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MARINE TRANSGRESSIONS AS A FACTOR IN THE FORMATION OF SANDWAVE COMPLEXES

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ABSTRACT

The genetic relation between the onset of a marine transgression and the consequent upbuilding of three ancient sandwave complexes is discussed and illustrated. These are:

a. The Lower Tertiary Roda sandwave complex of the southern Pyrenean basin.
b. The Lower Greensand sandwave complex of the Isle of Wight.
c. The Miocene sandwave complex of the Swiss Molasse.

Based on these examples, a model for the formation of a sandwave complex in relation to a marine transgression and tidal action is developed.

Finally, based on geological arguments derived from the sequential and structural analysis of these ancient sandwave complexes, the genesis of the modern sandwaves of the North Sea is related to the Holocene transgression.

INTRODUCTION AND PURPOSE OF INVESTIGATION

Sandwaves are giant ripples with heights up to an average of 10-15 m and with a wavelength of several hundreds of metres. Modern marine sandwaves are generally found on present-day continental shelves. Their internal structural organization is inferred to consist of giant crossbedding. In form they may be asymmetric or symmetric.

Ancient sandwave complexes consist of an association of several facies, the vertical and lateral sequence of which within a sandwave complex have a direct relation to the mode of formation of the sandwave. Thus a distinct sequential order of the several sandwave facies s.l. characterizes a true sandwave complex.

Many regional studies of the morphology and sedimentology of modern sandwaves on the present-day continental shelves exist (Van Veen, 1938; Stride & Cartwright, 1958; Jordan, 1962; Jones et al., 1965; Langeraar, 1966) and extensive studies have been made on modern sandwaves of the southern North Sea (Stride, 1963; Houbolt, 1968; Stride, 1970; Terwindt, 1971; McCave, 1971; Caston & Stride, 1973; Kirby & Oele, 1975).

Descriptions of ancient sandwave complexes, however, are scarce (Narayan, 1963, 1964 and 1971; Dike, 1972).

Studies of modern sandwaves (especially from the North Sea) have not resolved the question of sandwave genesis. Most authors agree, however, that present-day tidal currents cause migration of the sandwaves (Stride, 1963; Jones et al., 1965; McCave, 1971). McCave considers tidal currents as the main genetic factor. Further, as long as near-bottom current data are not available, as at present, the question as to whether sandwaves are migrating or not may not be answerable. Stride (1963) assumed that the migrational direction of sandwaves could be inferred from their asymmetry and therefore related this asymmetry to the direction of the strongest tidal currents. Terwindt (1971), however, assumed that the net movement of sandwaves is determined mainly by the difference between the total sediment transport during ebb and flood tide and does not believe in the existence of a relationship between the maximum current velocities and the net movement of sandwaves. Terwindt concluded, therefore, that the asymmetry of modern sandwaves is not a result of present-day hydraulic conditions.

The purpose of this paper is to show by geological rather than actualistic arguments, that sandwave complexes are commonly formed during marine transgressions. This is demonstrated by vertical and lateral sequential analysis of three fossil sandwave complexes (fig. 1):

a. The Roda sandwave complex in the Lower Tertiary basin of the southern Pyrenees, northern Spain.
b. The Lower Greensand sandwave complex of the Isle of Wight (data kindly provided by Dike).
c. The Miocene sandwave complex of the Swiss Molasse.

The timing of sea-level changes as related to the development of facies within the sandwave complexes is discussed and analysed. Finally, comparisons are drawn with occurrences of modern sandwaves in the southern North Sea and especially their genetic relationship to the Holocene transgression.

This paper is one result of a comparative research programme on modern and ancient sandwave complexes being carried out by members of the Sedimentology Group at the Universities of Leiden and Utrecht. Studies are being carried out in the Roda, North Sea, Bedford and Swiss Molasse sandwave complexes (fig. 1).

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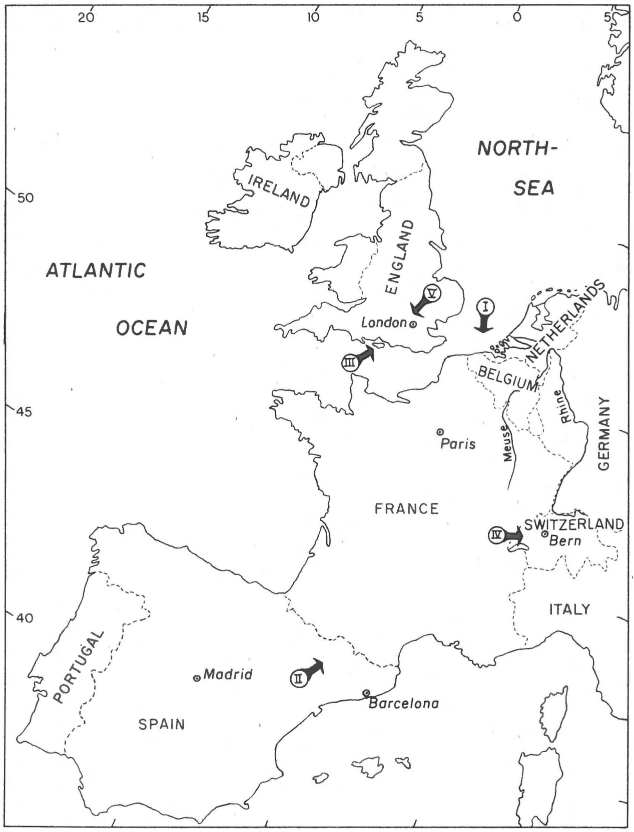


Fig. 1
Locality map for sandwave complexes discussed in the text.
I, North Sea sandwaves; II, Roda sandwave complex;
III, Lower Greensand sandwave complex of the Isle of Wight;
IV, Miocene sandwave complex of the Swiss Molasse;
V, Lower Greensand sandwave complex of Bedford.

THE LOWER TERTIARY RODA SANDWAVE COMPLEX OF THE SOUTHERN PYRENEAN BASIN

Geological setting

At the end of Cretaceous time several large basins formed south of the axial zone of the Pyrenees. One of these basins was the Tremp-Graus basin (fig. 2-A), where a two-tier sedimentary fill is recognized (fig. 2-B; Nijman & Nio, 1975):

1. A lower part of Danian to Ilerdian age consisting of thick neritic-lagoonal marls with intercalations of foraminiferal limestones and marine crossbedded sandstones; the Ager Group.
2. An upper part of Eocene age, which in general shows a regressive sequence; the deltaic complex of the Montañana Group and the fluviatile complex of the Campodarbe Group.

Synsedimentary tectonic movements had an important influence on the sedimentation pattern of this basin. At the transition from Ilerdian to Cuisian time, the Cotiella nappe moved south; its overthrust zone can be observed along the southwestern slope of the Cotiella Massif (Seguret, 1972; Soler and Garrido, 1970), and its front is supposed also to be represented by the Monsech overthrust (Garrido and Rios, 1972). Another major nappe movement took place at the end of the Eocene, and the Gavarnie nappe moved south. Here mainly Eocene sediments, which were deposited during the post-Cotiella period were involved.

The base of the Ilerdian sequence in the Isabena valley is formed by redbeds of the Tremp formation. Overlying these redbeds are alveolina limestones of shallow marine origin formed during a wide-spread marine transgression (fig. 2-B). A period of lagoonal-restricted bay sedimentation, which is manifested in the thick neritic marl sequence, followed, resulting in the sedimentary sequence shown on fig. 3-A.

Intercalations of foraminiferal limestones indicate occasional minor openings of the restricted bay facies. A gradual deepening of the basin to the West took place during this period; occurrence of relatively more open marine facies (turritella-, pattalophyllia- and nummulites globulus shales) can be found generally west of the Esera valley (Luterbacher, 1973; Schaub, 1973).

A calcareous sandstone lithosome is present in the upper part of this marl sequence (fig. 3-A). This member, the Roda sandstone, shows a very distinct structural sequence. The marls underlying the Roda sandstone belong, according to nannoplankton dating (Van Vliet, pers. comm.) to the upper part of the *D. binodosus* zone. The limestones above the Roda sandstone contain a rich Alveolina fauna (*A. leupoldi* or *A. agrigentina*), which can be put within the *A. corbarica* zone. The Roda sandstone itself is well situated within the Ilerdian and represents a preceding sedimentation period with respect to the Montañana deltaic complex. This also means that sedimentation of the sandstone body occurred before the main nappe movement of the Cotiella nappe unit. The Ilerdian basin can be considered tectonically unstable, where tangential nappe movement and locally strong subsidence of the basin floor occurred.

The Roda sandstone itself represents a major opening of the bay accompanied by a mass influx of a relatively more open marine fauna and a drastic change of the hydrodynamic conditions (fig. 3-A and B). This transgressive period, which probably affected mainly the northern part of the basin, starts with a marl sequence containing abundant foraminifers, in which the perforate species dominates such as *Nummulites*, *Operculina* and *Discocyclina* (Gaemers, 1971). Overlying these marls is an interval about 10 m thick, containing beds with flaser and linsen structures and several sandstone units which show mainly bipolar tabular crossbedding. This sequence, which indicates the initial stage of a renewed major transgression, preceded the deposition of the sandwave facies and can be interpreted as estuarine/tidal-flat sedimentation.

Overlying the Roda sandstone is an interval where again restricted bay or lagoonal sedimentation took place. Occurrences of perforate as well as imperforate foraminifers tallies

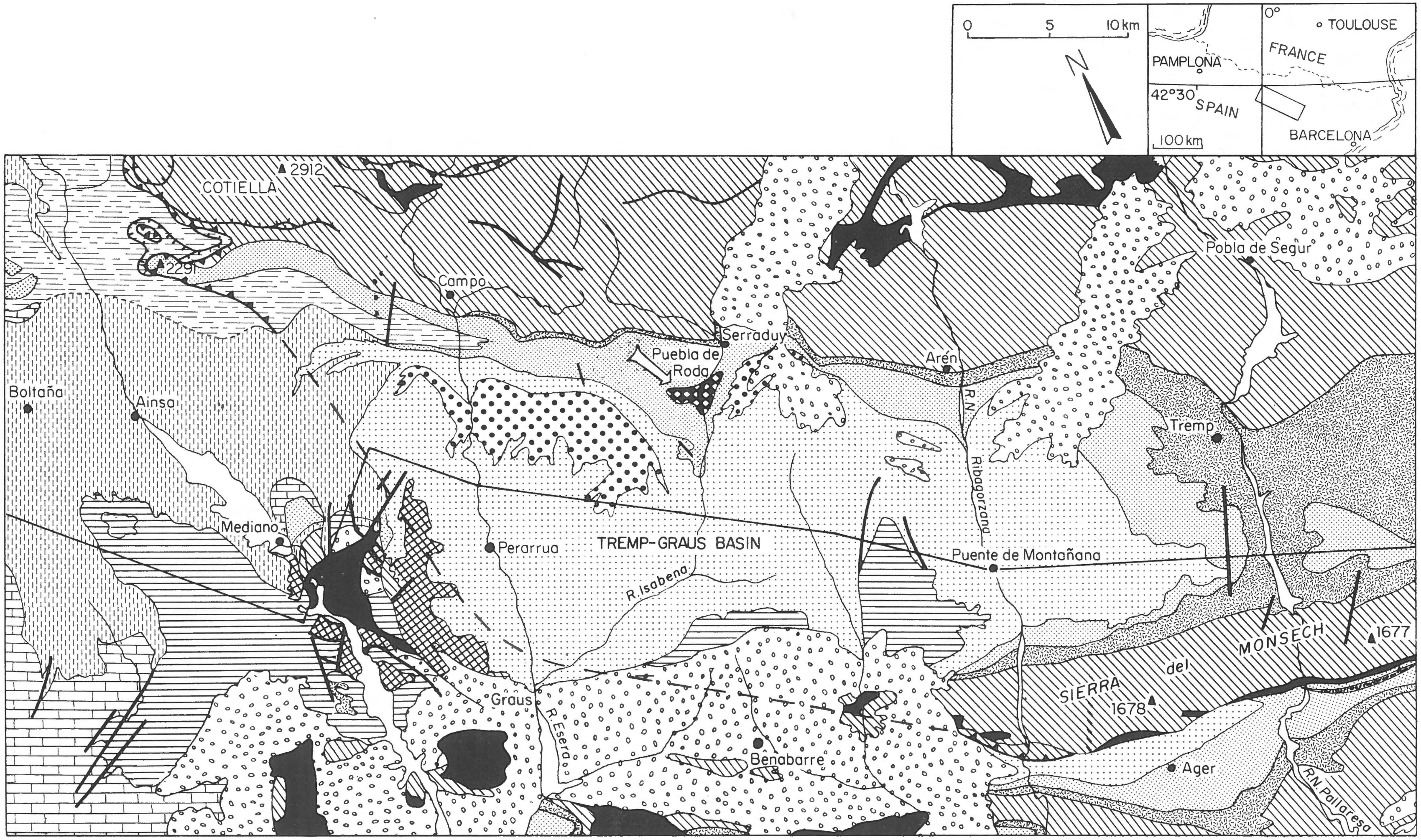


Fig. 2-A
Schematic geological map of the Rio Cinca-Rio Noguera Pallaresa sector of the southern Pyrenees.

