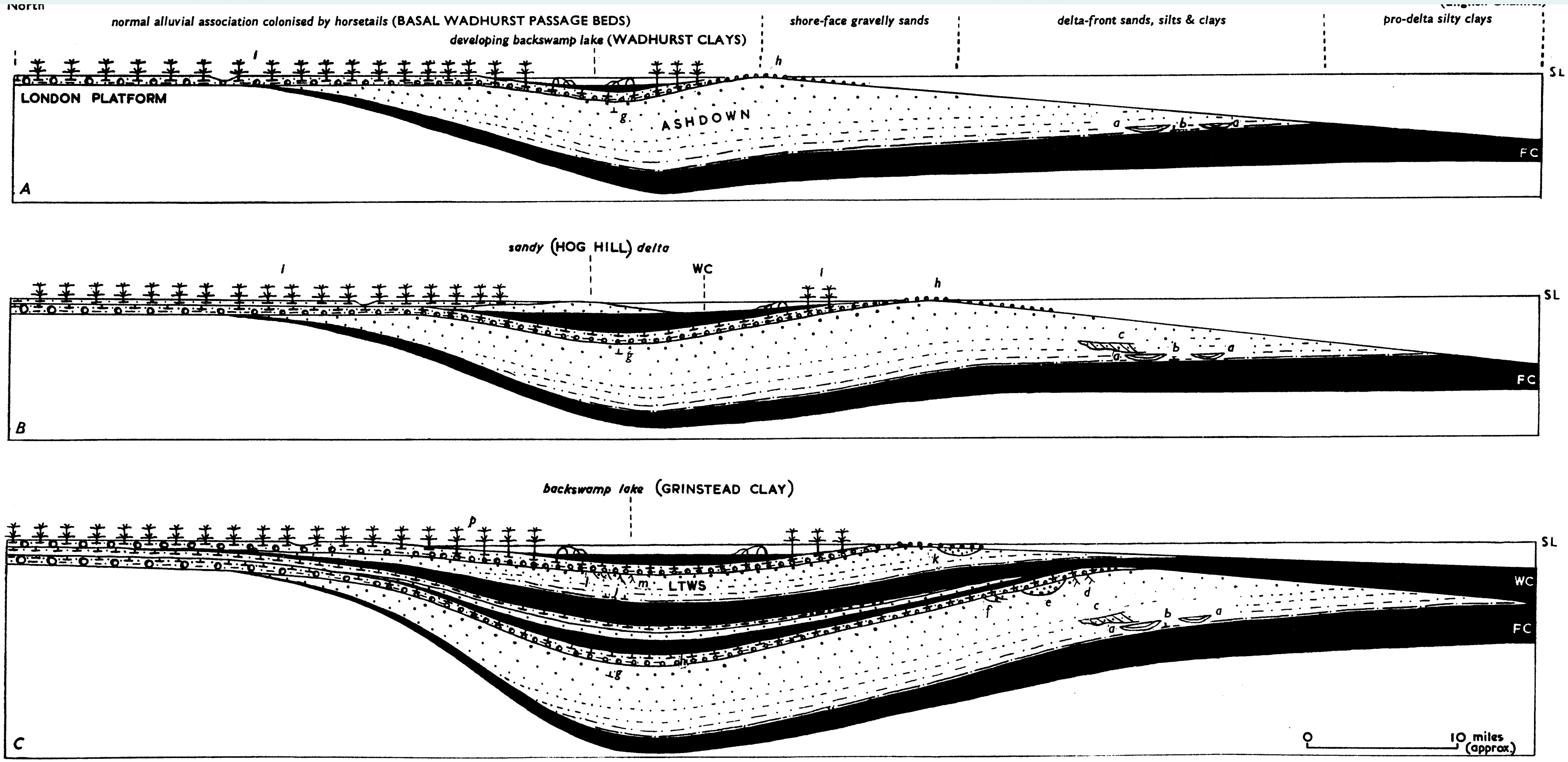

FIGURE 19 *A* to *C*. Hastings cyclothems: Interpretation 1 (1949*a*). Diagrammatic. Note: in this and the three succeeding alternative reconstructions (figures 20, 21, 22) the vertical scale has been grossly exaggerated and the stratigraphical successions are highly simplified. Consequently, the underwater slopes depicted—actually almost flat platforms—are greatly oversteepened. The Ashdown deltaic pile is probably composite, and other minor cyclothems may exist in the Wadhurst Clay. FC = Fairlight Clay, WC = Wadhurst Clay, LTWS = Lower Tunbridge Wells Sand, GC = Grinstead Clay.

a, a = Submerged channels at Covehurst Bay and Ecclesbourne Glen (p. 289).
b = Mid-Ashdown rootlet bed (p. 289).
c = Mouth-bar conelet at Fairlight Cove (pp. 289 to 290).
d = Roots (not *E. lyelli*) at Hastings (p. 290).
e = Minor plugged distributary channel at Northiam (p. 290 and figure 4).
f = Large foreset unit at Dallington (p. 290).
g = Tonbridge *E. lyelli* Soil Bed (p. 290).
h = Top Ashdown Pebble Bed (p. 291).
i = Brede *E. lyelli* Soil Bed. (p. 295).
j, j = High Brooms *E. lyelli* Soil Bed (p. 297).
k = Major distributary channel (figure 12).
l = Mouth-bar conelets at Pembury (p. 298).
m = Roots (not *E. lyelli*) at Pembury, Groombridge, East Grinstead (p. 298).
n = Minor plugged distributary channel at Pembury (pp. 298 to 299).
o = Top Lower Tunbridge Wells Pebble Bed (p. 300).
p = Lower rootlet bed (*E. lyelli*) at base of Grinstead Clay (figures 10, 13).
SL = Standing lake-level.
RL = Rising lake-level.

shell bed → dark ostracod-*Viviparus*-clays. Thereafter, levee replenishment continued to keep pace, ensuring for a very long time the almost uninterrupted accumulation in the interdistributary troughs of dark organic Wadhurst clays. Later, drainage capture by crevassing initiated the development of a sandy delta in one of the back-delta lakes and started off the next but smaller cyclothem, the subsequent history of which was as before (figure 19*B*). Repetition of these events then produced the observed sequence of Wealden cyclothems (figure 19*C*).

The above interpretation closely follows that of the Upper Estuarine Series by Black 1929 (see especially figure 7, p. 406). But though Upper Estuarine conditions may have partly resembled the Wealden, important differences between the two formations remain. The pebble bed and passage strata above (a far cry from the Estuarine Current-Bedded Sandstone and the Mississippi marsh subsoils (Scruton 1956, pp. 30–35; Shepard 1956*a*, pp. 2602–3)) are still not satisfactorily accounted for, and the homogeneity and thickness (up to 250 ft.) of the Wadhurst formation over a wide area do not accord well with deposition in separated ponds and lakes. Why are large-scale foresets so local in the sands, occurring only sporadically and chiefly in the southern part of each major cyclothem? How are they related in origin to the poorly bedded and well sorted sands into which they pass laterally? Why are there distinct types of rootlet in the sands? Why does the winnowed Top Ashdown Pebble Bed, admittedly sometimes lying on coarse pebbly sands in the south, spread northwards to form a quite startling gravelly parting in an otherwise pebble-free succession of fine silts and clays from which it could not possibly have been derived? If the pebbles are winnowings then they must have come from the *south*. They could then only be explained through secondary dispersal by a lake transgession, for the river that brought them ran in the opposite direction—down from the London Platform in the north! What is the significance of the peculiar lithology of the pebble bed, passage beds and soil bed above each sandy member? In particular, if some of the strata above the pebble beds are levee and marsh deposits, why are they never suncracked or rainprinted? And why are they lithologically much more akin to the Mississippi *delta-front* levees (e.g. Shepard 1956*a*, pp. 2602–3) than to those formed further back (e.g. at the right-bank sections above Baton Rouge)? Again, what is the significance of the great mass of Weald Clay, more than 1000 ft. thick in places? This formation includes thin sands, some of which are suncracked at the top and colonized with plants (1948; Kirkaldy & Bull 1948; Terrell, p. 313 above (footnote)). If the earlier explanation were true then the brackish Weald Clay, like the Wadhurst, must comprise chiefly onshore topset beds, deposited during a period when the levels of the marginal seas were either fairly steady or falling. This could only have been the time of the great Barremian regression from the Paris Basin (1955*a*). But then the upward increase in brackishness (culminating in the Lower Aptian transgression) would be difficult to explain. And again, the sedimentary structures in the Weald Clay (and perhaps certain Hastings clays (p. 289)) preserve evidence of contemporary movement of partially compacted sediment. This is much more in accord with deposition on an extensive slope margining the London Platform (cf. the pro-delta silty clays of the Mississippi: Scruton 1956; Shepard 1956*a*) than in onshore lakes and ponds.

(2) *Interpretation* 2

Once again, circumstantial evidence strongly suggests modification of the earlier interpretation. It impels consideration of the clay formations as *transgressive pro-delta lake sediments* deposited, not when the deltas were advancing, but during periods of retreat. Which horizons then in the Hastings cyclothems mark the beginnings of transgressions?

If, as seems suggested by signs of local erosion (pp. 295 to 306), the transgressive surface lies above the soil at the base of the overlying clays, then the peculiar graded pebble beds and passage strata remain unexplained. Any such modification of the original interpretation along 'Carboniferous' lines (figure 20*A* to *C*) is obviously untenable and, despite the seductively similar sequence from clay → sand → soil bed → 'mussel' band seen in both cycles, the argument by analogy must be abandoned. The local erosion of the soil beds must be explained in some other way (see below).

Clearly, the surface of transgression in each cyclothem can only be represented by the base of the pebble bed. There is consequently no escape from the conclusion that all the succeeding strata—passage beds, soil bed and roof clays alike—are delta-front and pro-delta sediments deposited under steadily deepening lake waters beyond the delta shore. This is the basis of the interpretation below.

(3) *Interpretation* 3 (*a* and *b*)

During recent years far-reaching results have been obtained from studies of modern deltas and other shelf environments. Following the notable researches of Trowbridge (1930), R. J. Russell (1936, 1940, 1948), R. J. & R. D. Russell (1939), Fisk (1944, 1947, 1952, 1955, 1956), Fisk, MacFarlan, Kolb & Wilbert (1954), Fisk & MacFarlan (1955), Morgan (1952), Morgan, Lopik & Nichols (1953), Bates (1953), LeBlanc & Bernard (1954), Scruton (1956), Scruton & Moore (1955), Moore & Scruton (1957), Shepard (1956*a*), Greenman & LeBlanc (1956) and other workers on the Mississippi birdfoot; of Kruit (1955), Duboul-Razavet (1956) and Duboul-Razavet & Kruit (1957) on the Rhône delta; and of Sykes (1937) and McKee (1939) on the Colorado delta, there is now a fair understanding of the sedimentology and sedimentary construction of typical large deltas of three extreme morphological types. Unfortunately, however, all these deltas are built out into the sea, with the result that the sediments become dispersed and deposited under conditions of hypopycnal inflow (Bates 1953). The turbid waters of the Hastings rivers, on the other hand, will have mixed far more completely with the fresh lake waters, probably dispersing the detritus by homopycnal inflow. Only when the rivers were overcharged are turbidity currents likely to have given rise to hyperpycnal conditions at the outlets. Hence, we should expect, *ab initio*, to find extensive areas of sediment formed under very shallow water, less well marked seasonal lamination (owing to absence of salt wedges) and a general deltaic form more nearly approaching Gilbert's classical type with steep foresets than that of either the Mississippi or Rhône. The relative scarcity of observable foresets in the Wealden sands must be due not only to the general fineness of grain but also to the rarity of major distributary mouths and the flatness of the underwater platforms. At any one time the shores of the advancing deltas will have consisted of long shelving beaches only occasionally interrupted by distributary passes. Subsequently, owing to bar formation, crevassing, over-extension of channels, etc., the positions of the passes will have changed.

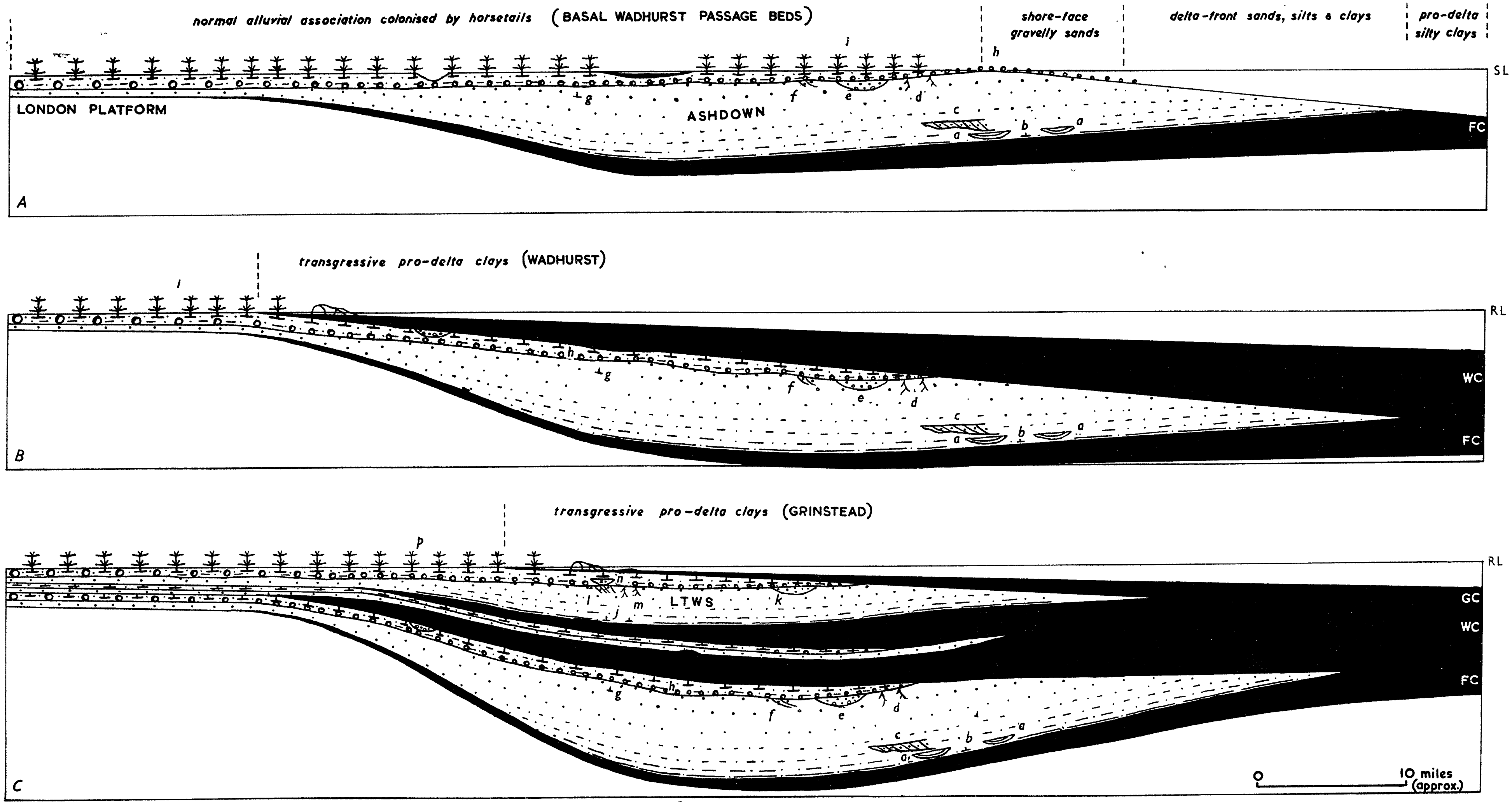

FIGURE 20 *A* to *C*. Hastings cyclothems: Interpretation 2. Diagrammatic. For legend see figure 19.