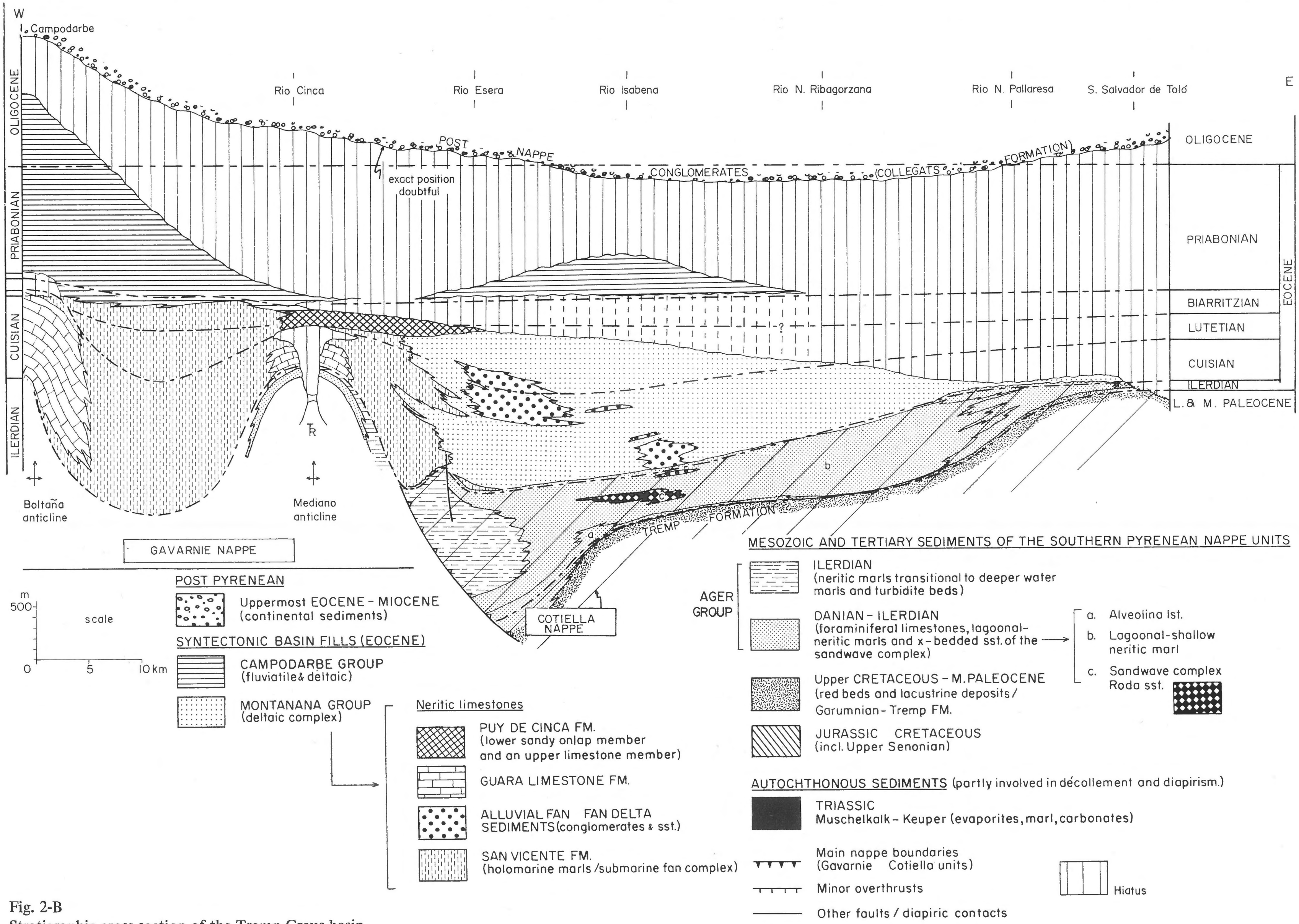


Fig. 2-B
Stratigraphic cross section of the Tremp-Graus basin.

well with this facies. Several minor thin-bedded sandstones indicate minor openings and short periods of marine influxes which also favoured the formation of several limestone intervals.

Description of the facies (figs. 3-B)

Only a brief description of the facies is presented here, but a detailed account will be presented elsewhere (NIO et al., in prep.).

Pre-sandwave facies: consists mainly of a marl sequence with some sandstone beds (thickness up to 2 m) showing bipolar tabular crossbedding. Also intercalated are some thin-bedded sandstone intervals with flaser and linsen bedding. An increase of the relatively more open marine fauna (nannoplankton, *Nummulites, Operculina*) can be found within the marls directly underlying the sandwave facies. The pre-sandwave facies is interpreted as the initial stage of a renewed transgression, where tidel-flat and estuarine sedimentation prevailed.

Initial sandwave facies (numbers in the text refer to numbers in figs. 4-A and B): consists of a 6 m thick interval of mega tabular crossbeds (set heights up to 1.50 m). The lower set boundaries are characterized by tangential bottomsets and show slight scouring (1). Sediment transport occurred probably mostly by bed load processes, where the stoss-side of the megaripples are flattened by erosion (2), and afterwards decked by a small-scale ripple interval (b2). The small-scale crossbedded interval (b2) generally develops laterally within the migrational direction into mega tabular crossbeds (a1), (a(a2and (a3). The avalanche faces are well defined and show several discontinuity planes. Discontinuities caused by a break in sedimentation and an observed change of the current direction (3) are called reactivation surfaces. Discontinuity surfaces (4) on the other hand are short breaks in sedimentation where erosional features are not obvious. Small-scale current ripples or thin clay layers can be found on these discontinuity surfaces. Erosional discordances (number 5 in fig. 5) represent breaks in sedimentation in association with erosion. Remnants of the initial sandwave facies occur beneath the sandwave facies and can also pass laterally into the sandwave facies.

Sandwave facies (figs 5-A and B; fig. 6): above an incomplete and partly eroded sequence of the initial sandwave facies (B1) is a 5-6 m thick interval, which consists of giant crossbedded sets traceable laterally for several hundred metres. The set thickness eventually increases laterally within the migrational direction to some 20 m (fig. 6). On top of B2a a new interval of the sandwave facies can be observed (B2b), which becomes laterally the main sequence (with set heights up to 10 m) as the upbuilding activities of B2a diminish. Note especially the deep scouring features at the base of B2b.

The avalanche faces of B2a are also well defined and several discontinuity planes similar to those of the initial sandwave facies can be recognized (numbers 3 and 4 in fig. 5-A).

Characteristic of this part of this facies unit are the regular occurrences of the foreset-bundles (n). In a more advanced stage of sandwave upbuilding (set heights larger than 10 m) these foreset-n-bundles tend to occur in more irregular intervals (B3 in fig. 6).

Erosional discordances (5) can be found more often in the sandwave facies and sometimes show a break of sandwave sedimentation (fig. 5-B). A change of the energy conditions tends to smooth off the avalanche faces and sometimes develops upslope crossbedding (x), which shows an increased importance of the reversing tidal current direction, or periods of intense wave reworking of the sandwave. Bundle-like upbuilding of the foresets and the different discontinuity planes indicate fluctuating flow conditions, which are a common result of tidal currents (Boersma, 1969; De Raaf & Boersma, 1971).

Post-sandwave facies (fig. 5-A and figs. 7A and B): the sandwave facies is overlain by deposits of the post-sandwave period, the slope facies.

The main structural feature of the slope facies are the low angle surfaces (dip generally less than 15°; figs. 7-A and B) which are laterally traceable for several hundred metres. No preferred dip orientation of the slopes could be observed. The smaller scale features on the low angle slope surfaces consist of several types of crossbedding. In contrast to the sandwave facies current directions possess a much wider spread (fig. 3-B). Up- and down-slope current directions are the dominant feature of the slope facies producing mega tabular and trough crossbedding with set heights up 1.50 m (figs. 5-A, 7-A and B). Foreset dips of the upslope crossbedding tend to decrease in the upslope direction.

Sedimentation of the slope facies occurred under lower energy conditions, which caused a slow-down and an eventual cessation of sandwave upbuilding. Slope sedimentation, which consists of up- and down-slope migration of mega ripples, became the dominant process, resulting in the erosion of the original sandwave morphology. Lateral progradation of the sandwave is minimal, whereas vertical accretion can still be considerable.

The transition between the sandwave facies and the overlying slope facies is characterized by a major erosion surface (comparable to those as described under number 5 in figs. 5-A and 8). The slope facies is not restricted to the vertical sequence of a sandwave complex, but also occurs lateral to the sandwave facies.

The top of the slope sequence is characterized by a completely bioturbated hardground layer of calcareous sandstone, which is traceable throughout the whole area. Abundant growth of reef corals and sponges on the completely flattened surface indicates a wide-spread break in clastic sedimentation. Bioturbation is in general much higher in the slope facies than in the sandwave facies.

Inter-sandwave facies: consists of a marl sequence where open marine fauna is lacking or scarce. It represents in general a renewed regressive period.

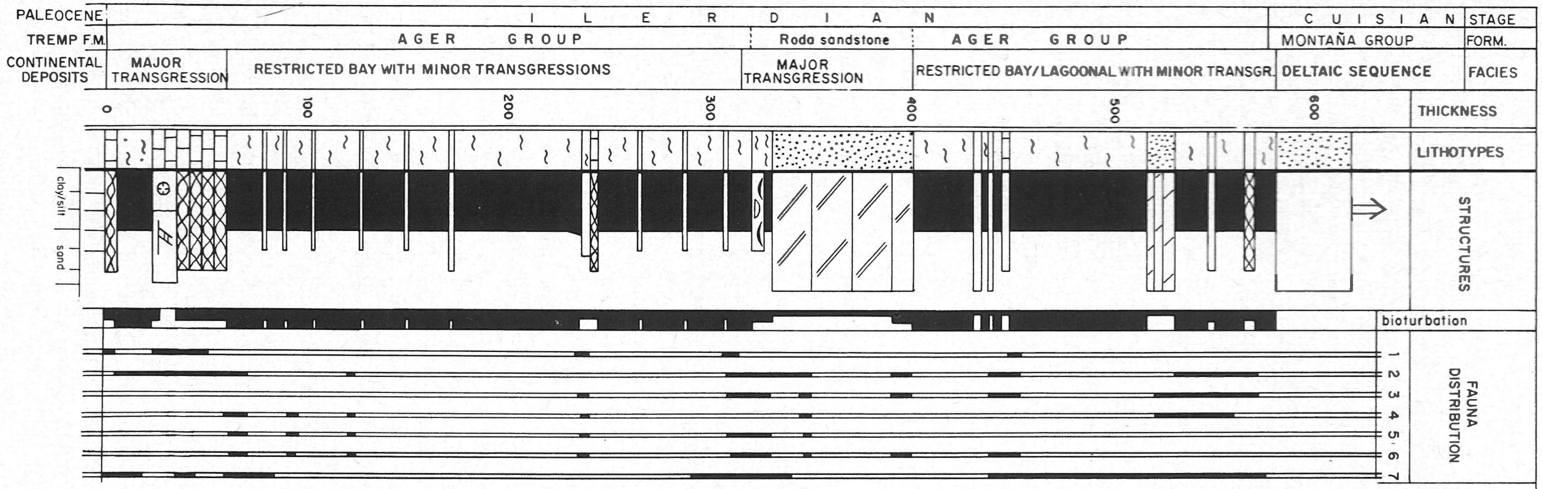


Fig. 3-A
Schematic stratigraphic section through the Upper Paleocene and Lower Eocene, Isabena valley, Prov. Huesca, N. Spain.

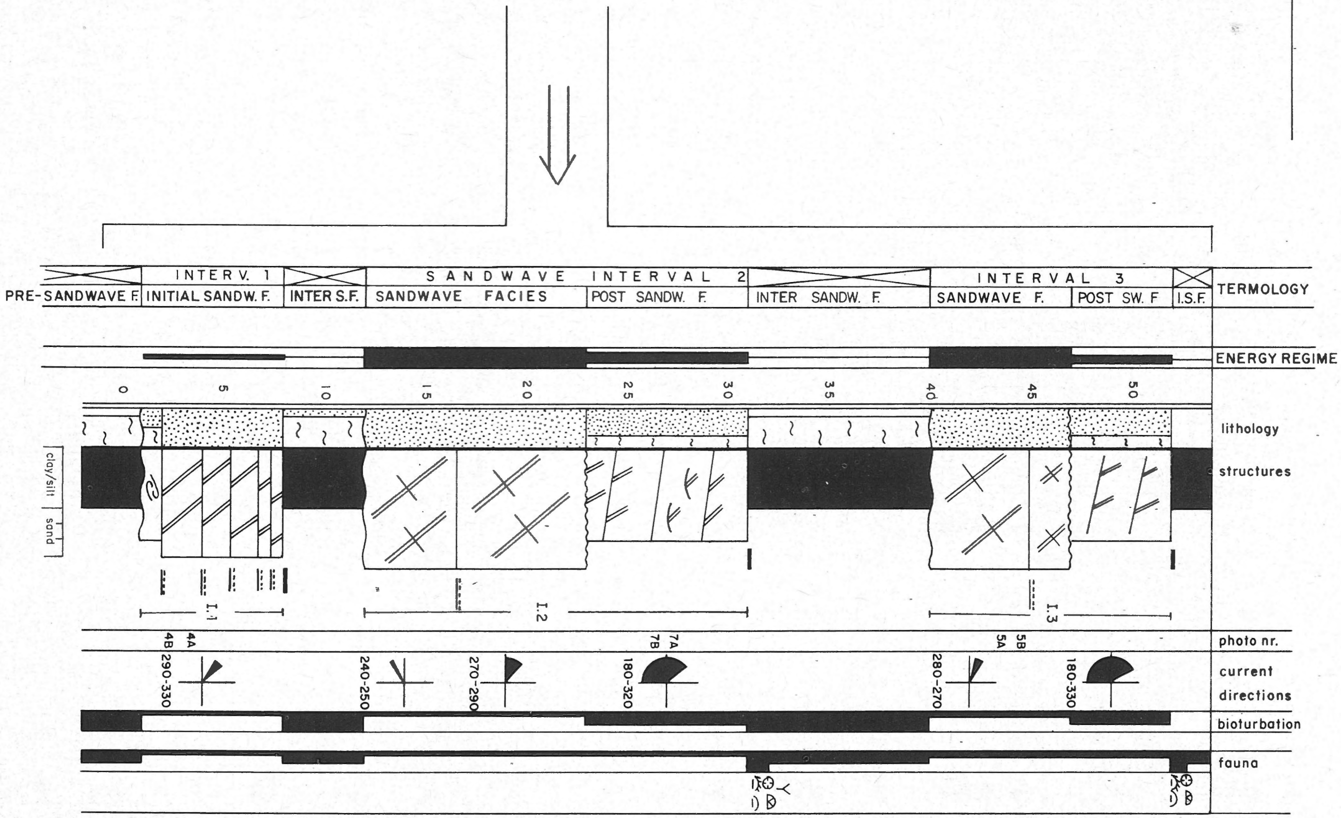
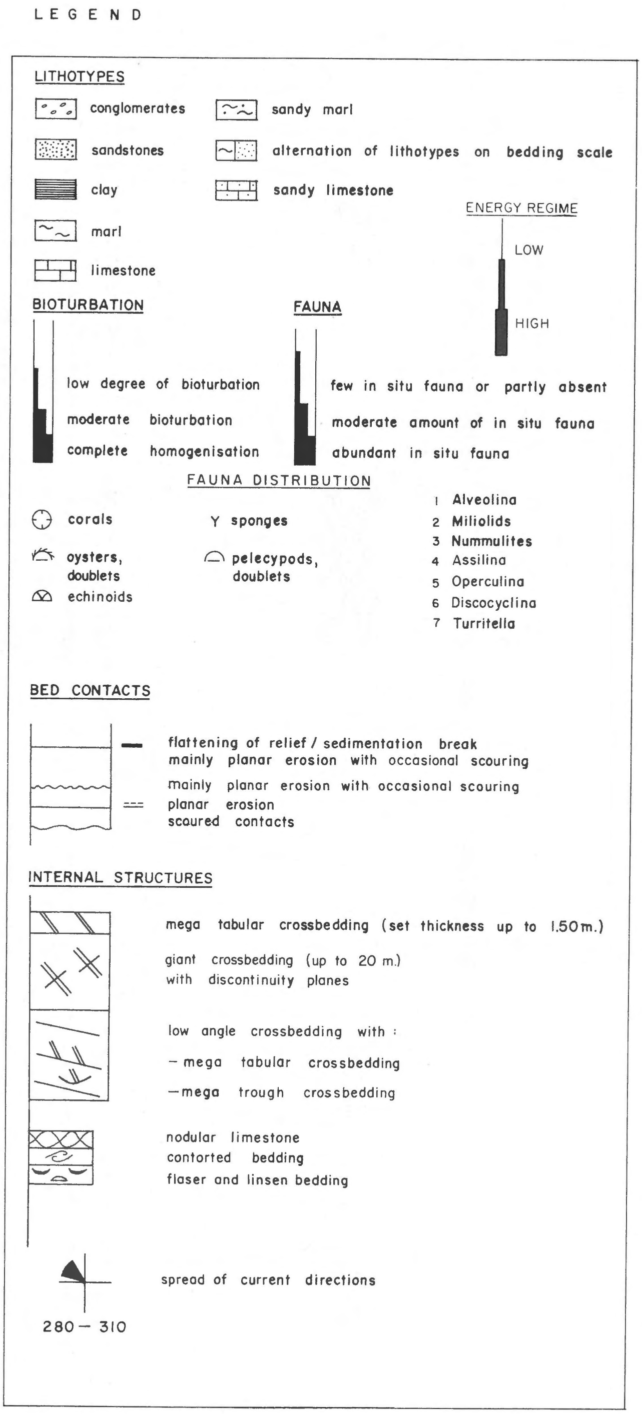


Fig. 3-B
Schematic composite sequence of the Roda sandwave complex.



Sequential development (fig. 3-B and 8)

The sequential order of the Roda sandstone shows a very regular pattern. The schematic sequence presented in fig. 3-B, which is a composite of different sections taken at several localities, can be divided into at least 3 main intervals. The three intervals are separated by a marl sequence (A2 in fig. 8) of the intersandwave facies.

Interval 1 (fig. 3-B) is a 6 m thick unit, which forms the initial sandwave facies. The base of the sequence is formed by a single problematical contorted bed (a in fig. 4-B). The thickness of the initial sandwave facies increases downcurrent and eventually develops into the giant crossbedding of the sandwave facies.

Interval 2 shows a sequence of the sandwave facies, which is commonly overlying remnants of the initial sandwave facies (fig. 5-A). Mostly, however, marls of the pre-sandwave facies directly underlie the sandwave facies, indicating a more advanced stage of sandwave upbuilding and downcurrent progradation.

Overlying the sandwave facies and laterally in downcurrent direction is the slope facies, followed by a marl interval of the inter-sandwave facies.

Generally an increased bioturbation can be observed with decreasing energy conditions.

An important feature of the sequential development is the vertical as well as a downcurrent lateral growth of the set thickness of the (initial)-sandwave facies, showing an aggrading sandwave sequence; this is followed by a vertical and lateral decrease of the set thickness from the sandwave facies into the slope facies, showing a degrading sandwave sequence.

This vertical and lateral change in sedimentation pattern can be explained by an initial increase followed by a decrease in the hydrodynamic energy conditions, accompanied with a deepening of the basin. The marl interval of the inter-sandwave facies indicates the presence of low energy conditions and represents a regressive period.

Current directions

The spread of the current directions is strongly related to the different facies units. Systematic measurements show a narrow spread of current directions for the (initial)-sandwave facies, indicating a dominant unidirectional flow.

Measurements within the slope facies, however, show a much wider spread. This multi-directional flow can be explained by a decrease of energy conditions and a growing importance of other hydrodynamic processes, such as reversing tidal currents or even wave action.

Finally, a drastic change in sand supply and an increased importance of wave action characterized the post-slope sedimentation.

Summary

The following conclusions are drawn from the Roda sandwave complex:

1. The Roda sandwave complex was deposited within a tectonically unstable basin. Local subsidence of the basin floor resulted in several transgressions, which can be observed from the character of the vertical and lateral faunal-lithological distribution. The marine transgressions within the Tremp-Graus basin during the Ilerdian was probably only important locally with minor influence in the rest of the basin.

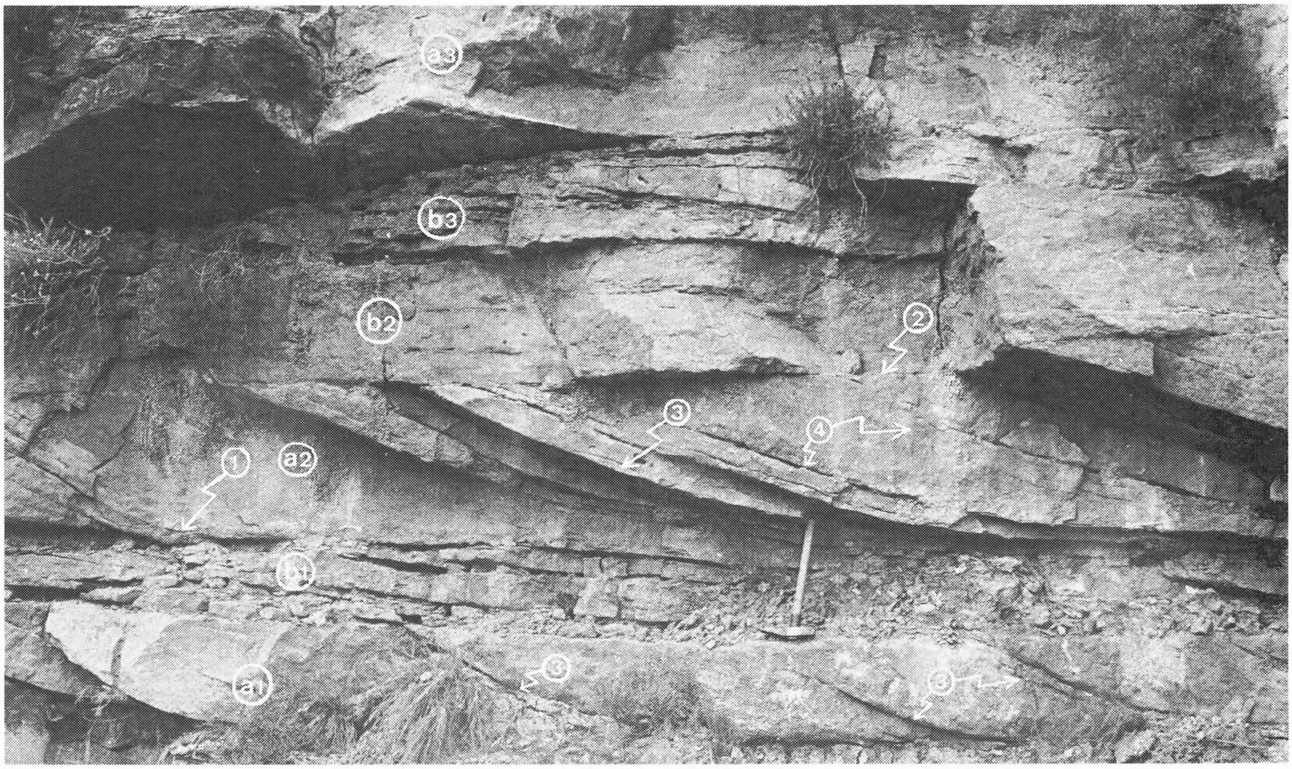


Fig. 4-A
Mega tabular crossbedding with small-scale crossbedded intervals of the initial sandwave facies.