Indeed, steep foresets are probably abundant in large deltas only in distributary-mouth conelets (bars) and subaerial alluvial fans (e.g. the middle Colorado (McKee 1939) and Millstone Grit deltas (Walker 1955)). Much of the so-called 'flat-bedded' Wealden sand and silt was undoubtedly deposited on delta-front platforms sloping too gently to be detectable now. Generally speaking, 'topset' sands and silts rest directly on 'bottomset' clays.

During Weald Clay times the increasing salinity changed sedimentary conditions considerably. Hypopycnal inflow probably became established and therefore direct comparison with modern shelf environments is likely to prove more valuable.

(i) *Ashdown–Wadhurst megacyclothem.* In the first megacyclothem examples of large-scale foreset bar sands deposited off the mouths of major distributaries are best exposed in the upper Ashdowns of the south-east Weald (Hastings coast (pp. 289 to 290) and Dallington (p. 290)). Like their Mississippi analogues (Scruton 1956, p. 37) they are not well sorted, even at the crests of the foresets, having been deposited at greater depths than most of the surrounding sands. The conelet at Fairlight Cove, for example, lies in a hollow excavated almost down to the underlying pro-delta (Fairlight) clays, and its height proves a water depth exceeding 30 ft. To all appearances the structure marks the place where an over-extended distributary from the north-eastern river burst its banks and established a new pass and bar. Unfortunately, there is no sign of further extension of the channel above the conelet, though it may well of course have meandered out of the plane of section (cf. pp. 298 to 299, 329, and Scruton 1956, p. 38). However, a washout comparable to what might have been expected has been seen at Northiam (figure 4) where, as in the case of the larger Mississippi distributaries, it is entrenched in its own thick bar deposits. These are massive, ungraded and badly sorted. Fluctuations in river discharge, possibly seasonal, are recorded in the case of the Fairlight conelet and slipping at the foot of the steep foreset slope was common. Occasional foresets on a smaller scale (less than 1 ft. high) apparently represent detritus deposited in shallow water off minor distributary passes (e.g. Icklesham). The sandstones with 'festoon'-bedding (concordantly filled and mutually interfering channels) undoubtedly mark stretches of irregular bottom, criss-crossed by submerged bars, small hollows and branching channels.

For the most part the rare foreset units in the south-east Weald are replaced laterally by massive well sorted silver-sands carrying abundant specks of carbon. In their particle size distributions and contents of land-derived wood they match up well with the shore sands of the Rhône (Kruit 1955) and Mississippi deltas (Russell & Russell 1939; Fisk *et al.* 1954; Fisk 1955), yielding similar types of curve to those of Doeglas (1946) and Andel & Postma (1954). Hence, the last Ashdown shorelines seem to have lain between the present anticlinorial axis of the Weald and the Sussex coast. Debris on the successive strand-lines may actually sometimes be present as the carbonaceous partings seen at Brede (p. 290). In the latter case the observed rhythm was possibly seasonal, due to annual destruction of foliage. Lengthwise along the shore, the beach sands drifted in by wind-wave transport from the mouths of the distributaries. Occasional pebbles accompanied them for short distances, some individuals rolling into deeper water from which there was no return. This gave the local sandstones scattered with pebbles.

While the deltas were advancing the base level set by the Wealden lake must have been fairly steady, or declining. Most of the abundant detritus carried by the rejuvenated rivers

(1954, 1955*a*) reached the pro-delta and delta-front areas and was widely dispersed in the fresh neutral or alkaline waters of the lake. Thus beyond the sandy shoreface there extended a broad, flat, shallow platform with delta-front silts and sands and rare patches of aquatic plants (Fairlight) with, beyond that, a wide belt of pro-delta silts and clays (Fairlight facies). The latter suggest no appreciable change of slope, and must have lain under shallow water, in places rather more than 30 ft. deep on their inner side. Large-scale foreset formations are therefore absent. In detail, the transition from Ashdown to Fairlight facies strongly recalls that from delta-front and bar-sand deposits to the pro-delta silts and clays of the present Mississippi delta (Fisk *et al.* 1954, p. 87). To summarize: the belt was wide and the supply of sediment, though fluctuating, was plentiful. These conditions contrast markedly with those subsequently established in the same zone during deposition of the Basal Wadhurst Passage Beds (p. 322). Farther out, over the present area of the English Channel, deeper water existed, laying down bottomset pro-delta clays of normal Wadhurst aspect (figure 21 *A*). Purbeck-type precipitation of carbonates and sulphates was long since defunct, largely owing to the increased flow of fresh river water consequent on the end-Jurassic uplift of the watersheds.

The silts and clays accumulated rapidly, frequent minor fluctuations of lake level—perhaps tidal in origin—becoming registered permanently in them as local footprints and mottling. It is unlikely that the mottled and structureless clays owe their peculiar characters to burrowing organisms. A tidal, or at least submerged, origin must surely explain the puzzling washout-like structures seen near the Fairlight–Ashdown junction on the Sussex coast (p. 289). Osborne White (1928, p. 39) ascribed that near Ecclesbourne Glen to the close approach of two subaqueous delta lobes, but his explanation hardly seems to account for the run of the bedding, parallel to the sides of the (?) channel. On the other hand, the structure strikingly resembles a filled-in tidal slough (see, for example, Häntzschel 1939). McKee investigated examples of these in the lower region of the Colorado delta, where they appear as remarkable 'synclinal' or 'festoon' structures (McKee 1939, plate II *E*) 'cut back through the banks of the distributary channels by the run-off of tidal waters and subsequently filled with mud-layers, which conform to the shape of the channel' (McKee, p. 79).* Subsequent experimental work by the same author (1957, pp. 132–133) suggests that when, as in the Ashdown channel, the filling sediments do not thin laterally towards the sides and are concordant to it, the channel (however cut) was completely submerged during plugging, and filled by settling of the detritus from the sides and above rather than by longitudinal currents. Perhaps, at this low level in the Wealden, we are witnessing the last tidal effects of the retreating 'Purbeck' sea, for such structures are not known to occur at any higher level. The horizon is close to that of the footprint beds; possibly it is the same. A region of tidal creeks would be an ideal environment for the preservation of such impressions. Larger fluctuations of lake level could account for certain of the more persistent beds of clay in the Ashdown, though some of these might well be onshore deposits (see below). Variations in the balance of sedimentation and subsidence are likely causes.

Behind the shoreline, deposition on the delta surface was very slow. Much of it was doubtless underwater. During all but exceptional floods the levees were probably sufficient to keep most of the coarser detritus within the channels. Only small amounts of clay in

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* It should be noted here that some present-day creeks are essentially *depositional* structures.

suspension spread across the delta top. Apart from this, the other onshore topset deposits will have been chiefly organic muds in the ponds and meres. Possibly these are now represented in the south by the upper Ashdown *Tempskya*-Clays, and further north by certain lenticular clays in the middle and upper Ashdowns of Ashdown Forest. Vegetation, now evidenced only by rootlets, clothed the delta surface and *Unio* lived in the water courses. Probably most of the plants were small waterside and aquatic pteridophytes, with some tree-ferns.

How long and how far the delta eventually extended southwards is not for the moment clear, but at last the movement was halted, and finally a retreat began (figure 21 *B*). If comparison with the Rhône is correct, this is first suggested in the back-delta area, where the upper Ashdowns assume the facies of a fine alluvial-like sandy silt. These silts are well exposed near East Grinstead, Penshurst (The Grove: 513429), Tonbridge, Cowden, and Reading Street (Ramsden Farm and Barrow's Land). They are poorly sorted, yielding particle size distributions comparable to Kruit's levee deposits (Kruit 1955, p. 400). Near Tonbridge this backswamp was colonized by horsetails and at East Grinstead suncracked on top. Here and there also, coarser sandy wedges with superior sorting have been found; these are apparently crevasse sands.

Such evidence suggests a change to conditions of widespread levee building (and perhaps crevassing). As Kruit shows, these processes are most likely to occur during a period of rising base level. Hence, somewhere to the south, the retreating Wealden lake had turned and begun to transgress across the Ashdown delta. This would cause a retreat northwards of the three shore zones, but with this difference: whereas hitherto the belts of shore sand and delta-front silt will have been broad and therefore thick (owing to an abundance of sediment reaching the front of the delta), *now they will rapidly contract as the supply of coarser detritus becomes more and more frequently cut off by floods farther back, overtopping and breaching the levees and spreading it across the surface of the delta.* In environments where thick courses of sand and silt once accumulated, now there will only be thin seams of sand and silt. While the transition from (Fairlight) clay to pebbly sands in the Ashdowns of the southern Weald needed several hundred feet of beds in which to take place, the reverse change back to (Wadhurst) clay is now completed in a few inches or feet of strata. Evidently transgressive passage beds, deposited during deltaic retreat and leading back to deeper water clays, are unlikely to produce stratigraphical successions simply mirroring those deposited during a previous advance.

The coarser detritus, dropped farther back, aggraded the lower courses of the subaerial distributaries. Consequently, the washouts at the top of the Ashdowns in the south-east Weald are normally filled with coarser material than those lower down, though this may be bedded concordantly to the channel sides (cf. McKee 1957). The channel illustrated (Northiam, figure 4), while also submerged when plugged, thus contrasts strongly with that near Ecclesbourne Glen. It contains much ill-sorted lag-gravel and seems to be entrenched in its own coarse bar deposits (cf. Lower Tunbridge Wells channel discussed later (p. 329)). Hence, as expected, point-bar deposits are not represented and there is no other evidence of meandering.

Retreat of the shore zone formed the graded succession: Top Ashdown Pebble Bed → lenticular siltstones and shales → horsetail soil bed → clay. Above the pebble bed all