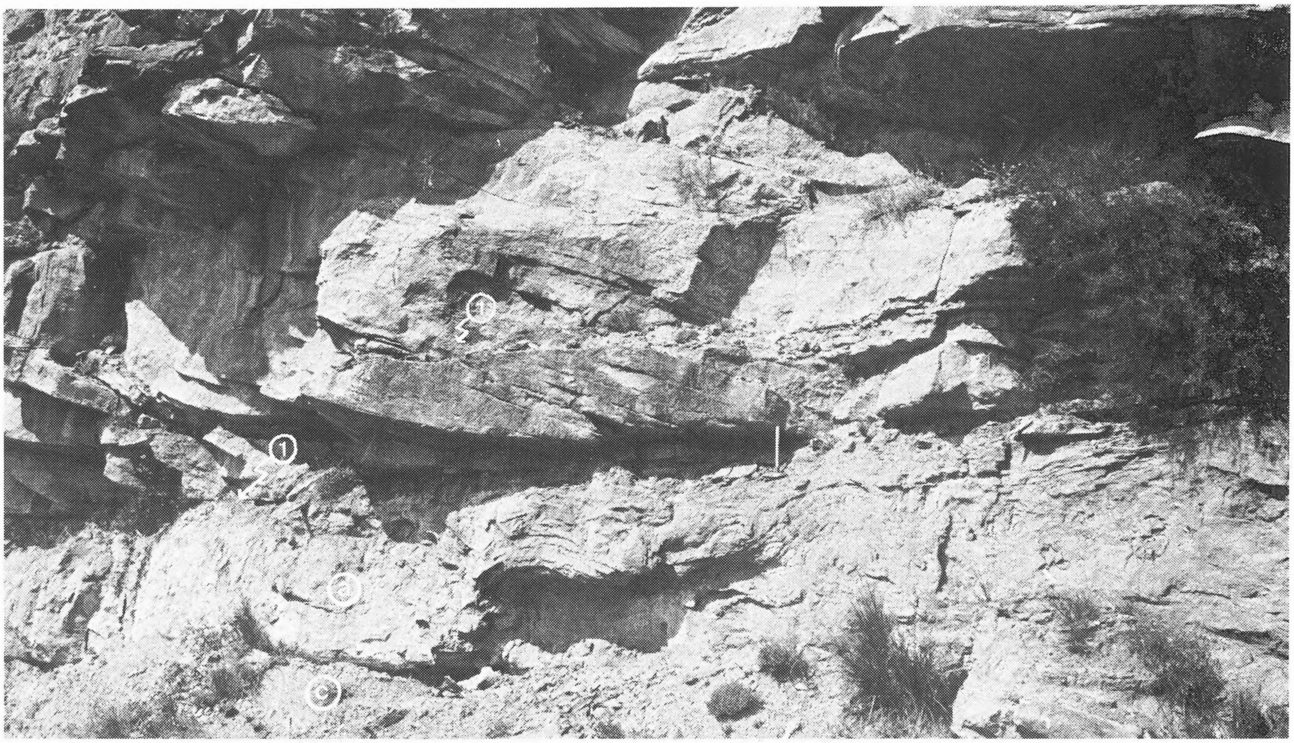
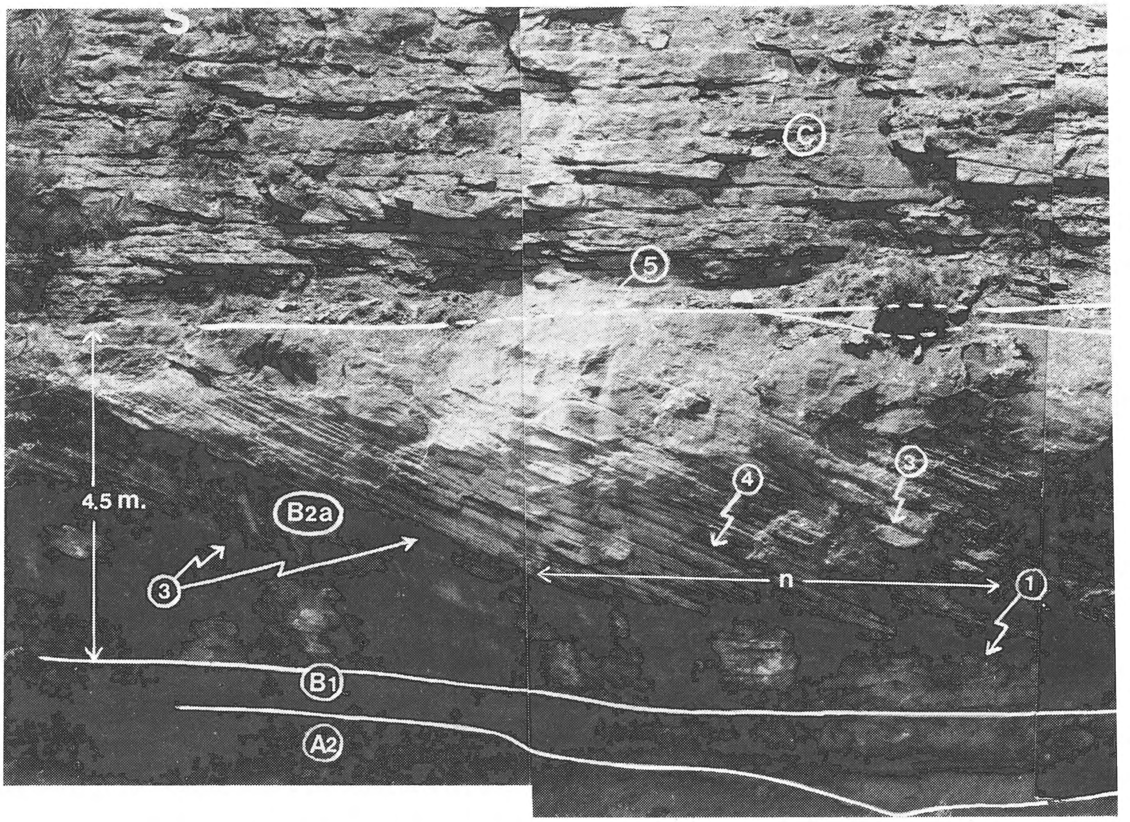


Fig. 4-B
Setting of the mega crossbedded sets within the initial sandwave facies.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5
4.5 m.
B2a
4
3
3
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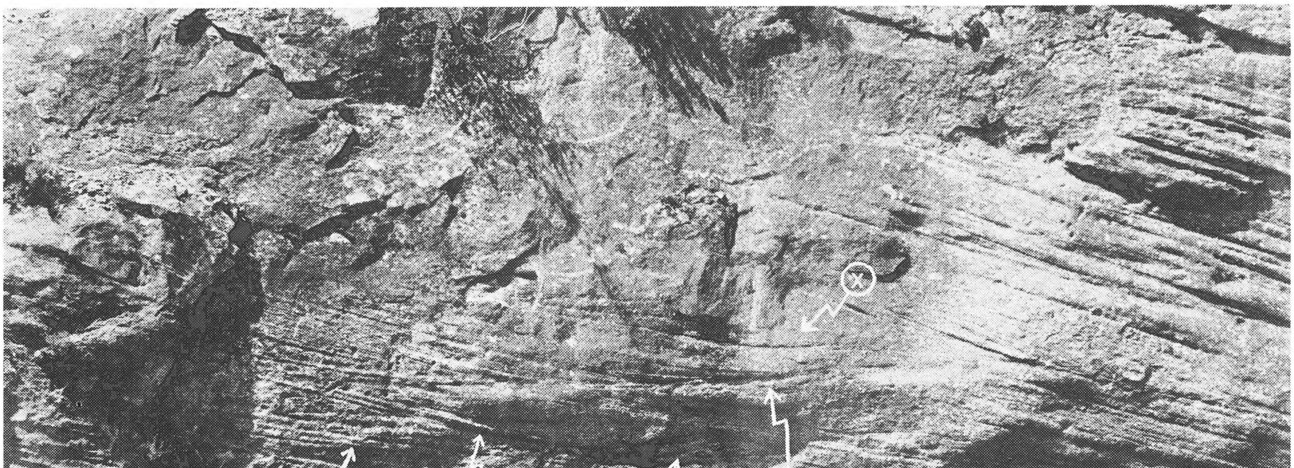
1
B1
A2


X
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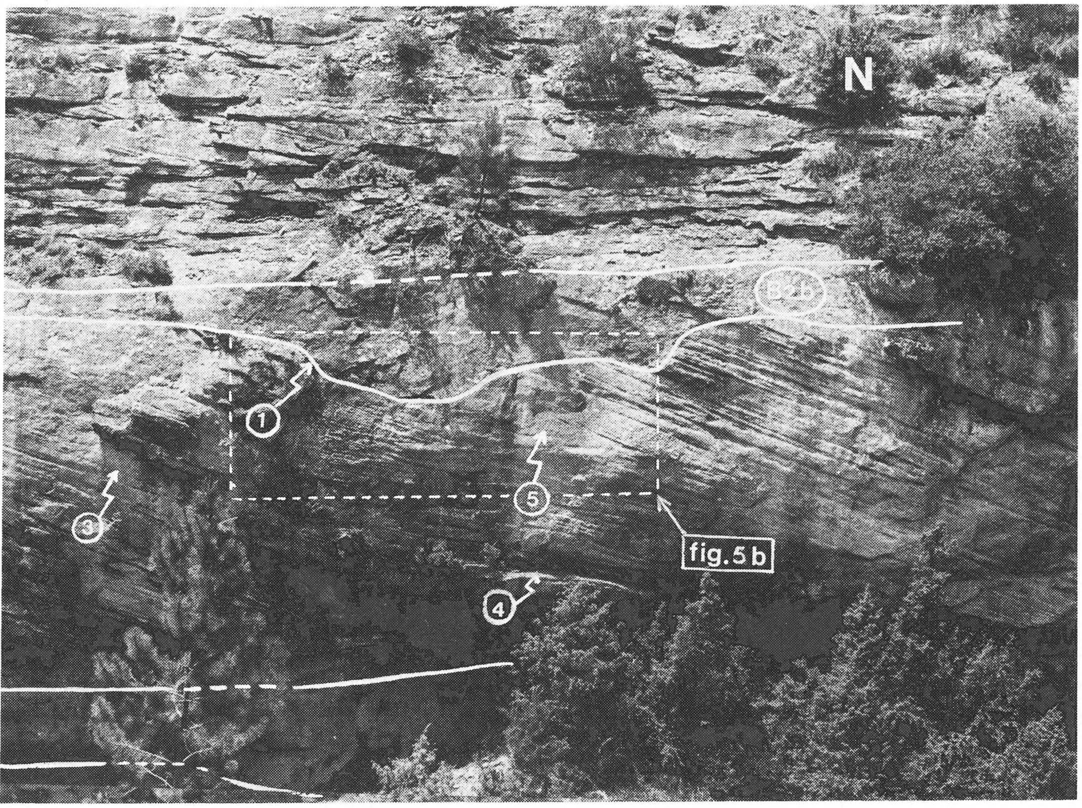


Fig. 5-A
Structural features of the sandwave facies of the Roda sandwave complex.