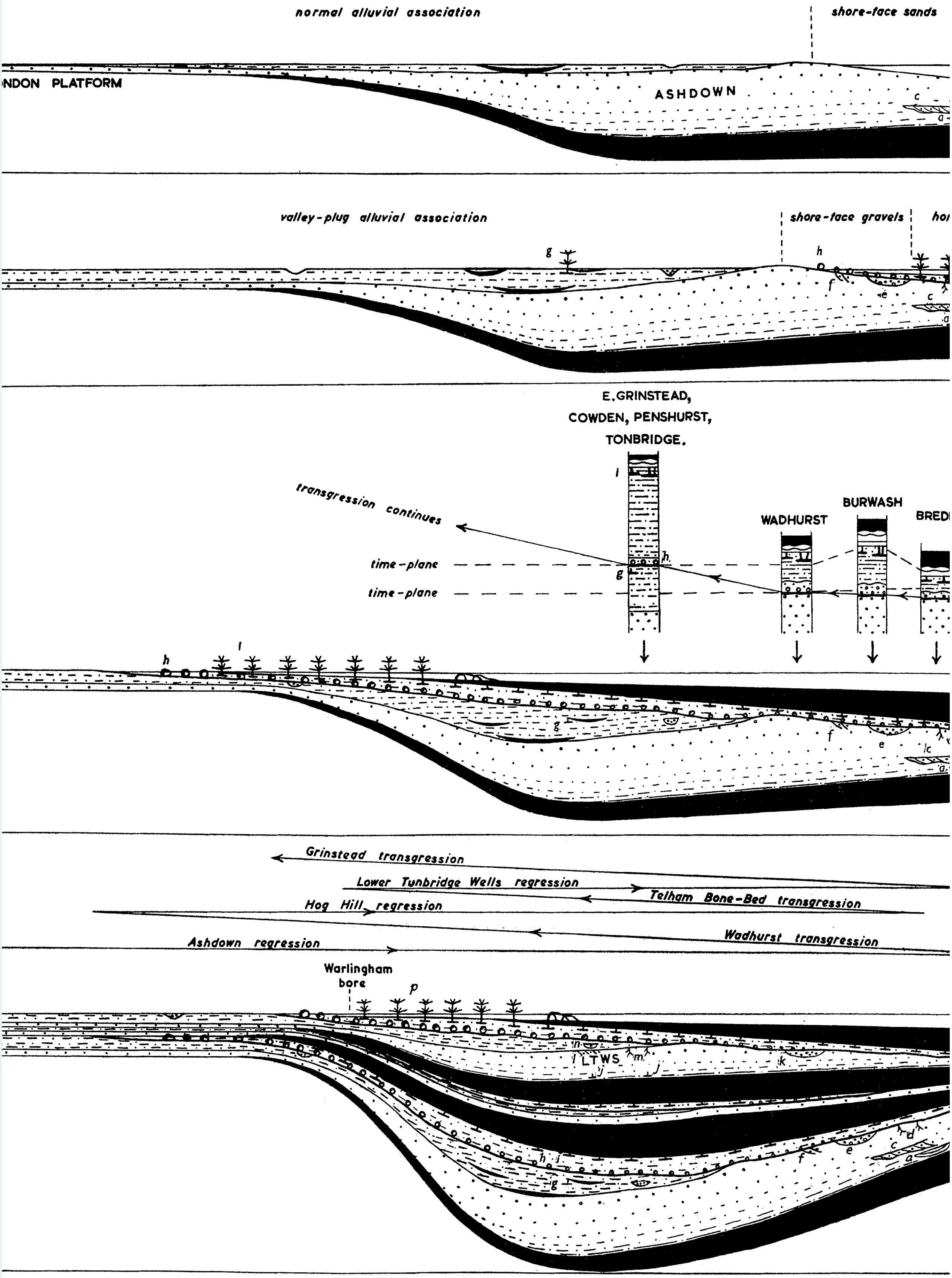
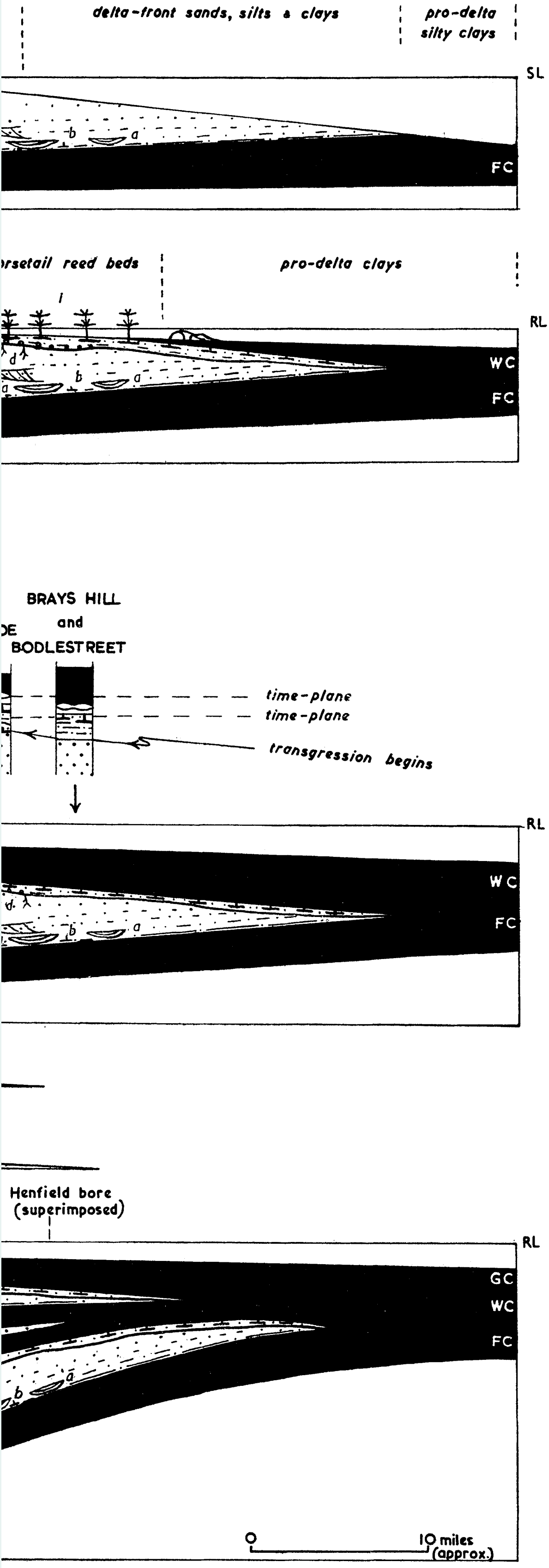


FIGURE 21 *A* to *D*. Hastings cyclothems: Interpretation 3*a*. Diagrammatic. Reconstruction assur was deposited *during the lake-transgressions*. Only *aquatic* vegetation growing in the area is d

N.B. The northward overstep by the Top Ashdown Pebble Bed (= *h*, a retreating strand-gravel) fron may be observed between Wittersham and Reading Street, and along the northern flank of Ashdow



ming that the bulk of the onshore alluvium lepicted. For legend see figure 19.

m shoreface sand on to silty onshore alluvium n Forest (figure 2 and p. 323).

(Facing p. 322)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

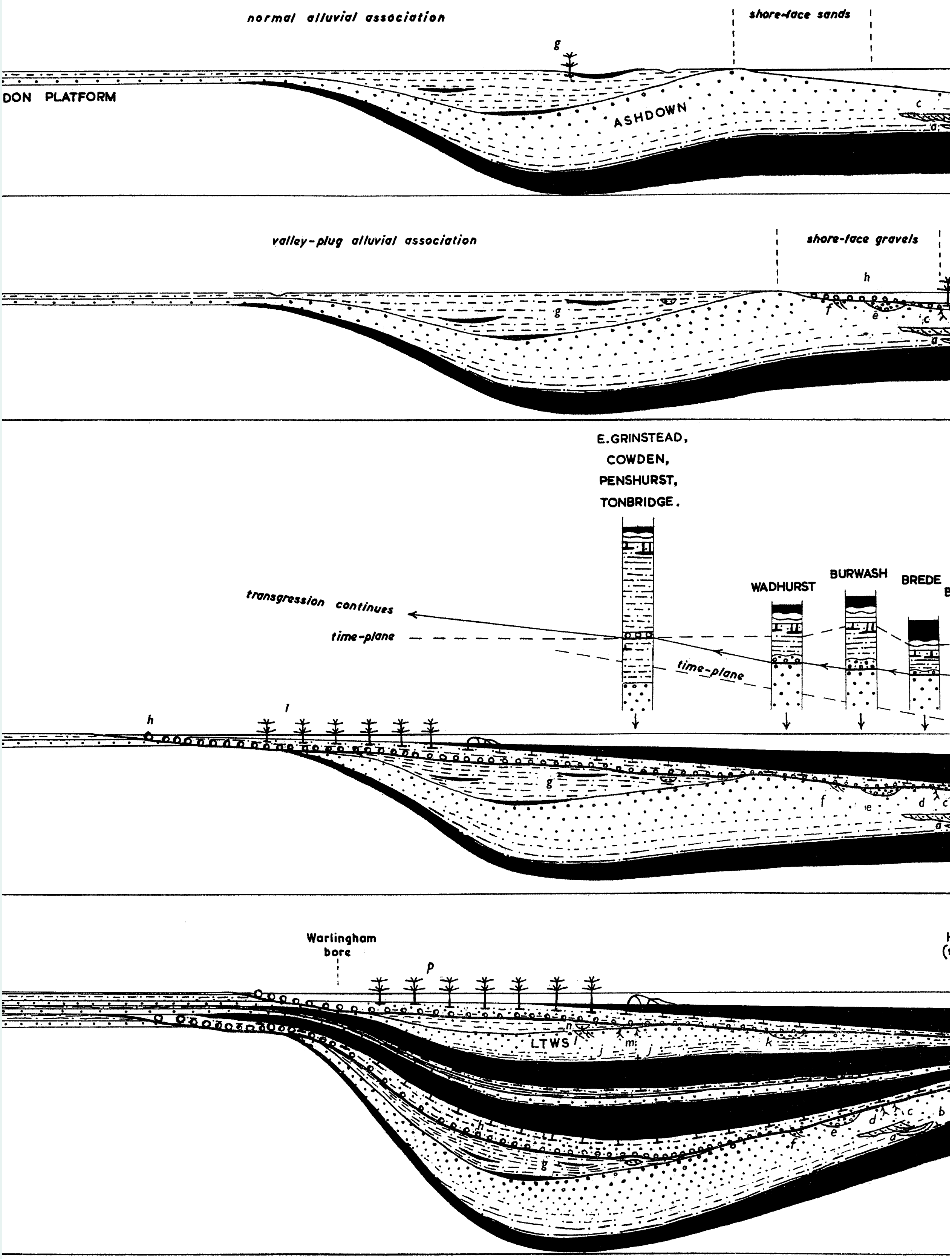
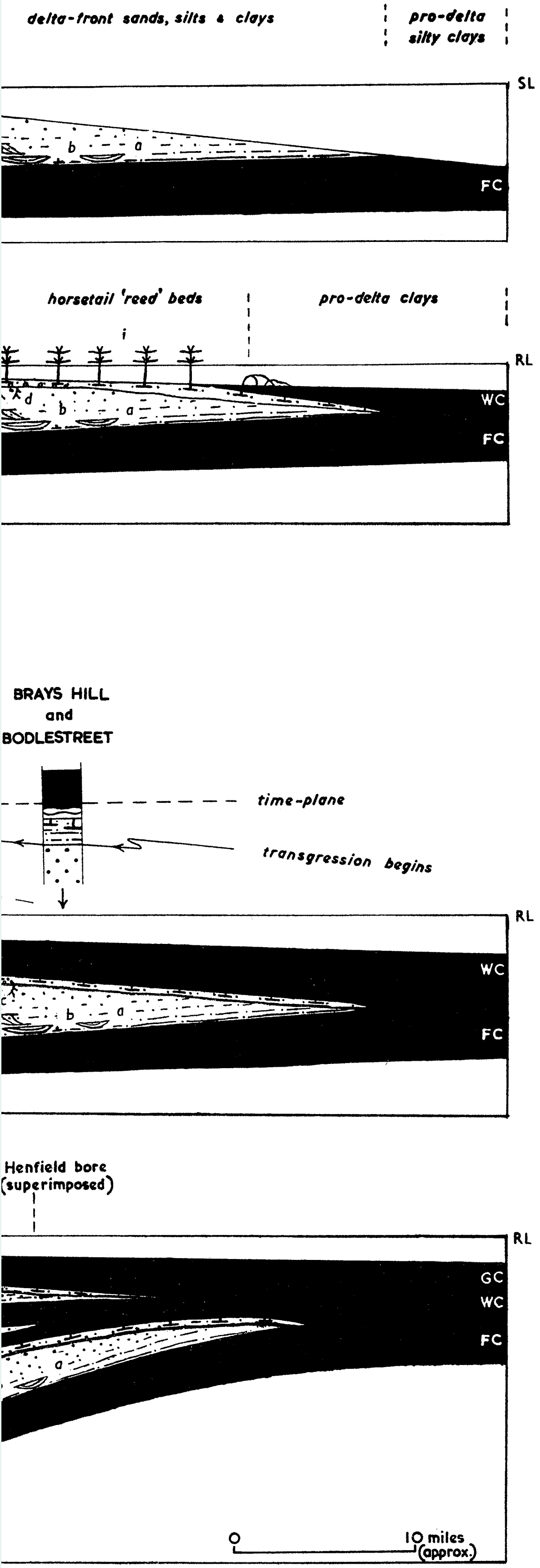


FIGURE 22*A* to *D*. Hastings cyclothems: Interpretation 3*b*. Diagrammatic. Reconstruction assumi was deposited *during the growth southwards of the deltas*. Only *aquatic* vegetation growing in the area i



ing that the bulk of the onshore alluvium
is depicted. For legend see figure 19.

signs of subaerial exposure cease. The most southerly point reached by the delta is marked by the outer limit of the pebble bed. This runs parallel to the present anticlinorial axis and 3 or 4 miles beyond it (1949*a*, figure 2; 1954, text-figure 1). As the coast retreated the scattered pebbles and other debris, gathered on the strand-line by the rising waters, were washed across the earlier-formed shoreface sands. Hence, the belt where the pebble bed rests directly on delta-front deposits provides an independent check on the position of the delta's farthest shore (figures 6, 21 *B*, *C*).

Away to the north, levee building continued uninterrupted, laying down extensive sheets of sandy silt as the distant 'tide' came in. This was bound to be so while the coarser sediments remained in the channels; that is, so long as crevassing was not serious and levee building could keep pace with the rise in base level.

But clearly, down in the south, not far behind the retreating shoreline, there was always a point lakeward of which this did not apply. As the water levels rose plugging and crevassing gained the upper hand, and eventually the levees gave way, flooding a new portion of the delta plain. Pebbly sand, hitherto confined to the channels, began to escape and merge with that on the shore, spreading a thin sheet across each new inundation. At the same time waves and currents stirred up and eroded the underlying shoreface sediments, giving the puzzling relation now observed between particle size of matrix and pebbles. When any of the pebbles rolled into slightly deeper water, either because of the rising level or transport down-beach, they stayed there. Thus a graded sheet of gravel was formed covering the foreshore from breaker zone to wave base. Further deepening of the water caused finer sediment to be laid on top. Similar conditions now exist in places on the southern fringe of the Rhône delta where the coast is retreating, as at Stes. Maries-de-la-Mer (Kruit 1955, p. 456). In the Mississippi delta pile also, the transgressive strand-plain sands and gravels capping each of the Pleistocene deltas and passing gradually up into marine pro-delta clays are exactly analogous to the Top Ashdown Pebble Bed. They too were formed during times of rising base level (ice sheets melting), in contradistinction to those deltas which developed better, like the late Recent ones, during periods of still-stand (Fisk 1955; Fisk & McFarlan 1955). The surface of the Ashdown gravel sheet still retained something of the original topography, broad hollows with deeper water marking the partly obliterated sites of former channels (1949*a*, pp. 301–303). In this respect the present interpretation again differs from the earlier one, for the top Ashdown hollows were originally thought to represent delta-front current-trenches indicating *early* stages in the formation of the distributary pattern. Apart from clay in suspension, little new sediment now arrived for, added to the leaking levees, the distributary mouths were themselves retreating.