Fig. 5-B
Detail of erosional discordance surface of the sandwave facies.

2. The pre-sandwave facies, which indicates the initial stage of a major transgression, consists of tidal-flat and estuarine sediments.

3. The Roda sandwave sequence shows a well-defined lithological and structural order. It is characterized by a lower aggrading sequence from the initial sandwave facies into the sandwave facies. This is followed by a degrading sequence from the sandwave facies into the slope facies. The sequential order can also be explained by changing hydrodynamic conditions. An initial increase of the energy conditions, where unidirectional flow is dominant, is followed by an increased variability of energy conditions, which allows the development of other hydrodynamiprocesses, such as reversing tidal currents or wave action.

4. A vertical change occurs from a restricted facies, where open marine fauna is poor, into a fully marine facies at the top of the sandwave sequence. This indicates a deepening of the basin during deposition and upbuilding of the sandwave complex.

5. Bundle-like upbuilding of the foresets and the presence of numerous discontinuity planes indicate the occurrence of fluctuating flow conditions, which was probably largely the result of tidal currents.

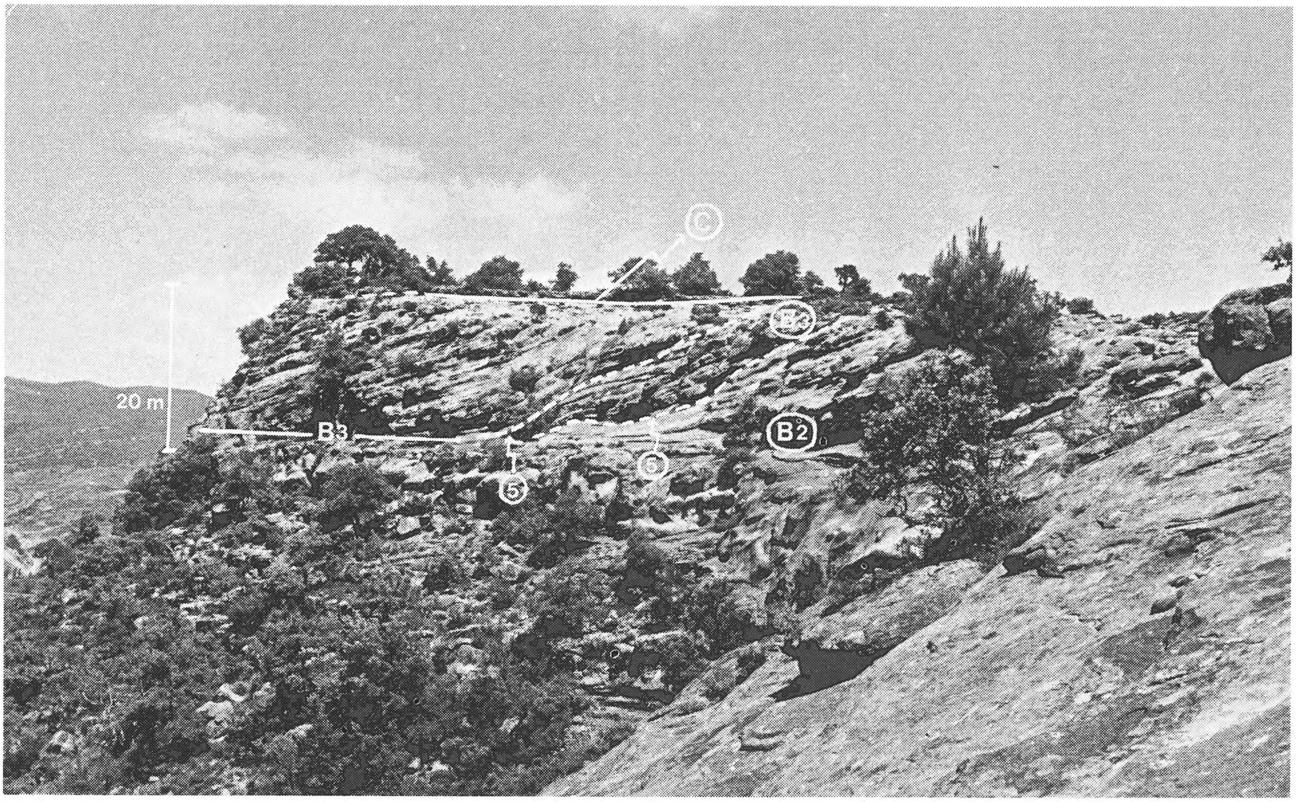
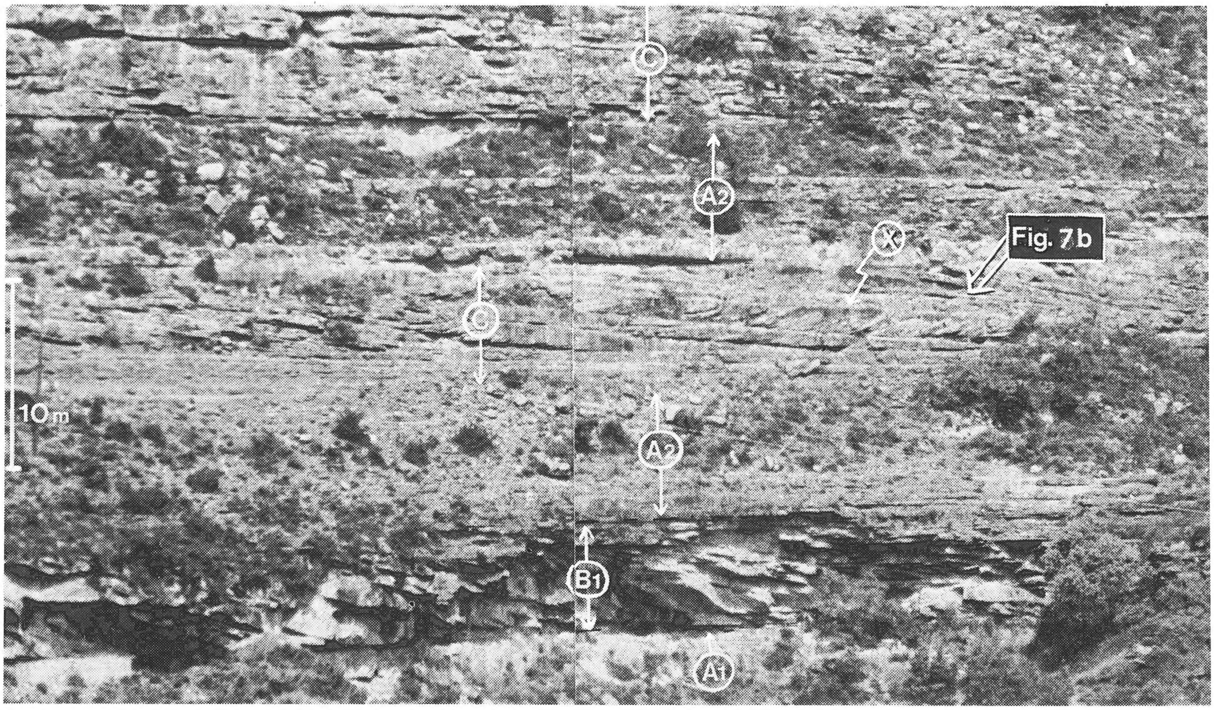


Fig. 6
Last-stage upbuilding of the sandwave facies, Roda sandwave complex.



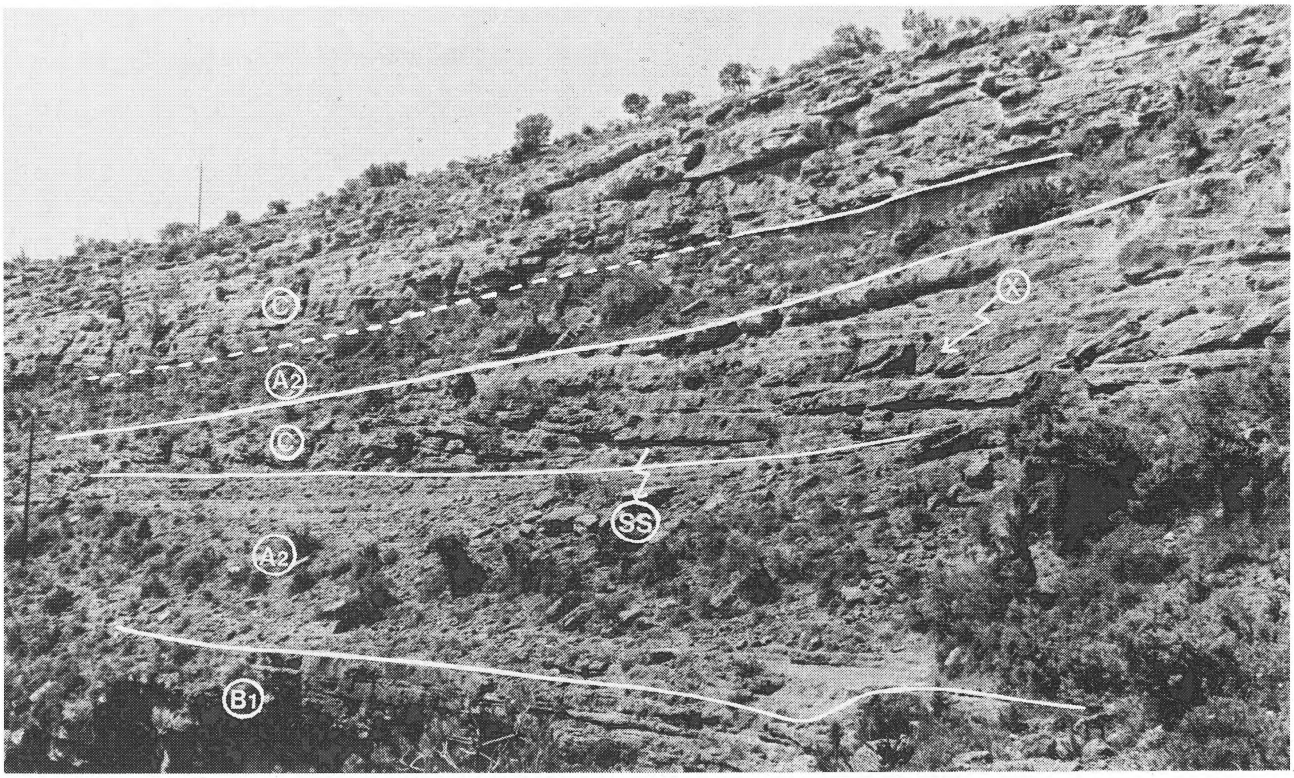


Fig. 7-B
Detail of the upslope crossbedding of the slope facies.

THE SANDWAVE COMPLEX OF THE LOWER GREENSAND OF THE ISLE OF WIGHT

Most of the data used here come from Dike's excellent study of the sedimentology of the Lower Greensand on the Isle of Wight (Dike, 1972). Some of his sedimentological sections (Chale Bay and Sandown Bay; fig. 9-A) were compiled and redrawn for the present paper, to give a schematic picture of the sequential development of the Lower Greensand of this area (fig. 10-A).

Comparative studies of this section with the Roda sandwave complex revealed striking similarities in the overall sequential development and also the position of the sandwave complexes within the stratigraphic column. The general facies development as described by Dike is similar to that of the Roda sandstone and only minor re-interpretation of the section at Little Stairs Point (fig. 10-B) was made.