As the inundation proceeded the sheet of strand-plain gravel was extended northwards, completely overstepping and eroding the shore sands beyond Ashdown Forest and the Isle of Oxney.* From them it spread across the newly formed levee-silts of the north Weald (previously initiated by the transgression itself), giving the hitherto puzzling succession observed between East Grinstead and Tonbridge, and Wittersham and Reading Street (figure 21 *C*). The actual depth of shore (and dune?) sand removed is doubtful. Concurrently, the pebbles increased in size and frequency northwards, owing to the breaching of

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* In previous interpretations (pp. 315, 318 above; also 1954, 1949*a*), it should be noted, the gravel is considered to have spread *southwards*.

successively higher reaches in the distributaries, and thus accentuated the size-discontinuity previously referred to. Beyond the water's edge (and now seen stratigraphically above the gravel) the detritus declined rapidly in coarseness. Probably the (Wadhurst) clay belt moved close inshore, though it was nowhere very deep, and the underwater platform must have become even flatter (figure 21 *B*).

In the fluctuating breaker zone the coarse pebbly sands were continually reworked up and down the indented beach and augmented by erosion of the sediments underneath. Locally, large quantities of land-derived 'sawdust' became concentrated along the strand-line ahead of the pebbles, forming the parting now often seen at the base of the pebble bed. Occasional patches of finer sediment were temporarily exposed and suncracked. Just below the strand-line, constant agitation by currents up and down the muddy shoreface slope cut, grooved and filled flutes, moulded and remoulded the finer sands into thin irregular patches and eroded ripple marks, and internally cross-laminated and often graded-bedded them. Grooving of the flutes, if not a compaction effect, was presumably carried out by bounding and rolling sand grains (compare the shale fragments of Dzulynski & Radomski (1955)) prior to the filling with sand.

The minor sedimentary structures are so perfectly preserved that burrowing organisms must have been virtually absent from the bottom fauna. They also show, with the evidence of local bone beds and the extreme thinness of the graded units compared with those in the top Ashdown, that deposition was by now slow. At frequent intervals, the vagaries of currents and fluctuations of river stage caused rapid changes in competence, often permitting only silt or clay to be carried in. Offshore, under a few feet of water, movement on the bottom degenerated to mere oscillation, moulding the clayey silt into interfering sets of short symmetrical ripples and hardly grading it. The deficit of arenaceous sediment in the delta-front zone now became so serious that often all the coarser material was swept up as patches and ripples, leaving them isolated on an otherwise muddy (and relatively inerodible) floor. But, whereas new accessions of coarse detritus became more and more intermittent, suspended clay continued to arrive throughout.

Hence, the passage up to and including the Brede Soil Bed shows features (graded bedding, fine cross-lamination, peculiar lenticularity, distribution of wood fragments, scattered shells, scarcity of animal burrowers, rapid lithological alternation, lack of suncracks, etc.), strongly resembling the Mississippi delta-front silts and sands now accumulating on the shallow-water platform off the minor distributaries (Scruton 1956, pp. 35–37; Shepard 1956*a*, pp. 2602–2603). This was confirmed by direct comparison with actual Mississippi cores and other records obtained by the Scripps Institution of Oceanography (arranged through the courtesy of Dr F. P. Shepard) and the Humble Oil Company (through the courtesy of Dr H. N. Fisk). Ripple-like lenticles, partings and flute-fillings like those seen in the basal Wadhurst were clearly represented. Hence, the offshore transition from sands and silts to pro-delta clays was concluded to have been lithologically similar in the two cases. Since then, this has been convincingly confirmed by the publication of the important paper of Moore & Scruton (1957) on the fine details and distribution of the Mississippi delta structures. No doubt can remain that the basal Wadhurst passage strata correspond precisely with these authors' zones of 'regular' and (farther offshore) 'irregular layers', primary and secondary. On the east side of the Mississippi delta the offshore passage from sediments with 'regular layers' to those beyond the platform with 'irregular layers' shows just the same changes in lithology (sheets and lenses becoming less abundant, smaller, finer grained, more poorly sorted and thinner (p. 2733)) as may be seen at the base of the Wadhurst. Moore & Scruton's zone of highly 'irregular layers' and of mottled structures are presumably not represented owing to the paucity of the bottom fauna and/or the lack of an appreciable pro-delta slope. Consequently, the submerged part of the retreating Wadhurst delta would seem to have consisted of an extensive shallow-water platform (owing to vertical exaggeration not well depicted on figures 21 and 22), very flat and shelving gently towards deeper water which was probably not normally more than 24 ft. deep (1949*a*). If the submerged portion of the earlier Ashdown delta had had this form then its lack of large-scale foreset beds is readily understood. Regarding the bottom fauna, it is perhaps significant that irregular layers and mottled structures, in the sense of Moore & Scruton, become more abundant in the Weald Clay (p. 332).

The pre-modern Mississippi deltas show similar features. Thus the Humble Oil Company's boring at Buras Levee, Scott Bay, Plaquemines Parish (Louisiana), penetrated delta-front and pro-delta sands, silts and clays hardly distinguishable from those at the base of the Wadhurst. One core from 560·5 to 561 ft. depth shows examples of thin sandy seams and lenses of both ripple and flute-like form separated by clay-partings, all within 6 in. of strata. In direct contrast, the marsh and levee deposits examined over the Mississippi region (e.g. right-bank sections above Baton Rouge) and the Rhône delta (e.g. east side of the Étang de Vaccarès) were found to have little in common with the Basal Wadhurst Passage Beds.

Thus the change from Ashdown to Wadhurst conditions may be geomorphologically very significant. The passage from sand back to clay is accomplished in only a few feet of delta-front beds; and the sedimentary facies, sandy and Rhône-like in Ashdown times, becomes strongly reminiscent of the Mississippi immediately following the Wadhurst transgression. Indeed, part of the Wadhurst Clay succession could well represent a bird-foot (though this is later considered unlikely (pp. 327, 328)), for lenticular sands are one of its characteristic features.

Two interesting consequences follow from the present interpretation. The first is that the horsetail consocies of the Brede Soil Bed can now be explained as growing (with leafy liverworts (?) and *Physa*, but no apparent reed competitors) *a few yards offshore* of the delta, *in the lake*. As already inferred (1941), the horsetails flourished in a foot or two of water, and this must have been at the outer boundary of the silt zone. They did not grow, as analogy with other deltaic cyclothems had led one to suppose, on the surface of the delta. That is why broken fragments of the stems appear (with other wood) at the base of the pebble bed, and continue spasmodically through the sediments above. This represents flotsam from the reedswamp thrown up on the strand-line. Inevitably much of the horsetail debris was concentrated locally inshore, ahead of the pebbles; but, under the shallow water farther down the beach, the silts and muds also received a fair sprinkling. The rare scattered valves of *Neomiodon* are also accounted for. *Neomiodon* lived (see below) almost entirely beyond the reed beds, which effectively prevented many of the dead shells being washed inshore (cf. *Cardium* along Étang de Vaccarès today). Locally along the lake margin, however, as along many lake margins today, they were cast up more abundantly on the shoreface (= Basal Wadhurst Passage Beds) and strand-line (= Top Ashdown Pebble Bed) *opposite gaps in the reeds.* This is well seen in the Wittersham–Iden–Winchelsea tract (pp. 292, 295), where erosion (presumably due to the approaching Hog Hill delta) has removed most of the Brede Soil Bed (figure 6: *inset*). It follows that the reeds, there lying close to a pass of the north-eastern river, were scoured away progressively, and not in one single violent episode.

The common restriction of *Equisetites lyelli*, within the Wealden, to passage beds transitional *from* silt *to* clay further suggests which ecological factors helped to control the distribution of the plants. Water depth, wave and current erosion, sedimentary pH and organic content, rate of sedimentation, apparently all had some effect. Certainly on the inshore sides of the reed beds the horsetails could not tolerate much water movement or erosion of the bottom. They only became established in the quieter waters offshore, where even oscillatory movements were dying away; and they never colonized the pebble beds or sands on the beach except through an overlying blanket of silt or clay (p. 292)—probably in sheltered bays. Pure stands of some modern species of aquatic horsetail (e.g. *Equisetum fluviatile*) are known to be intolerant of bottom erosion and silting under certain conditions (Pearsall 1918, 1921; Tansley 1939, p. 617). Further, since similar soil beds do not often occur (as might otherwise have been expected) low down in the cyclothems at horizons either where clay is passing upwards into silt (e.g. in the middle Ashdowns or near the Wadhurst/Lower Tunbridge Wells boundary: but see pp. 297, 306) or in any other facies, *rate of sedimentation* may also have set a limit to their spread inshore. Like the effect of erosion, this was probably more important than slightly varying depth in shallow waters. Even without major angiosperm competitors *E. lyelli* was thus commonly unable to establish itself in front of a rapidly growing delta and the cause was only partly the greater depth of the silt/clay transition during these periods. Water depth by itself probably only became limiting on the outer side of the *transgressing* reed bed, when the silt and clay zones came close inshore and there was quite obviously a critical maximum beyond which the horsetails failed to grow. Apparently the reed waters were acid and the soils organic (cf. *E. fluviatile* reedswamp in certain angiosperm-poor 'primitive' lakes today; also Pearsall 1921, Tansley 1939). Bearing in mind the extreme thinness of the strata involved, it seems that the belt of water occupied by the plants must always have been narrow, despite the very gentle slope of the bottom.

The second consequence of the new interpretation is strong confirmation that the lake waters were fresh. The absence of soil beds above some of the sandy formations in the Weald Clay may thus be explained by the increased salinity of the latter.

As the transgression continued and the river mouths retreated still further, the supply of inorganic sediment (now entirely suspended silt and clay) at any one spot became very small. Gradually the water deepened. After a few years of life the horsetails were killed off, and in the succeeding Wadhurst Clay facies *Neomiodon* flourished. Throughout the transgression feeble movements along the bottom washed large numbers of empty shells on to the step at the outer margin of the reeds: hence the formation of the Brede Shell Bed, followed by clays with ironstones and thin seams of the same bivalve. The 'halo' of impure clay-ironstone nodules (often enclosing the shells) may be attributed to the original precipitation of 'limonite' caused by acid water from the decaying reeds meeting the neutral or alkaline open water of the lake. Subsequent burial in the organic and anaerobic bottom-mud will have reduced and carbonated it (Moore & Maynard 1929) to siderite, as around some deltas today (Andel & Postma 1954).

Finally, in the deepest water of all, the sulphide-rich Wadhurst Clays with ostracods and *Viviparus* were deposited. These contain more *Neomiodon* partings, less wood, thin seams and lenses of fine silt (only sometimes penecontemporaneously broken or distorted) and no graded bedding. The general lack of slumping and frequent courses of nearly structureless clay suggest prolonged periods without movement, and continuous settling rather than abundant burrowers. All these characters reveal that the sediments were changing lakewards towards a facies closely analogous to that of the pro-delta clay zone fronting the Mississippi delta today (Scruton 1956, pp. 38–41), but lacking its increased slope. Probably the water seldom exceeded 24 ft. in depth, as mentioned earlier.

Ultimately, the cycle closed with the lake waters lapping against the London Platform, and a vast empty sheet of water stretched southwards across the Weald. The minimum speed of transgression may be gauged roughly from the average life time of the reed beds. If these normally lasted not less than 2 or 3 years and were only a few tens of yards wide, then the lake waters must have taken at least a few thousand years to submerge the delta completely from Hastings to London. Rapidity of the transgression is suggested by the thinness of the passage beds. Its speed will have increased somewhat as time went on owing to (1) reduced sedimentation, and (2) the higher proportion of clay being deposited, resulting in greater compaction and therefore quicker and wider subsidence. The acceleration is also suggested by the thinning of the Top Ashdown Pebble Bed northwards towards Goudhurst, Benenden and Reading Street (figure 6). Nevertheless, the inundation was probably less rapid than some Upper Carboniferous transgressions. In the Coal Measures cyclothems, for example, the roof shales usually lie directly on the transgressive surface.

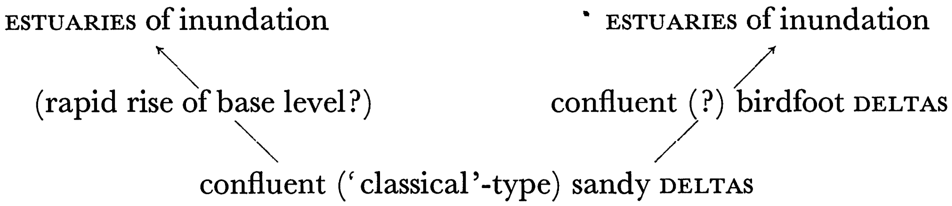
Some while later the sands of the minor cyclothem spread across the lacustrine muds, preceded and accompanied by local erosion. Erosion was most vigorous in the south-east Weald where channelling and lensing (resulting in local removal of the soil and shell beds) are proved and the sands thickest. At one stage it was thought that the Hog Hill Sands might represent barrier islands retreating across the subsiding Ashdown delta (cf. Gulf Coast barrier islands: Shepard & Moore 1955, 1956; Shepard 1956*b*; Fisk 1955, 1956). But now it seems practically certain that they were simply a further ('classical' type?) delta building out again from the London–North Sea Platform uplands; and again, in view of their thinness and small-scale cross-bedding, they evidently entered shallow water. Such a contention is supported by the cyclothemic succession, which repeats all the chief features of the main encompassing Ashdown–Wadhurst cycle. The major cause could then have been a temporary halt in the rise of base level, or a recession. Some of the sand undoubtedly came from the north-eastern river. The relatively thick development in the Stone–Iden–Winchelsea–Icklesham district appears to be a bar sand, formed at the mouth of a distributary and, like its Mississippi analogues, deeply entrenched (to at least 20 ft.) in its own delta-front and pro-delta deposits.

Soon, however, the long-term rise reasserted itself, and the transgressing lake waters strewed the pebbly Telham Bone Bed across the drowned lower reaches of the north-eastern river, gathering up as they went pieces of Wadhurst ironstone excavated during the previous phase. To a large extent the exotic pebbles remained in the south, opposite the partially obliterated channel from which they had been liberated: possibly the transgression advanced more rapidly after that. Horsetails established themselves behind the retreating coast as before, and the episode closed beneath the deepening waters of the lake, as in the preceding megacyclothem (figure 21 *D*).

It must be remembered, however, that in the present state of knowledge, the Hog Hill Sands might all represent narrow distributary and bar deposits, winding their ways through the otherwise argillaceous sediments of a *birdfoot* delta. This could have been initiated by sudden (local?) deepening of the waters near the main north-eastern pass, possibly associated with the rising base level. The sands in the south-east Weald would as before have been deposits of the north-eastern river, the surrounding clays pro-delta sediments, and the overlying passage beds (with their soils) transgressive delta-front deposits.

Any distinction between a 'classical' and a birdfoot form must rest upon the presence or absence of thin sandy 'wings' (interdistributary bay deposits) and clay 'wedges' between the relatively thick sandy developments like that near Rye. Such evidence only future and more detailed mapping can supply. But, whichever explanation is correct, there must next have ensued a long period when the main mass of middle and upper Wadhurst clays was deposited. So far as is known these are without large sandy intercalations. Together with their very constant facies, this strongly suggests that they too are all pro-delta lake clays, rather than onshore mere deposits continuous with onshore soil beds below. They must be transgressive, either *with* the underlying soil beds and pebble bed or *across* them. The first possibility seems to be the correct one, from which it follows that they are probably part of a minor cycle closely similar to the encompassing Ashdown–Wadhurst megacyclothem. But whichever is true it is clear that deeper open water was established again, leaving no trace of near-delta facies, birdfoot or otherwise. By this stage the lake waters had undoubtedly drowned the lower reaches of the rivers on the London Platform, transforming them into estuaries.

To sum up: the main drift of palaeogeographical evolution in the area during Ashdown–Wadhurst times took place along one of the two routes outlined below:



At present the balance of evidence favours the first alternative.

(ii) *Lower Tunbridge Wells–Grinstead megacyclothem.* Eventually the lake level began to fall again, and sandy deltas spread once more across the Wadhurst muds, ushering in the second (Lower Tunbridge Wells–Grinstead) megacyclothem. Ashdown and Wadhurst history was then almost exactly repeated, bed by bed. Non-tidal conditions are indicated throughout by the type and rarity of scour marks on the shoreface (true swash and rill marks are not present) and by other evidence.

Beaches of sand and silt became established for several miles east and west of a main distributary pass running southwards from London. Drifted wood and rare pebbles mark the successive positions of the southward-advancing strand-line. This ran roughly east and west, at right angles to the axis of the distributary, as shown by the ripple strikes. Rhythmic lamination in the beach sands at the top of the formation suggests a climatic cycle (cf. pro-delta sediments of Mississippi: Scruton 1956, p. 37), but whether the minor laminae are annual accumulations or not is unclear. If they are annual, then the minimum rate of deposition averaged about 2 mm per year. Also near the main pass at about the same time were local mazes of large oscillation ripples or small sand bars and braided channels, lying beneath shallow water and possibly also developing rhythmic (actually 'festoon') bedding. Offshore, the sandy bottom, still richly strewn with plant debris, merged into a broad zone of silts, and beyond that lay pro-delta clays of Wadhurst facies. Hence, east and west of the major distributary pass the change to Lower Tunbridge Wells conditions took place by gradual passage, due to building of the delta southwards. The underwater shoreface slope was exceedingly flat, merging into an extensive delta-front and pro-delta platform, so that minor (obviously non-tidal) fluctuations of lake level laid bare extensive areas of foreshore, slumping is unknown, and the sands now appear to have had horizontal bedding. Almost everywhere, rapid silting and frequent erosion prevented plants colonizing the shallows, but at High Brooms and Pembury *E. lyelli* secured a foothold, establishing local reed beds at the outer margin of the silt zone analogous to the mid-Ashdown rootlet bed at Fairlight (p. 289).

On the surface of the delta grew plants larger than Lyell's horsetail, now represented only by the lower parts of their extensive root-systems, as at East Grinstead, Groombridge and Pembury.

In contrast, the Wadhurst–Tunbridge Wells boundary *along* the line of the north to south distributary is often very sharp. Foreset bar sands of southward-growing conelets are sometimes seen lying on an eroded floor of pro-delta Wadhurst Clay (cf. passes of Mississippi (Scruton 1956, p. 38), Ashdown and Hog Hill deltas (pp. 320, 327)). Minor distributaries are also known, usually trending roughly north to south (figure 6). Most instructive are those running south-east through Pembury. These little channels have apparently built out across their own mouth-bar deposits, and wander from side to side like any modern pass that is both extended and free (e.g. Mississippi: Scruton 1956, p. 30). No point-bar deposits have been identified, though they traverse suitable fine-grained alluvium (cf. top Ashdown channel, p. 290): initial cutting of the rivers was presumably through crevassing. This is recorded by their floors of pellet breccia, reminiscent of the clay pellets found at the bottom of some Mississippi channels today (Shepard 1956*a*, pp. 2602–3). While part of the surrounding alluvium may have been deposited during the early construction of the delta (in which case the whole section is properly assigned to the Lower Tunbridge Wells formation) it is more likely on general grounds that most or even all of the alluvium, and of course the channel-fill, accumulated during the subsequent Grinstead transgression. In that case, like the top Ashdown silts of the north Weald (p. 323), it probably represents levee silt which accumulated very much more quickly once the distant Grinstead inundation had begun to affect the frequency of flooding on the delta top. Probably the pebbly development in the top Lower Tunbridge Wells Sands at Founthill (Newick) marks the gravelly centre of the major distributary, at a place where it was not completely eroded during the transgression.

After a long life the Lower Tunbridge Wells delta too was buried beneath the waters of another lacustrine transgression. From then on the sequence of events almost exactly repeated Wadhurst history. The succession immediately becomes extremely homogeneous, thinnish horizons being extraordinarily widespread (as might indeed be expected in a deepening lake) and possibly also slightly unconformable to the underlying sands (Milner 1923, p. 286, figure 40). Study of the pebbles in the retreating beach gravel (figure 12; and 1954, text-figure 1), the orientation of its ripple marks, plant debris and cross-bedding, and the orientation of the flute casts in the delta-front passage beds suggest that the inundation came from the south (figure 6), passing across a succession of retreating east-to-west shorelines north of Haywards Heath. The beaches continued to be interrupted by the distributary pass in the longitude of West Hoathly; and, from the evidence cited above together with that concerning the rare scour marks surrounding the pebbles (p. 304), it is evident that they continued to shelve almost inappreciably southwards throughout. Superimposed on the generally rising lake level short-term recessions sometimes exposed the pebbly strand, the muddier parts of which became suncracked and its giant ripples washed by heavy rain. But since the passage beds are neither suncracked nor rain-affected, these fluctuations were never sufficient to expose the sediments further down-beach.

As the transgression worked its way up the large distributary, progressively erasing it, the liberated pebbles were spread well beyond the line of obliterated levees. Nevertheless, they remained biggest and most abundant on the site of the old channel—a feature still recognizable today. Repeated washing over the margins sometimes produced heavy-mineral concentrates: and these are known along some modern shores that are now retreating (e.g. Rao 1957). Plant and animal remains from the delta top, lake and water-courses, became finely comminuted and intimately intermingled. Exactly how much alluvium, dune and old shore sand was removed is doubtful. Beyond the flat and now wellnigh sandless shoreface (the arenaceous deficit being due to the same causes as in Wadhurst times) *E. lyelli* reedswamp became established and followed the receding coastline as before (figure 6: *inset*). As in Wadhurst times, too, the reeds were apparently scoured away locally at least once by renewed erosion along the estuary marking the drowned distributary. The only area that escaped (or recovered, if the disaster actually reached it) lay to the west of the estuary, near Balcombe. This was outside the main swathe of destruction—presumably cut by the temporarily swollen waters of the northern river. Beyond the horsetail beds *Neomiodon*, *Viviparus* and ostracods flourished and the bottom sediment was chiefly dark chemically reduced lake-clay. Balls of sandstone in the pro-delta clays near the base of the Grinstead succession (p. 306), while possibly associated with temporary renewal of erosion along the site of the old distributary channel, are strongly reminiscent of sandy lumps occurring in the analogous pro-delta clays of the Mississippi (Scruton 1956, pp. 42–47; Shepard 1956 *a*, pp. 2602–5; Greenman & LeBlanc 1956, pp. 815, 821 (figure 37); Moore & Scruton 1957).

No suggestion of a birdfoot facies of sedimentation is known in the Grinstead succession. On the contrary, there is some indication that during its recession the delta retained much the same ('classical'?) form. The main change seems to have been, as already suggested, greatly accelerated alluviation in the back area. Thus, if the Pembury section is interpreted aright, the silts and clays with pellet breccias above the conelet sands are topset alluvium deposited almost entirely *after* the lake transgression had begun far to the south.

The pellet bed at the base then represents the first serious flooding of the vegetated delta surface, when an earlier-formed veneer of alluvium, together with its backswamp soil and some underlying beach sands, was removed. The levee silts above then become analogous to those in the Ashdown back-area nearby (p. 323), and the pellet beds within them record repetitions of exceptionally severe floods. In this sense, the alluvial silts and clays have been rightly grouped by the Geological Survey (for purposes of mapping) with the Lower Tunbridge Wells strata, though they may actually be 'Grinstead' in age. Minor cyclothems like the Pembury one are obviously not strictly comparable with the megacyclothems, though due essentially to the same cause.

Unfortunately, it is not yet quite certain that the Grinstead transgression (evidenced by true Grinstead lake-clays) actually reached the Pembury area. Further west too, though the beach gravel extends as far as the most northerly outcrops, it has only been seen overstepping on to comparable back-delta deposits around Balcombe. But from analogy with the previous megacyclothem we may predict (figures 21 *D*, 22 *D*) that somewhere between East Grinstead and the London Platform the pebble bed will be found to occur sandwiched between silts as a thin parting sharply dividing a predominantly *fine-grained* alluvial succession.*

The Grinstead transgression finally ended with a third major fall in lake level. Arrival of an Upper Tunbridge Wells delta is signified by the thick passage lithology of the top Grinstead Clay (figure 13), supporting at least one patch of reeds offshore (Balcombe)—a succession closely similar to those at the top of the Wadhurst (High Brooms, Pembury) and Fairlight clays.

(iii) *Weald Clay*. In the above light the thick Weald Clay, which succeeds the Hastings Beds, must also represent a prolonged period during which much of southern England lay beneath the waters of the final lacustrine transgression, or transgressions. The gradual increase in brackishness then heralds the approach of the Barremian–Aptian Sea, and transformation of the lake into a gulf ringed by estuaries, with the consequences of hypopycnal inflow. Expressed in thickness of strata the change was slow, and it is not impossible that some of the well-known sandy courses represent birdfoot deltas. Certainly by the time of the Clock House cyclothems the supply of arenaceous sediment had become extremely limited, even in the northern Weald, and pebbles were very nearly unavailable. The transition back to clay was consequently abrupt, the horsetails in the lower cyclothem sending their rhizomes across recently buried current-rippled and suncracked surfaces of sand. Perhaps they now grew closer inshore.

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* The Warlingham borehole, put down by the Geological Survey (in 1957) since the above was written, is to some extent confirmatory. Though only 10 miles closer to the London Platform, the Hastings succession there proved to be much finer grained that at outcrop, with more silt and more rootlet beds; coarse sand was virtually absent. Two pellet conglomerates have been located in the cores; also one bone bed, and at least two *E. lyelli* soil beds (possibly equivalent to the Brede and High Brooms horizons). If the identities of the soil beds can be established their diachroneity may eventually prove recognizable through Hughes's detailed palynological work (1958 (preliminary report)) or F. W. Anderson's on the ostracods (in preparation). According to Interpretation 3 they would of course 'young' *northwards* (opposite to the arenaceous beds below), whereas the other explanations predict their 'younging' *southwards* (like the underlying sands). Access to the Warlingham cores and permission to publish this footnote were kindly granted by the Director, Geological Survey.

Sedimentary structures corresponding with Moore & Scruton's 'irregular layers' and mottled structures (1957) are commoner in the Weald Clay than in the Hastings Beds. This may be attributed to a more abundant bottom fauna consequent upon the increased salinity. As in the Wadhurst and Grinstead lake-clay formations, the sediments become remarkably homogeneous over wide areas, even their thinnest horizons.

(iv) *Summary*. The larger Wealden cyclothems represent alternations of classical-deltaic and estuarine phases in a non-marine basin of slow general subsidence. Figure 21 *A* to *D* summarizes the present Interpretation 3 *a* assuming, as seems most likely, that the bulk of the back-delta alluvium was deposited *during the transgressions*. The analogous sequence of events (Interpretation 3 *b*), assuming the alluvium to have been formed *during the growth southwards of the deltas*, is shown in figure 22 *A* to *D*.

The maximum thickness of sediment was deposited well to the south of the London Platform, coinciding roughly with the present major axis of uplift. Overlap and overstep around the margin of the platform (Oxford district, Bas-Boulonnais, etc.), may therefore have resulted from concurrent isostatic adjustment (cf. uplift and Recent–Pleistocene unconformity north of the present Mississippi delta plain (Fisk & McFarlan 1955)).

Again, like the Mississippi, Rhône and Nile accumulations, the beds form a great lens or 'ladle' thinning to the north and south, becoming finer grained in both directions (figures 21, 22). Northwards the succession is more alluvial, southwards more lacustrine. If Interpretation 3 is correct, the individual deltaic sands should prove to be lenticular also, probably separated from the lacustrine clays by slight unconformities (figures 21, 22), as, indeed the Lower Tunbridge Wells Sands seem to be (Milner 1923, p. 286). Overstep would be towards the north, and this is supported by the increasing depth in that direction of the highest suncrack bed in the top sands (figure 10). The work of Reeves (1949, especially figures 27, 31 and 33) and the few borings sunk beyond the region of outcrop (e.g. Warlingham in the north, Henfield and Portsdown (Lees & Cox 1937; Taitt & Kent 1958*) in the south) are to some extent confirmatory. After the beds disappear underground the sandy formations rapidly become subordinate, and there is a mounting predominance of silt and clay.