The main features of sandwave development within the Lower Greensand of the Isle of Wight are summarized below:

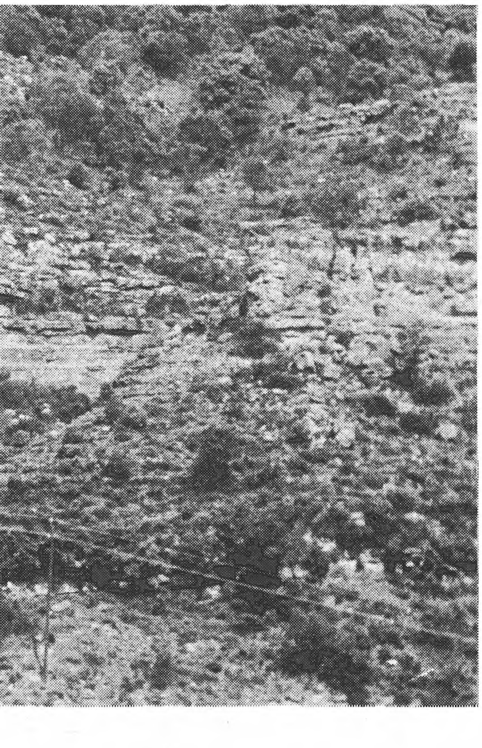


Fig. 7-A
Sequence of the post-sandwave slope facies and the overlying inter-sandwave facies.

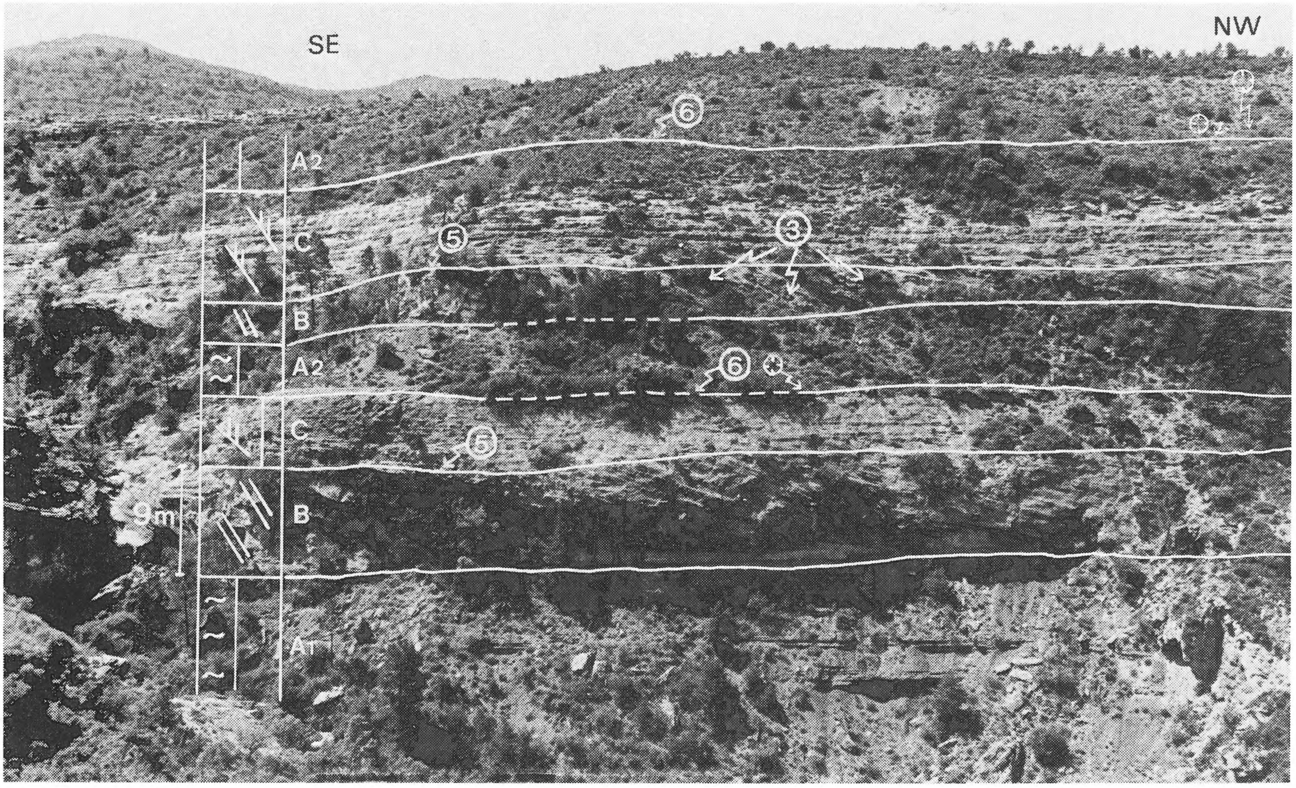


Fig. 8
Panorama of two superimposed sandwave intervals, showing the sequential development of the Roda sandwave complex.

1. The Lower Greensand of the Isle of Wight is a clastic sequence (128-250 m thick), which in general represents a transgressive sequence from the brackish Wealden Shales (Barremian) into the marine Gault Clay (Albian) (fig. 9-A). The sequence is characterized by periods of major transgression followed by short intervals of regression (fig. 10-A).
Several facies associations were defined by Dike upon which the following division of the Lower Greensand was made:

a. *The Atherfield Clay* (facies association AC1-AC3)
After an initial major transgression at the basal Perna Beds, deposition of fine-grained sediments dominated. Sedimentation probably took place within a more or less restricted environment (protected shelf?).

b. *The Limonitic Sands* (facies association FS1-FS4)
The gradual beginning of another transgression is manifested in an interval which can be interpreted as an estuarine/tidal-flat sequence (FS1). Overlying this unit is a sequence with giant- and mega crossbedded sands (FS3), followed by a fine-grained sequence representing another period of restricted sedimentation.

c. *The Glauconitic Sands* (facies association FS5-FS6)
Characteristic for this facies unit is the dominating occurrence of giant crossbedded sands (FS6), overlying a sequence which is interpreted as estuarine/tidal-flat sedimentation.

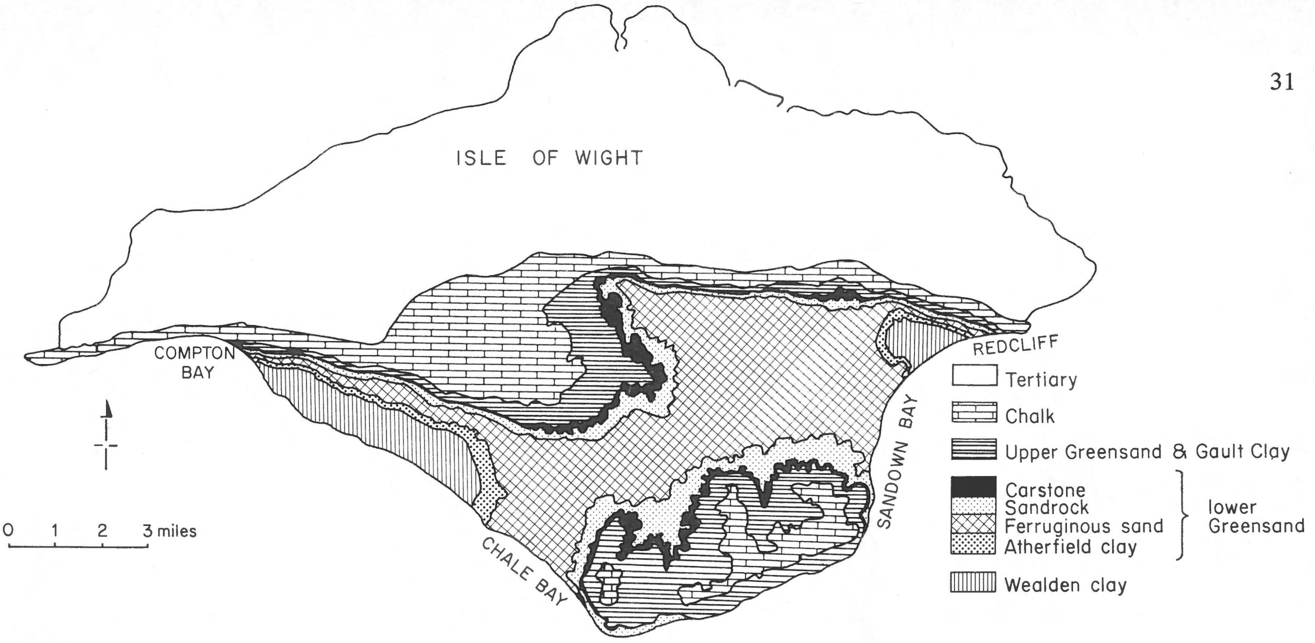


Fig. 9-A
Schematic geological map of the Isle of Wight.

d. *The Sandrock* (facies association SS1-SS4)
The basal part of this unit consists of a regressive barrier- and backbarrier complex. This is followed by another transgressive sequence with evidence for estuarine sedimentation. The Sandrock terminated in a regressive sequence.

e. *The Carstone*
In continuation with the underlying Sandrock facies unit, evidence for restricted sedimentation can be found for at least the basal part of the Carstone. This is followed by a final transgressive sequence.

2. Differences in sediment thickness reveal a distinct topography of the Lower Greensand basin (fig. 9-B). Maximum thickness of the sequence is at Chale Bay (250 m), whereas a decrease of the thickness can be observed eastward towards Redcliff (195 m), and even more rapidly westward towards Compton Bay (128 m). Sandwave complexes are described mainly in the area between Sandown Bay and Chale Bay.

3. Occurrences of sandwave complex intervals coincide with transgressive periods and are mostly underlain by estuarine sediments.

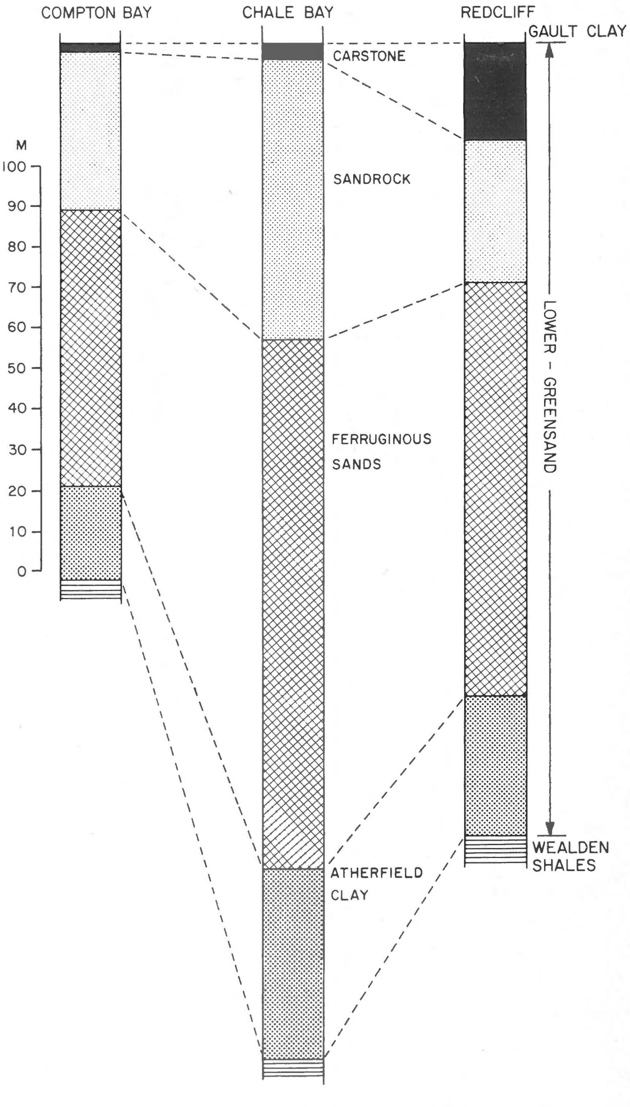


Fig. 9-B
Lithostratigraphic sections through the Lower Greensand of the Isle of Wight.