The repeated changes from deltaic to estuarine conditions and back again were due to major fluctuations of lake level, either absolute or relative, superimposed upon the general subsidence. If relative, they may have been caused by major fluctuations in the speed of subsidence itself; or, assuming the subsidence to have been steady, simply by repeated diversions (through over-lengthening, plugging, etc.) of the main river channels. As in the Recent Mississippi (Russell 1940, 1948; Fisk & McFarlan 1955; Fisk 1956), the last process would have periodically shifted the main foci of deposition, leaving a trail of abandoned deltas to subside beneath the waters of landward-moving transgressions which involved no absolute changes of sea level. Apparently weighing against this is the suggestion (1954) that the main 'heads of passes' of at least two successive Hastings deltas

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* Dr F. W. Anderson's revised correlation of the Henfield succession (based on ostracods) is given in this publication (pp. 11–13). None of the reliable marker-bands (soil beds, bone beds, pebble beds, etc.) known at outcrop in the Hastings Beds are reported, and the '*Cyrenae*' and plant spores do not appear to have been identified or utilized. Consequently, and especially in view of the inevitable diachroneity of the Hastings Beds, the new correlation must still be considered tentative.

(Ashdown and Lower Tunbridge Wells) lay in about the same position (West Wickham); but a close parallel already exists in the recent Mississippi delta, where the Teche–Mississippi and Lafourche–Mississippi both developed major heads near Houma.

Obviously the problem cannot be solved from the Weald alone, and it is necessary to look further afield.

III. Wessex basin

To a large extent, the Wessex basin (figure 1) was separated from the main basin of the Weald by the stable Portsdown swell (figure 24; see also, Lees & Cox 1937; Taitt & Kent 1958). Apart from derived Kimeridge materials in the Isle of Wight (Casey *in* 1955*a*, p. 274), its kaolin-felspar-tourmaline-rich detritus (locally accompanied by much biotite, topaz, andalusite, cassiterite and sillimanite) came almost entirely from the Cornubian Highlands in the west. This distinctive material never mixed with that in the Weald, except perhaps during Weald Clay times (p. 313: also Groves 1931, p. 70; Hayward *in* Groves 1931, p. 96; 1948). The interesting facies developed do not, so far as is known, throw any light on the present problem. Cyclothems like those in the Weald are not developed.

IV. Bas-Boulonnais and Mons basins

Similarly, the formations of Wealden facies in the Bas-Boulonnais and Mons basins (figure 1) do not assist in solving the problems of the English lacustrine transgressions. Both successions are made up of detritus derived from an easterly extension of the same massif as that which bordered the Weald basin, and some of the Belgian sands are undoubtedly deltaic. But cyclothems of the Sussex type are so far unknown, and it seems that the changes of lake level in England did not affect either of these basins. They were therefore hydrologically isolated from the Weald in some way, or else separated from it in time.

Both possibilities remain. First, correlation with the standard succession in the Weald is still quite uncertain (1955*a*). Secondly, the Artois (Paris Plage) axis (an extension of the Portsdown swell (figure 24)?) at times probably sealed off the Bas-Boulonnais from the main Paris basin to the south, and a similar 'lip' may have bounded the southern margin of the Mons basin.

The rather special flora of the Belgian Wealden facies and the belatedness of the marine (Albian) inundation, also suggest an environment geographically isolated in some way. This environment has been tentatively interpreted as an upland basin set among the forested Brabant foothills (1955*a*, p. 278). The petrology of the Belgian 'Wealden' also has a parochial air. Detritus derived from pre-Mesozoic sediments to the north dominates all the size fractions. Thus in the conglomeratic seams at Thieu (Chateau St Pierre) there are pebbles of Upper Carboniferous sandstone, Viséan chert (with *Earlandia*, *Plectogyra*, *Globivalvulina*, *Palaeotextularia*, *Calcisphaera*, *Stacheoides*, etc.—kindly identified by Dr R. H. Cummings) identical petrographically with that exposed at Dinant, probable Devonian and Lower Palaeozoic sandstones, quartzites and greywackes (see also Marlière 1933, p. 177 and 1934, p. 21), and cataclasites of uncertain origin. The sands, composed chiefly of quartz, chert, clay, glauconite, zircon, black iron ores, tourmaline and titania-minerals (see also, Tavernier 1947, p. 74), similarly have a marked 'second cycle' air. As a whole they are strikingly different from the nearest Wealden, bearing few petrographical resemblances either to that over the northern watershed in Holland and Germany, or to that in the Bas-Boulonnais farther west along the flank of the same massif.

V. Pays de Bray

(a) *General*

One of the most intriguing petrological features of the Sussex cyclothems is the occurrence of small but appreciable quantities of high-grade metamorphic detritus along the southern fringes of the pebble beds and their underlying sands (1947*b*, 1948, 1949*a*, 1953, and above). On general grounds this precocious 'Lower Greensand' mineralogy is most likely to have come from 'Armorica', suggesting that the Norman Wealden should be dominated by it and that the French and English basins may have been connected at times. One is reminded of the marginal deposits surrounding the Mississippi delta, derived from the Appalachian metamorhics and elsewhere (Scruton 1956; Shepard 1956*a*).

Obviously if connexion could be proved, then the Sussex cyclothems might be linked with events in the Paris basin, and their causes discovered. The hypothesis must stand or fall on the petrography of the French deposits, which will now be examined in this light.

(b) *Sedimentology of Wealden*

(1) *Succession*

The lower (pre-Hauterivian, =Hastings?) deposits of the Pays de Bray (figure 1) are about 200 ft. thick and chiefly non-calcareous sands (1955*a*), with important thicknesses of kaolinitic clay (Millot 1953, p. 75), including fireclay. At some horizons thin seams and lenses of pebbles (mostly less than ½ in. long) occur (e.g. Savignies, Gournay, Neufchâtel). Occasionally ill-sorted pebbly beds of fluviatile aspect are developed, several yards thick, strongly false-bedded and with a peculiar white kaolinitic matrix (e.g. Mt Benard, south-west of Savignies). The lithology changes rapidly from place to place, but there is no suggestion of cyclic sedimentation comparable to that in the Weald. Lignite and plant remains occur frequently throughout the formation. Other fossils are rare. Those so far recorded belong apparently to the common vertebrate and molluscan genera of the Weald. Rootlet beds have not been found.

Above, the sands associated with the Hauterivian marine intercalation are coarse, well sorted and often extensively false-bedded. Large ironstone nodules recalling those at the base of Wadhurst Clay are frequently developed. Grains of mica (muscovite, biotite, chlorite, hydrobiotite) up to 4 mm are not unusual. From their sorting the sediments seem to be beach sands.

The Upper Wealden (0 ft. (in north) to 80 ft.), lying above the clayey marine intercalation, consists chiefly of variegated speckled silts and plastic clays ('argiles bariolées' and 'argiles panachées'). Subordinate sandstones come in locally. Fossils are rare or absent.

Samples for petrological comparison with Sussex were collected from the Lower Wealden at the following localities: Blacourt, Neufchâtel, Forges-les-Eaux, Serqueux, Le Fosse (Forêt de Bray), Saumont-la-Poterie, Gournay, La Chappelle-aux-Pots, Savignies.

(2) *Petrology*

The pebbles (from Savignies, Gournay and Neufchâtel) and light grains are dominated by quartz and metamorphic quartzose rock-fragments. Chert is virtually absent and felspar (orthoclase and oligoclase) was observed only near Saumont-la-Poterie. A little glauconite occurs in most places, and calcareous ooliths at Blacourt. The light assemblage is thus very similar to the 'south-western' detritus of the Weald (1949 *a*).

The identity is virtually clinched by the heavy fractions (table 4). Everywhere throughout the Pays de Bray they are extremely bulky, forming up to 1 % by weight of the whole detritus. This is more than ten times the average for the sands of the Weald and suggests closer proximity to a crystalline source. They are also entirely dominated, apart from micas and the normal 'ubiquitous' species, by the 'characteristic' minerals of the south-western inflow in Sussex. From table 4 it is seen that staurolite, kyanite, sillimanite and monazite attain many times their combined abundance in the Weald (cf. with table 1 (p. 308) above, table II (pp. 312–313) in 1949 *a* and table 1 (p. 236) in 1948). Yet nearly the same *relative* proportions of high-grade metamorphics are maintained. Staurolite is everywhere the commonest, averaging about 7·9 times the combined amount of kyanite and sillimanite, compared with 9·7 and 6·9 (mean = 8·3) respectively in the pebble beds of the two Sussex megacyclothems. Quite as striking is the virtual absence of the London–North Sea Platform minerals: glauconite, garnet and apatite.

TABLE 4

mineral	mean % in Pays de Bray	% in Top Ashdown Pebble Bed at Woodlands Corner, Bodle Street, Sussex (S. Weald)
'ubiquitous' species		
black iron ores and leucoxene	45·0	43·5
zircon	18·6	16·2
rutile	5·0	9·8
tourmaline	13·4	19·7
anatase	6·6	3·0
brookite	0·19	<0·1
'characteristic' species		
garnet	0·12	0·34
staurolite	6·7	6·7
kyanite	0·76	0·11
sillimanite	0·10	<0·1
andalusite	1·6	0·0
monazite	0·50	<0·1
ceylonite	0·01	<0·1
muscovite	not counted	not counted
biotite	not counted	not counted
chlorite	not counted	not counted
unknown (including ? corundum)	1·6	0·69

Pays de Bray: mean zircon size index, 53·9 μ; mean zircon shape index, 10·7 %; number of samples, 15; average number of grains per heavy subsample, 1679.

Affinity between local details in the two areas is just as remarkable. Some samples from the Pays de Bray are hardly distinguishable mineralogically from those obtained in Sussex along the south-western margin of the Top Ashdown Pebble Bed. The pairs of comparisons in table 5 illustrate this. These figures are not adjusted for differences due to authigenic minerals (notably anatase). Similar comparisons have also been obtained from the underlying Ashdown beach sands and from the Top Lower Tunbridge Wells Pebble Bed. The differences between pairs of analyses are less than those expected from the 'patch' and 'locality' variances (1949*a*). There thus appear to be spreads of unadulterated Pays de Bray-type sediment at three horizons in the southern part of the Weald. Consequently, it is not surprising also to find that, locally, the pebble beds sometimes show compositions closely approaching the *average* for the Pays de Bray. This happens, in the Top Ashdown Pebble Bed, at Bodle Street (Sussex). The analysis from this locality is set out in the final column of table 4.

Table 5

	mean %					
	I		II		III	
mineral	Saumont-la-Poterie, Pays de Bray	Windmill Hill, Sussex	Blacourt, Pays de Bray	Horam, Sussex	Savignies, Pays de Bray	Sandhill, Dallington, Sussex
'ubiquitous' species						
black iron ores and leucoxene	46·6	46·5	56·4	56·6	39·0	44·5
zircon	19·4	20·6	13·1	17·8	23·7	21·9
rutile	5·1	5·5	4·5	10·4	8·3	7·9
tourmaline	14·9	18·9	10·4	11·8	12·0	17·1
anatase	8·8	3·4	12·3	1·0	10·3	4·5
brookite	0·4	0·07	0·04	0·10	0·56	0·15
'characteristic' species						
garnet	0·00	0·00	0·04	0·40	0·00	0·09
staurolite	2·2	2·3	1·3	1·3	2·3	3·1
kyanite	0·36	0·95	0·11	0·20	0·79	0·13
sillimanite	0·07	0·51	0·00	0·10	0·11	0·11
andalusite	0·29	0·00	0·00	0·00	0·11	0·00
monazite	0·50	0·01	0·07	0·01	0·34	0·00
unknown	1·4	1·2	1·8	0·20	2·6	0·5
number of grains counted	1390	1367	2674	989	887	4686

Table 6

			regression equations of	
detrital mineral	r	significance of r	% (F) on size (S)	size on %
staurolite	+0·934	$P_t<0{\cdot}01$	$F=0{\cdot}36S-12{\cdot}7$	$S=2{\cdot}42F+37{\cdot}7$
kyanite	+0·875	$P_t<0{\cdot}01$	$F=0{\cdot}030S-0{\cdot}86$	$S=25{\cdot}5F+34{\cdot}5$
sillimanite	+0·622	$P_t<0{\cdot}05$	$F=0{\cdot}0048S-0{\cdot}165$	$S=79{\cdot}6F+46{\cdot}2$

The petrological kinship between Weald and Pays de Bray goes deeper: staurolite, kyanite and sillimanite increase in quantity with increasing coarseness (zircon size index) in both areas. All three associations in the Pays de Bray are close, significant and linear, as shown in figure 23*A* to *C*. This is summarized in table 6. The accord between the two areas is also illustrated for staurolite and sillimanite in figure 23*A* and *C* by insertion of the regression lines from the Sussex megacyclothems.*

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* Mr R. G. C. Bathhurst's observation (*in litt.*) that in the Dorset (Wessex) Wealden staurolite and kyanite are sometimes commonest in the finer sediments further emphasizes this special relationship.

The high-grade minerals in Sussex and the Pays de Bray thus almost certainly came from the same area of coarse schists: Armorica. Further confirmation is being sought by comparing the physical and chemical properties of the staurolite grains with those of staurolite crystals in the Brittany schists. Optical comparison has proved fruitless, for they resemble normal staurolites from several other areas. Spectrographic analyses of the trace-elements, however, carried out in collaboration with Dr Th. Hügi, look more promising. Using concentrates of clean inclusion-free crystals, Dr Hügi has obtained the semiquantitative results shown in table 7. Despite the severe handicap of gross insufficiencies of Wealden material (2 to 3 mg samples of staurolite), he has proved the practicability of the method and shown that the Pays de Bray staurolites have at least three trace-elements (Cr, Ni, Cu) in common with those of the Brittany schists.