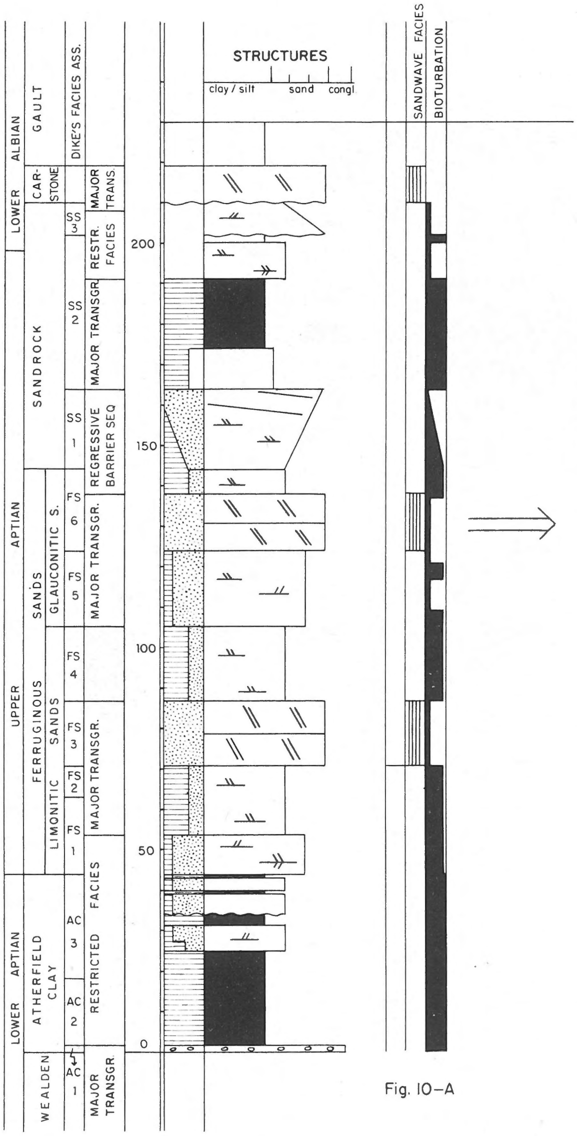


Fig. 10–A

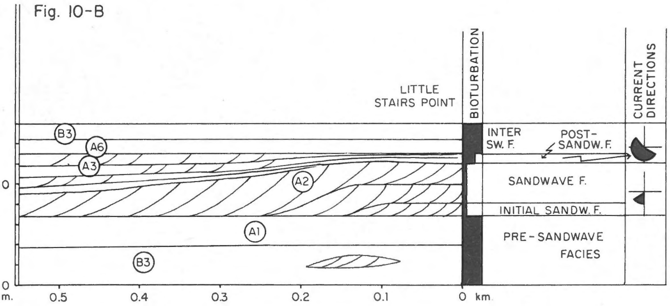


Fig. 10-B
Detailed section of the members FS5 and FS6 of the Glauconitic Sands at Little Stairs Point.

Fig. 10-A
Composite schematic section through the Lower Greensand, showing the vertical relationship of the different facies units and intervals of sandwave formation.

4. A detailed section at Little Stair Point reveals a distinct vertical and lateral sequential order (fig. 10-B).

The pre-sandwave facies consists mainly of mud and several sand layers which is interpreted as an estuarine/tidal-flat sequence.

The overlying sandwave facies shows giant tabular crossbedding with set heights up to 5 m. Current directions of this interval are within a narrow spread.

The overlying unit consists of a low-angle sequence with several types of crossbedding and is interpreted as the slope facies.

Current directions are found to be within a much wider spread. The following finer-grained sequence shows a regressive tendency. Dike assumed, that deposition of the sandwave sequence occurred during slow and uniform rise in sea-level and a gradual decrease in current velocities as the

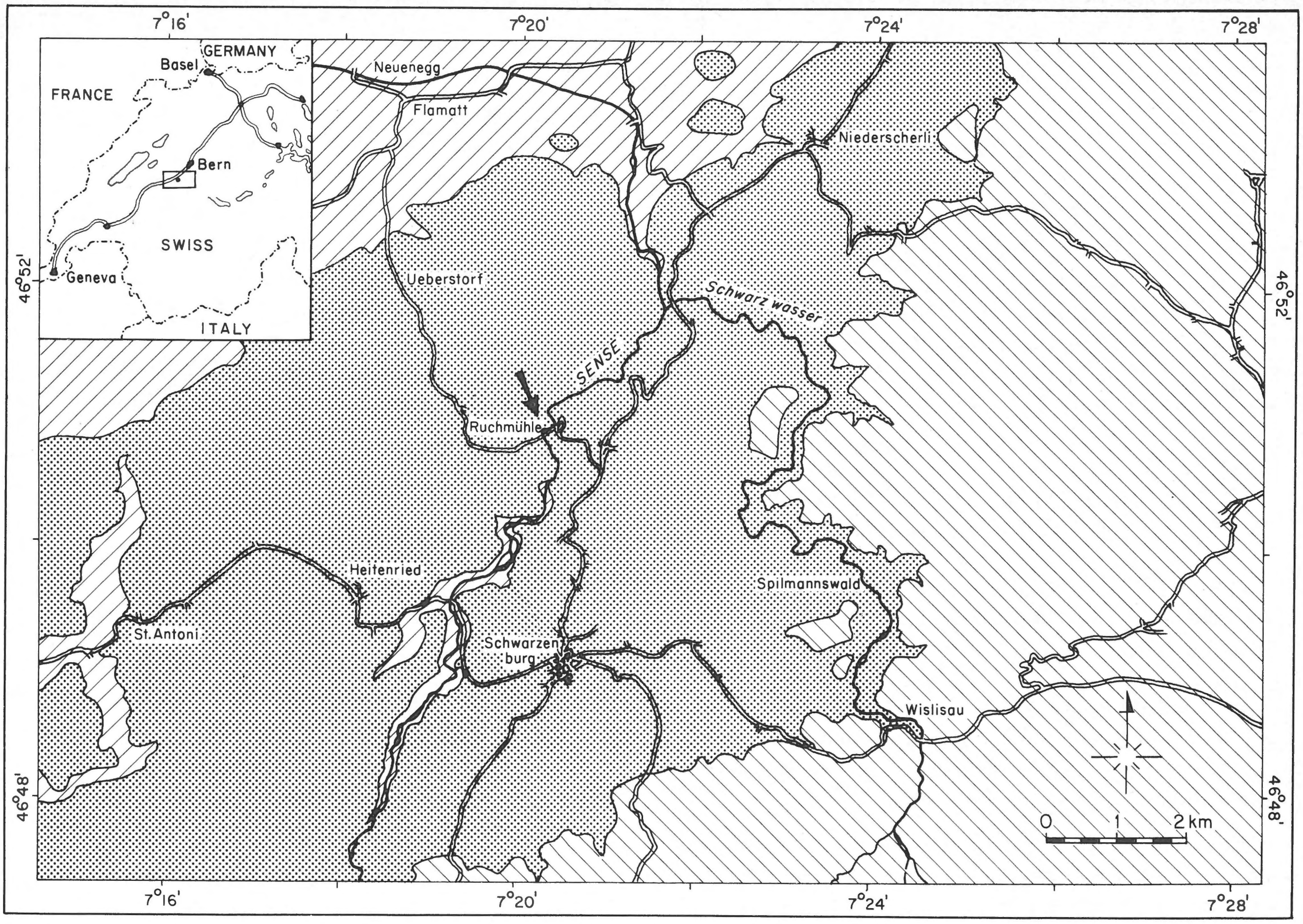


Fig. 11-A
Schematic geological map of the Sense-Schwarzwasser area, Canton Bern, Switzerland.

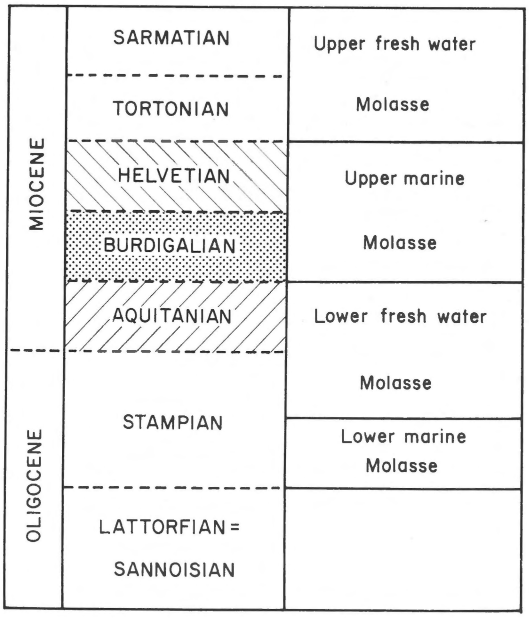


Fig. 11-B
Schematic stratigraphic scheme of the Oligocene and Miocene of the Swiss Molasse.

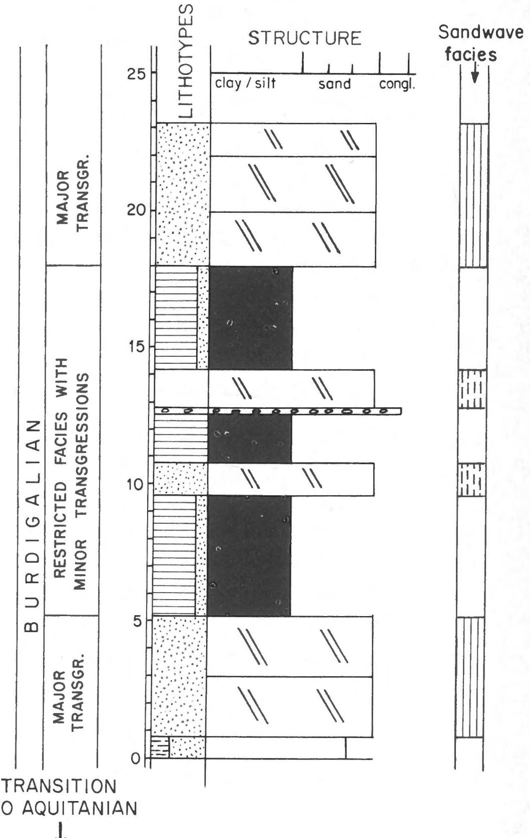


Fig. 11-C
Schematic sedimentological log through the Lower Burdigalian.

basin deepened. This conforms with the observations and interpretationon of the Roda sandwave complex.

5. The upper surface of facies A2 and A3 (fig. 10-B) are flattened by erosion and strongly bioturbated. This indicates a major break in sedimentation comparable with the transition of the slope facies to the overlying marl interval of the inter-sandwave facies of the Roda sandwave complex.
Generally a thin layer of reworked sand covers the eroded and bioturbated surface.

THE BURDIGALIAN SANDWAVE COMPLEX OF THE SWISS MOLASSE

Occurrences of several giant crossbedded sequences within the Upper Marine Molasse (Burdigalian) in the Sense-Schwarzwasser area were described by van der Linden (1963; fig. 11-A).

His study did not contain a detailed description of the sequence, but merely defined its position within the Burdigalian transgression. Some aspects of the several sandwave intervals, however, are summarized here:

1. The Burdigalian transgression in the Sense-Schwarzwasser area was confined within the so-called peri-Alpine depression, a longitudinal basin connecting two larger basins in the South and in the East. Vertical and also horizontal tectonic movements during this period gave the basin an unstable configuration.

2. The transgression overlies the Lower Freshwater Molasse of the Aquitanian and reaches its maximum during the Helvetian.
The filling of the basin occurred rather rapidly by large alluvial fan deposits especially during the lowermost Burdigalian.

3. The described sequence (fig. 11-C) is only a fraction of the total Burdigalian sequence of this area (ca. 370 m). It mainly represents the lower part of the Burdigalian, during which time the transgression was still in progress. The section, therefore, is not very representative for the development of the whole Burdigalian.