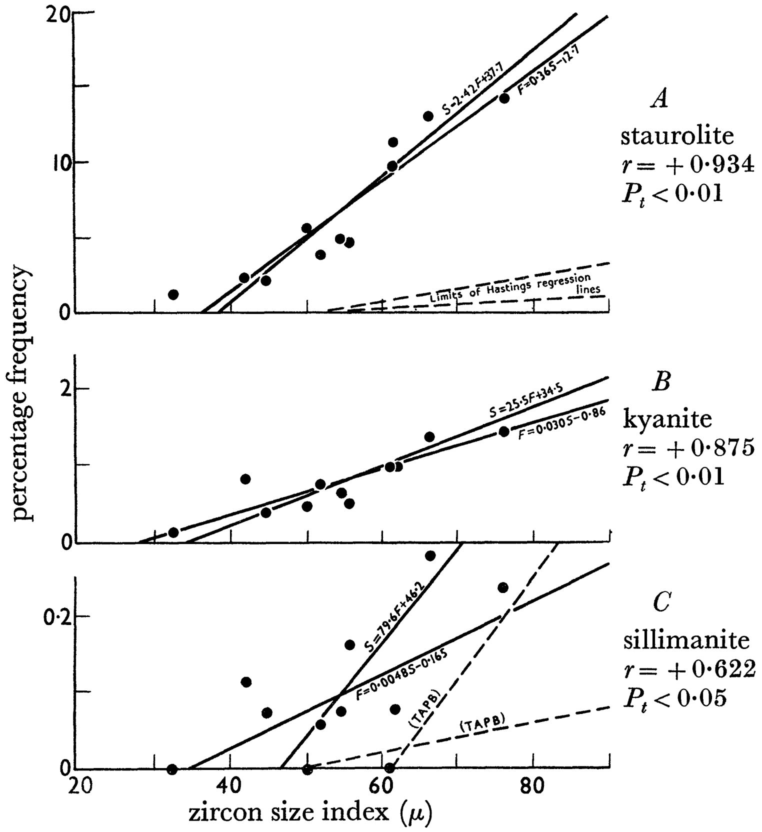

FIGURE 23*A* to *C*. Lower Wealden, Pays de Bray, France. Scatter diagrams and regression lines showing the relationship between the coarseness of the sediment (measured as the zircon size index (*S*)) and the percentage frequency (*F*) of staurolite (*A*), kyanite (*B*), sillimanite (*C*). In the cases of staurolite and sillimanite the positions of corresponding regression lines from the Hastings Beds (Top Ashdown Pebble Bed (TAPB), top Ashdown sandstone, Top Lower Tunbridge Wells Pebble Bed) of the English Weald are indicated for comparison.

Since the Pays de Bray is nearer to Brittany than the Weald, it is not surprising to find certain less stable metamorphic minerals appearing in appreciable amounts. The most striking is andalusite, which usually outnumbers both kyanite and sillimanite in the coarser sands. The grains are mostly clear of inclusions (mean % without inclusions $=67\cdot4$), though some are densely crowded (mean % with abundant inclusions $=13\cdot5$). The frequency of the mineral is closely controlled by particle size. As in staurolite, kyanite and sillimanite, the relationship is close ($r = +0{\cdot}898$), significant ($P_t < 0{\cdot}01$) and linear ($F = 0{\cdot}129S - 5{\cdot}36$; $S = 6{\cdot}20F + 44{\cdot}0$). The grains evidently originated in the same general area.

Equally, the absence of garnet and apatite throughout the Pays de Bray is very striking. Apatite was not observed, and almandite only at Serqueux (0·15 %), Savignies (0·11 %) and Blacourt (0·04 and 0·09 %: just below the marine Hauterivian clays). Strangely enough andradite, where it occurred, was commoner (Serqueux, 1·02 %). Evidently the Pays de Bray was *entirely* under the aegis of the Armorican highlands, and the 'characteristic' minerals of the London–North Sea uplands never reached it. This is confirmed again by the 'ubiquitous' minerals, for the percentages of euhedra among the black iron ores (mean = 0·47 %), zircon (mean = 10·7 %) and tourmaline (mean = 1·26 %), and of total tourmaline, are higher than at any known horizon in the Weald. The increase in tourmaline stresses the affinity of Armorica with the nearby or contiguous Devon–Cornwall (Cornubian) uplands to the north-west. These sent great numbers of tourmaline grains into the Dorset (Wessex) Wealden, many being aggregates of small crystals. Correspondingly, the average proportion of aggregate grains in the Pays de Bray (1·26 %) is considerably higher than anywhere in the Weald below the Horsham Stone cyclothem, though lower than in Dorset. Often the tourmalines are large, reaching 1 mm at Savignies.

TABLE 7

	staurolite-schist			Wealden (?Hauterivian) sand		
element	Chapel du Mur, Morlaix, Brittany 18639*	Forges-neuves-en-Plorigneau, Brittany 50698*	50698†	½ km S.S.E. of Serqueux, Pays de Bray	Neufchâtel, Pays de Bray	3 km W.N.W. of Gournay, Pays de Bray
Cr^{+3}	200‡	140	20	10	< 10	< 10
V^{+3}	400	300	22	—	—	< 10
Li^{+1}	400	400	n.d.§	n.d.	n.d.	n.d.
Ni^{+2}	250	125	20	< 5	< 5	< 5
Co^{+2}	140	80	10	—	—	—
Cu^{+2}	50	10	10	< 10	< 10	10
Zr^{+4}	125	125	40	—	—	—
Sr^{+2}	—	—	—	n.d.	n.d.	n.d.
Ba^{+2}	60	40	n.d.	n.d.	n.d.	n.d.

Al, Si, Fe, Mg, Ca, Ti, Mn, Na, K: = major elements (~1 % or more).
Be, Cs, La, Mo, Pb, Rb, Sc, Sr, Sn: absent, or present in amounts < sensitivity.

* Cambridge University Museum of Petrology catalogue number.
† treated with benzene and methylene iodide.
‡ all amounts given in parts per million. Error 30–50 %.
§ n.d. = not determined.

Compared with these sands, the overlying clays of the Hauterivian marine band are multi-source sediments, showing striking new detrital elements. Appreciable quantities of sphene and hornblende appear near Blacourt, possibly derived from the Massif Central. They suggest, like their fossils (1955*a*, p. 277), that the transgression came from the south or south-east.

The Upper ('Barremian') Wealden has not been intensively investigated. So far, it appears to differ petrographically from the Lower Wealden only in the appearance of small quantities (0·15 %) of hornblende (X = yellowish < Z = dark green, $Z \wedge c = 15°$).

(*c*) *Significance of petrology*

Thus the sands of the Pays de Bray (1) consist almost entirely of detritus from high grade metamorphic rocks, and lack completely the London–North Sea Platform detritus of the central and northern Weald; (2) show closely similar relative proportions of the high grade minerals found in the southern Weald, though the absolute content is higher; (3) are locally identical in mineralogical composition with the strand-line pebble beds and shore-face sands of the Sussex megacyclothems; (4) are probably partly fluviatile and partly beach sands. Clearly, therefore, during times of lake transgression some of the Armorican detritus discharging into the Paris basin actually found its way into Sussex, by-passing Wessex en route. Hence, the Weald and Paris basins must have been directly connected at these periods* (figure 24).

The marine clays yield a fauna and some detrital minerals apparently derived from the south or south-east. It is appropriate therefore to continue across France in searching for the ultimate causes of the cyclothems.

VI. PARIS BORINGS

(*a*) *General*

Forty-odd miles south of the Pays de Bray, deep borings have penetrated Wealden at Ivry (Richard Frères brewery) and Pantin. Stratigraphical and palaeontological details have been published by Lemoine, Humery & Soyer (1939), and the cores are under the care of M. Soyer in the Musée Nationale, Paris.

(*b*) *Sedimentology of Wealden*

(1) *Succession*

Broadly, the succession is like that of the Pays de Bray, and again there is no suggestion of cyclic deposition comparable to that in the Weald. Unfossiliferous variegated and speckled clays occur at the top, and sandy beds with plants and occasional pebbles at the bottom, with a possible marine band in between. Certain grey silts in the Pantin boring, labelled 'argiles avec tubulares' but with no recorded depth, contain badly preserved casts of what may be stems, rhizomes and roots of *Equisetites lyelli* 'growing' *in situ*. (Reading Univ. Geol. Dept. Mus. No. S3907). There is also some evidence that the non-marine beds in these bores may be thinner than those of the Pays de Bray, and the possible marine band correspondingly thicker.

(2) *Petrology*

The pebbly and sandy beds in the Lower Wealden at Ivry and Pantin are dominated by quartz, as in the Pays de Bray. Glauconite and a little orthoclase ($-2V \sim 15^\circ$) also occur at most horizons.

The heavy fractions are bulky and, apart from the 'ubiquitous' minerals, dominated again by the staurolite group (table 8).

Whether the frequencies of the 'ubiquitous' minerals are still controlled by particle size,

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* Long subsequently, when the Aptian Sea widened and permanently established the connexion, great quantities of similar Armorican sand were washed into southern England, accounting for the distinctive Lower Greensand suite of detrital minerals (see also Wood 1957).

and in the same way as before, is indeterminable owing to the small number of analyses. Since the lowest percentage of staurolite (1·12 %, between 738·09 and 740·21 m depth at Ivry) is associated with the highest zircon size index (79 μ), and the highest percentage (10·7 %, between 847·9 and 849 m depth at Pantin) with the lowest index (54 μ), a change in the source area may be indicated. This is also suggested by certain other minerals. Tourmaline (though not its mean proportion of aggregates, now 5·3 %) has declined, andalusite has virtually disappeared, and almandite garnet reappeared *without apatite* (Ivry, 738·09 to 740·21 m depth, 1·0 %). Biotite, still abundant, shows pleochroic haloes for the first time (Ivry, between 700·73 and 744·2 m). Muscovite and chlorite are common at most horizons, the last mineral showing a wide range of composition.

TABLE 8. PARIS BORINGS (IVRY AND PANTIN)

mineral	mean % in Paris borings	mineral	mean % in Paris borings
'ubiquitous' species		'characteristic' species	
black iron ores + leucoxene	63·3	garnet (almandite)	0·25
zircon	11·7	staurolite	6·2
rutile	1·8	kyanite	0·37
tourmaline	9·7	sillimanite	0·22
anatase	3·7	? andalusite	< 0·01
brookite	0·02	monazite	0·03
		muscovite }	not counted
		biotite }	not counted
		chlorite }	not counted
		unknown	2·7

Mean zircon size index, 64·7 μ; mean zircon shape index, 10·0 %; number of samples, 6; average number of grains per heavy subsample, 812.

(c) *Significance of petrology*

Deposition of Wealden detritus was evidently continuous between the Pays de Bray and Paris. New sources are indicated, almanditiferous rocks playing a greater, and andalusite- and tourmaline-bearing rocks a smaller, role than further north (figure 24). We are here passing beyond the dominance of the Cornubian-Armorican type of Hercynian terrain. But whether the new source areas were part of southern Armorica or the Massif Central cannot yet be decided.

VII. SOUTH-EAST OF PARIS BASIN

Further south-east, the outcrops between Cher and Meuse reveal, in addition to marine Hauterivian beds, signs of an earlier and more local transgression (1955*a*). This has been assigned to the Valanginian. The deposits appear to represent narrow marine fingers penetrating the Vosges–Morvan gateway (figure 24). In places they pass laterally into sands of dune facies (Debrenne 1955). The Hauterivian is more fully developed than in the Pays de Bray and Paris, and is also more fully marine. Beyond, in the Jura, the transgression seems to be echoed as a temporary change to deeper water marls.

VIII. ULTIMATE CAUSES OF THE WEALDEN CYCLOTHEMS

The outstanding feature of the Wealden in the Paris basin is thus the evidence it provides of two major marine transgressions. These clearly came from the south, through the Vosges–Morvan straits, bringing in a Jura fauna and sweeping along detritals of Massif

Central aspect (figure 24). The first transgression did not reach Paris, the second went further, nearly reaching the Channel coast.

Such forward surges of the Neocomian sea may of course have been eustatic or due to subsidence. But, whatever their cause, it is reasonable to suppose that the water levels in the Sussex morass were deeply affected. Is this the key to the cyclothems? If so, the possibility of long range correlation independent of fossils arises. In the present state of knowledge a likely correlation is that given in table 9. This is essentially similar to that already put forward on other grounds (1955*a*, *b*) and differs slightly from that of Hughes (1958) based on plant spores.

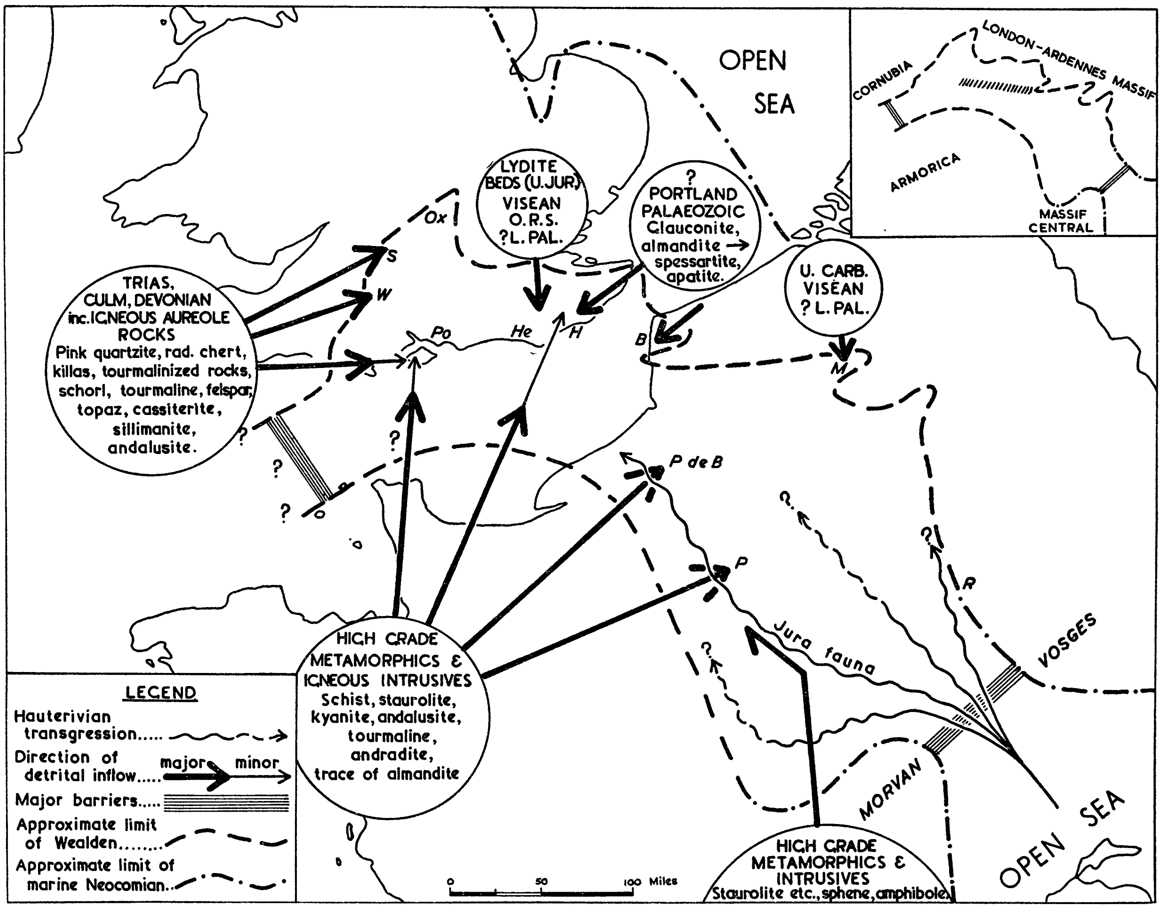

FIGURE 24. Sources and movements of detritus during Lower Wealden times, suggesting hydrological continuity between the English and Paris basins. *B* = Boulogne, *H* = Hastings, *He* = Henfield bore, *M* = Mons, *Ox* = Oxford, *P* = Paris, *P de B* = Pays de Bray, *Po* = Portsdown, *R* = Revigny, *S* = Swindon, *W* = Vale of Wardour.

Inset: postulated barriers (tectonic?), thought to have been periodically breached by the Neocomian sea, and the Portsdown—Paris Plage swell (hachures).

The present re-interpretation (3) of the megacyclothems is thus broadly consistent with events in the Paris basin. Following the Berriasian regression, the Neocomian sea returned on at least three occasions: in the Valanginian, Hauterivian, and Upper Barremian to Lower Aptian. The transgressions increased in importance in that order, temporary withdrawals separating the second and third, and probably also the first and second.

The Valanginian and Hauterivian movements together seem to have comprised not less than three separate surges through the Vosges–Morvan straits (Stchépinsky 1955; Debrenne 1955). Like the final transgression, they may have affected salinities in the Sussex area; but it is not known yet if any of the clays of the pre-Horsham Stone cyclothems show signs of brackishness. Evidently there is every likelihood that the Neocomian transgressions and regressions played some role in forming the megacyclothems, whatever the attractions of a simple theory based only on channel cut-off and steady subsidence (p. 332). Indeed, the transgressions may have acted partly through actually causing channel abandonment, and the regressions partly through tending to 'fix' the main channels.

TABLE 9

mega-cyclothem (Weald)	formation (Weald)	trend of lake level (Weald)	Neocomian sea (Paris basin)
IV	middle & upper Weald Clay*	rising	Upper Barremian to Lower Aptian TRANSGRESSION
	Horsham Stone	falling	Barremian REGRESSION
? III	lower Weald Clay	rising	Hauterivian TRANSGRESSION
	Upper Tunbridge Wells Sand*	falling	Later Valanginian to early Hauterivian movements
II	Grinstead Clay	minor rise	
	Lower Tunbridge Wells Sand	falling	
I	Wadhurst Clay*	rising	Valanginian TRANSGRESSION
	Ashdown Beds	falling	Berriasian REGRESSION

* Including minor cyclothems.

Unfortunately, contemporary knowledge of the French Neocomian is insufficient to decide whether there were lesser movements across the Paris basin, accounting for the minor cyclothems. Some of the latter, such as those within the Upper Tunbridge Wells Sands, are likely to have been caused by more local factors, for example simple channel abandonment, slight uplift in the catchment areas, fluctuations of climate, minor alterations in the gain/loss water-balances of lakes and ponds on the subsiding delta surface, etc. Their interpretation is a matter of some complexity, and they are still under investigation. The situation may have been further complicated by early surges from down-Channel, for there is some evidence suggesting that an Aptian transgression eventually came this way (Arkell 1947, p. 169). But, had that been so, why do not the Wealden deposits of the Wessex basin show a rhythm similar to that in the Weald?

Grateful thanks are given to the Royal Society, the Leverhulme Trust, the Shell Petroleum Company Limited, Esso Research Limited, Cambridge University and the Research Board of Reading University for financial assistance. During my work in the laboratory and travels over the Wealden of Europe and America and the illuminating sediments of the Rhône, Var and Mississippi deltas, I have received the help of good friends and organisations from many different countries. These are too numerous to mention individually here, but I wish to take this opportunity of thanking them and of recording my sense of privilege to be working on a task that happy events like these show to transcend man-made frontiers.

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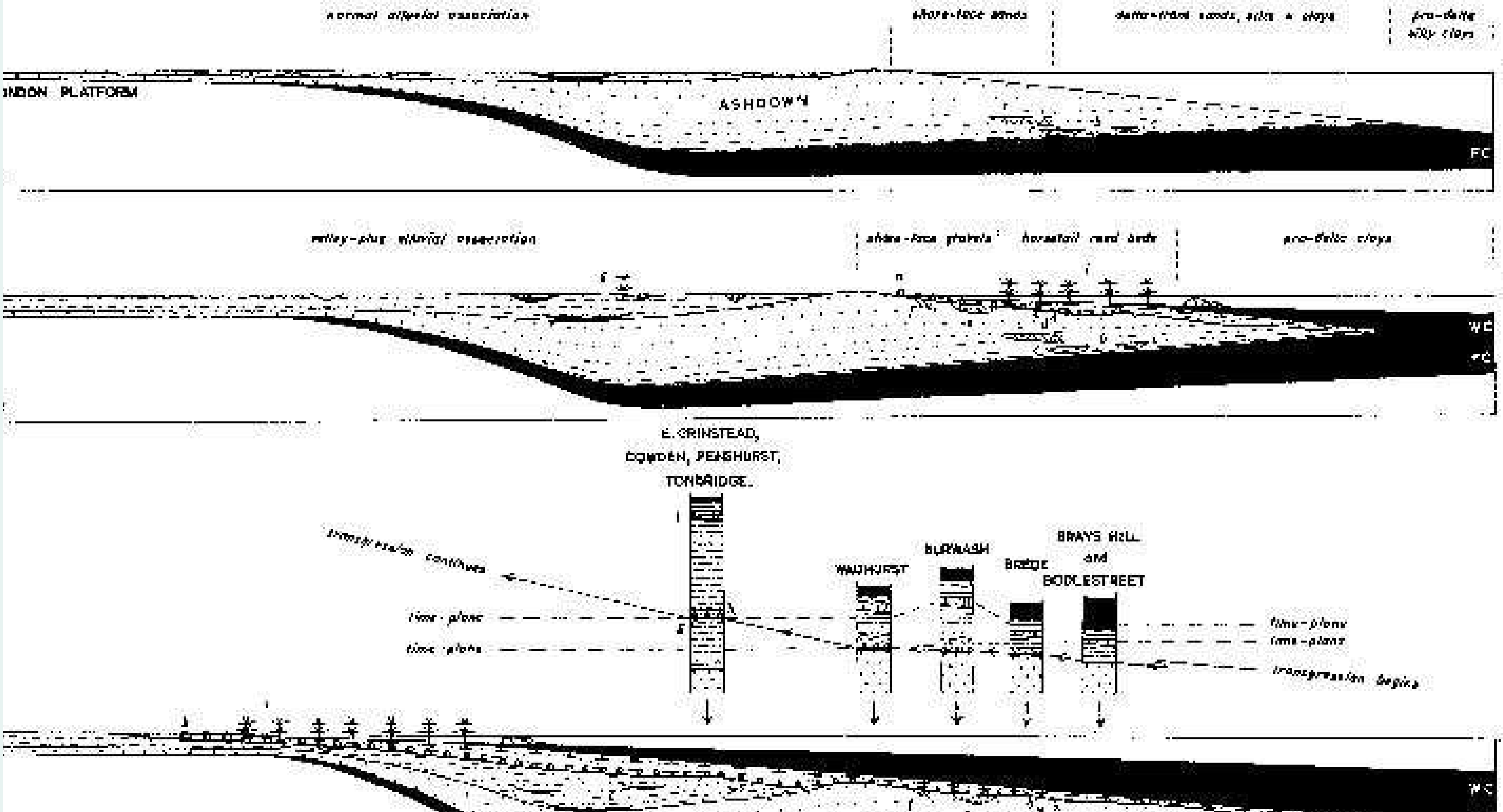

FIGURE 21 *A* to *D*. Hastings cyclothems: Interpretation 3a. Diagrammatic. Reconstruction assuming that the bulk of the onshore alluvium was deposited *during the lake-transgressions*. Only *aquatic* vegetation growing in the area is depicted. For legend see figure 19.

N.B. The northward overstep by the Top Ashdown Pebble Bed (– *k*, a retreating strand-gravel) from shoreface sand on to silty onshore alluvium may be observed between Wittersham and Reading Street, and along the northern flank of Ashdown Forest (figure 2 and p. 323).

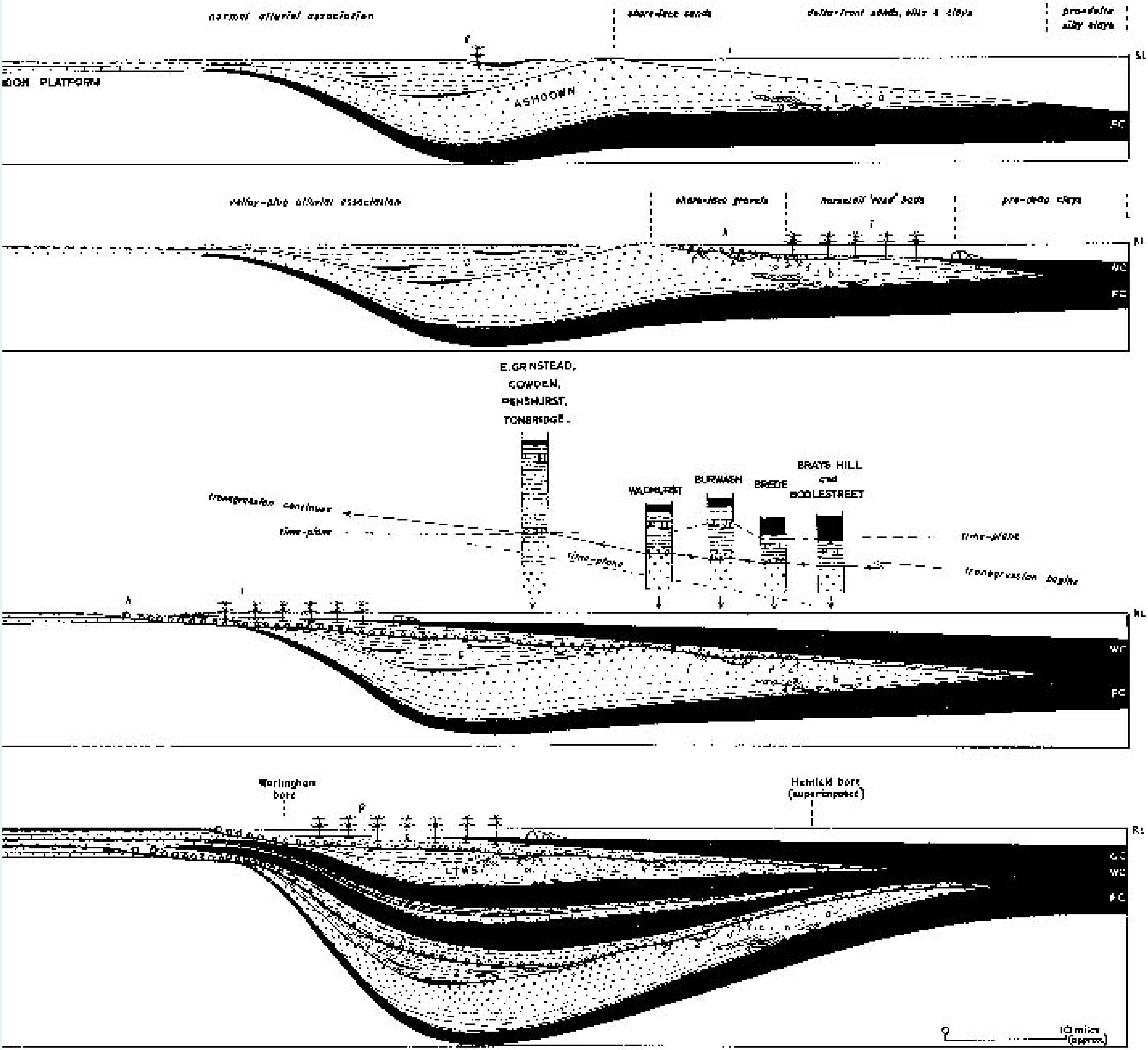

FIGURE 22 A to D. Hastings cyclothems: Interpretation 3b. Diagrammatic. Reconstruction assuming that the bulk of the onshore alluvium was deposited *during the growth southwards of the deltas*. Only *aquatic* vegetation growing in the area is depicted. For legend see figure 19.