4. The best described section, where at least two intervals of sandwaves can be recognized is the Ruchmühle road exposure (fig. 11-C). The two intervals are separated by a finer-grained sequence with intercalations of two major sandstone beds, showing crossbedded sets of less than 1 m thickness.
This sequence also shows intervals with flaser bedding. The sequence has been interpreted in general as a restricted facies.

5. It can be concluded that the giant crossbedded sequences are within a clear transgressive period of the Burdigalian and are related to several major fluxes of transgression.
Further information about the internal structural organization of these complexes will be needed before more conclusions can be drawn.

THE RELATION BETWEEN MARINE TRANSGRESSIONS AND SANDWAVE FORMATION

Some conclusions can be drawn from these sequential studies of ancient sandwave complexes:

a. Ancient sandwave complexes occur within transgressive sequences. Sandwaves within the basin seem topographically localized.

b. The sandwave complexes are mostly underlain estuarine/tidal-flat sediments; the top of the sandwave sequence, however, is characterized by a fully marine facies.

c. Active upbuilding of the sandwave complexes decreases in general with a deepening of the basin and ceases with the termination of slope facies sedimentation.

d. Slope facies sedimentation is followed by a period of low sedimentation and a flattening of the topography, which seems to coincide with a maximum stage of the transgression.

e. The internal structural organization of the (initial)-sandwave facies indicates the presence of strong tidal currents.

Marine transgressions in association with tidal action in effect are the genetic factor for sandwave complexes.

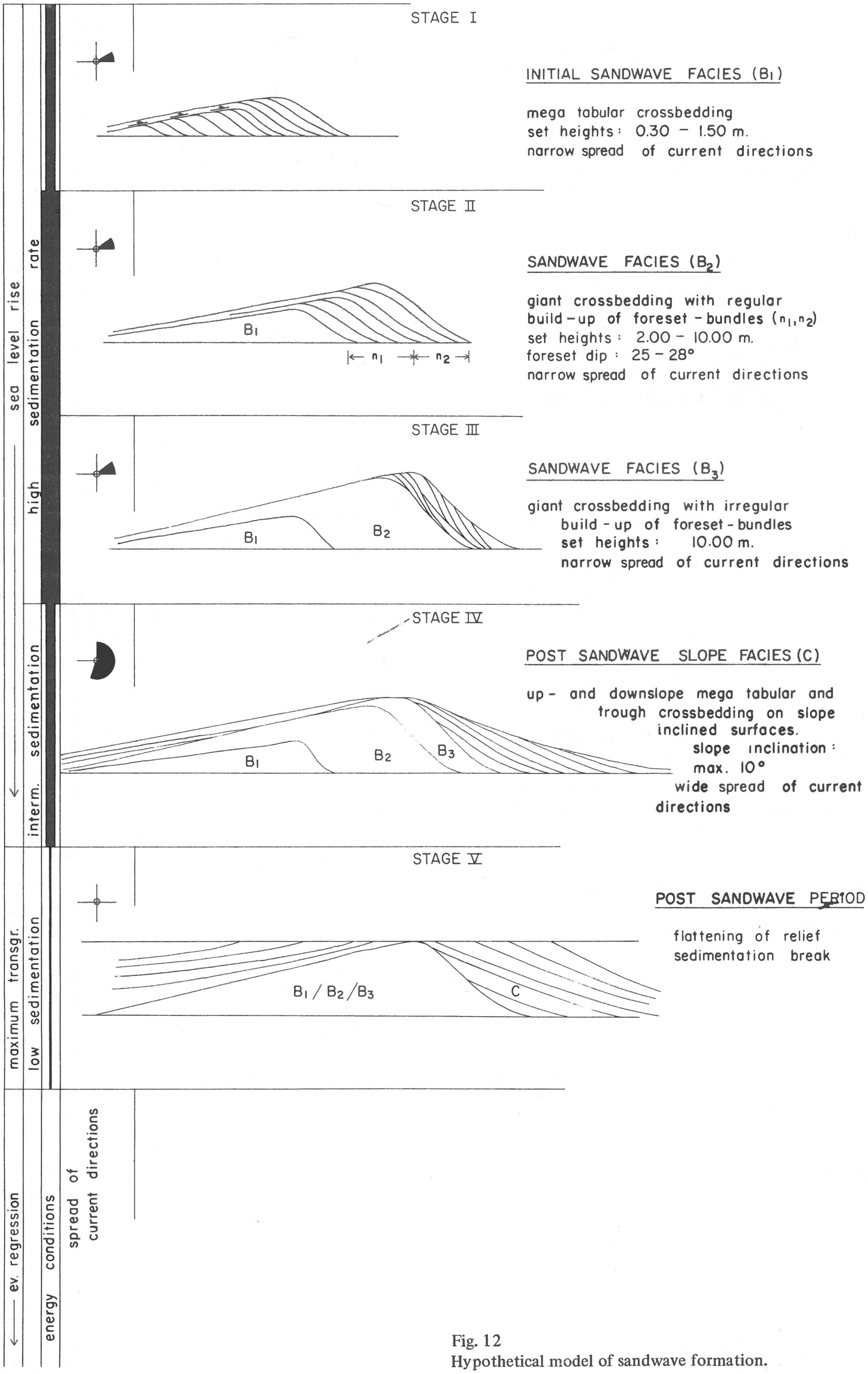
Based on this assumption a hypothetical model can be reconstructed (fig. 12):

1. Flooding of the land area, which marks the beginning of the marine transgression, will drown existing river valleys and/or depressions of the existing topography. Estuarine and tidal-flat sedimentation will prevail within the transitional zone.

2. Smaller sandwaves (initial sandwave facies) can be formed within the estuaries and the depressions of the existing topography with rising sea-level.

3. With a protracted transgression sandwaves of larger dimensions will be formed (sandwave facies, B2). Bedload transport on the stoss-side of earlier formed smaller sandwaves caused a lateral migration and a vertical accretion of the sandwaves. Fluctuations and change of current direction produced several forms of discontinuity planes. Current direction variations, however, are restricted to a narrow spread within the sandwave facies.

4. In an advanced stage of the transgression confined flow conditions decreased and lateral migration of the sandwave occurred only during periods of higher energy conditions (sandwave facies, B3); for instance those produced by storm-induced currents. Sedimentation on the flanks of the sandwave and in the troughs increased in importance.



INITIAL SANDWAVE FACIES (B_1)

mega tabular crossbedding
set heights: 0.30 – 1.50 m.
narrow spread of current directions

SANDWAVE FACIES (B_2)

giant crossbedding with regular build-up of foreset-bundles (n_1, n_2)
set heights: 2.00 – 10.00 m.
foreset dip: 25 – 28°
narrow spread of current directions

SANDWAVE FACIES (B_3)

giant crossbedding with irregular build-up of foreset-bundles
set heights: 10.00 m.
narrow spread of current directions

POST SANDWAVE SLOPE FACIES (C)

up- and downslope mega tabular and trough crossbedding on slope inclined surfaces.
slope inclination: max. 10°
wide spread of current directions

POST SANDWAVE PERIOD

flattening of relief
sedimentation break

Fig. 12
Hypothetical model of sandwave formation.

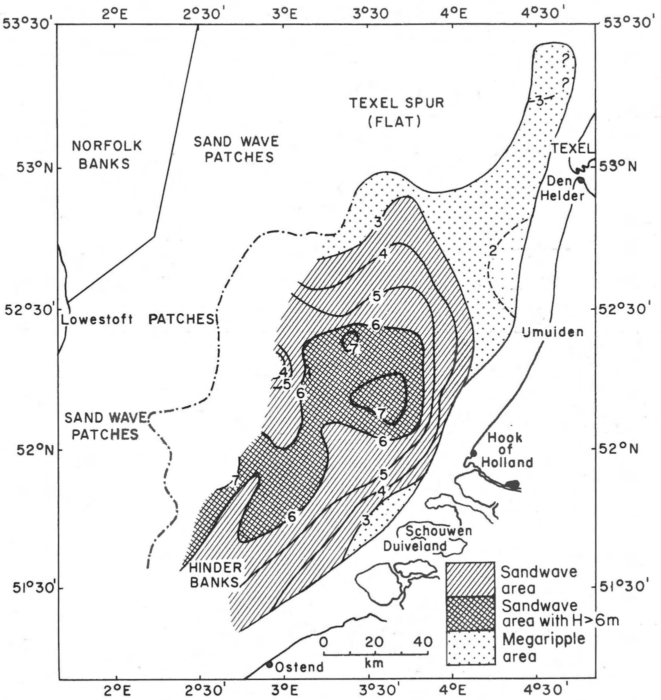


Fig. 13
Distribution of significant sandwave heights in the southern North Sea.

5. With a further deepening of the basin lower energy conditions cause sedimentation on the slopes and troughs (slope facies) to be dominant. Migration of megaripples on the slopes caused lateral migration of the sandwaves, which in general is very slight; vertical accretion, however, can still be considerable.

6. During the maximum stage of the transgression flattening of the existing topography occurs and no further upbuilding of the sandwave can occur.

SANDWAVES OF THE SOUTHERN NORTH SEA

The purpose of this section is to utilize the analyses of ancient sandwave complexes in order to explain the genesis of modern sandwaves with geological arguments rather than by an application of present-day hydrodynamic conditions to morphologic analysis of the sandwaves [1]. The best studied examples of modern sandwaves are those of the southern North Sea.

Ripples with heights larger than 2 m represent sandwaves, which are comparable with the giant crossbedded sets of the sandwave facies. Ripples with heights smaller than 2 m are comparable with the megaripples of the initial sandwave facies or the mega-ripples occurring within the slope facies. McCave's (1971) extensive studies revealed some interesting features concerning the distribution of the significant sandwave heights in the southern North Sea (fig. 13):

a. A high sandwave area ($H > 6$ m) occurs in the centre of the sandwave area south of 52°30′, which appears as an oblong field with its axis more or less parallel to the Dutch coast.

b. The lateral extension of the sandwave area itself protrudes further to the N (Caston & Stride, 1973); in contrast its lateral extension to the Dutch coast is very small.

c. No clear boundaries exist to the W, where there occurs a gradual transition to an area with patches of megaripples (or sandwaves?).

The question of sandwave migration under the present-day hydrodynamic conditions is still controversial (Stride, 1963; Houbolt, 1968; McCave, 1971; Terwindt, 1971). Recent measurements with more accurate methods revealed only slight migration, which is in all cases well within the normal navigational error.

No observations exist to indicate a large-scale migration and an effective upbuilding of the sandwaves. The relations between the main Holocene transgression and the inferred development of the sandwaves can be explained as follows (figs. 14-A and B; fig. 15):

1. The Holocene of the North Sea is characterized by several transgressive periods (Jelgersma, 1961; Hageman, 1969; fig. 15).
Major flooding of the North Sea basin started about 9300 years B.P. together with the formation of an extensive Rhine-Meuse estuary complex. Data on the rate of sea-level rise during the Holocene were obtained by radiocarbon dating of the different peat layers (Jelgersma, 1961; fig. 14-B).
A strong sea-level rise took place within the period 8300-7000 B.P. and a gradual leveling off after this period. More reliable data on sea-level rise is obtained from measurements of peat layers within the Rhine-Meuse estuary (dashed line in fig. 14-B); this shows the presence of several transgression peaks within the period after 6000 B.P.

2. Smaller sandwaves (comparable to the megaripples of the initial sandwave facies) will be formed within the initial Rhine-Meuse estuary (fig. 14-A, number I). Well developed sandwaves could already exist within the narrow confinement of the transgressive channel (number II in fig. 14-A/2, 3, 4, and compare also figs. 13-B and 15).

3. The area of well-developed large sandwaves (see fig. 14) fits well within the area of the former Rhine-Meuse estuary complex. Sandwaves beyond this area are in general smaller.

4. With the deepening of the basin active sandwave upbuilding and migration became less. The present sea-level energy

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[1] The Sedimentology Group in cooperation with Rijkswaterstaat and the Geological Survey of the Netherlands is carrying out a long-range research programme on the sandwaves of the southern North Sea.

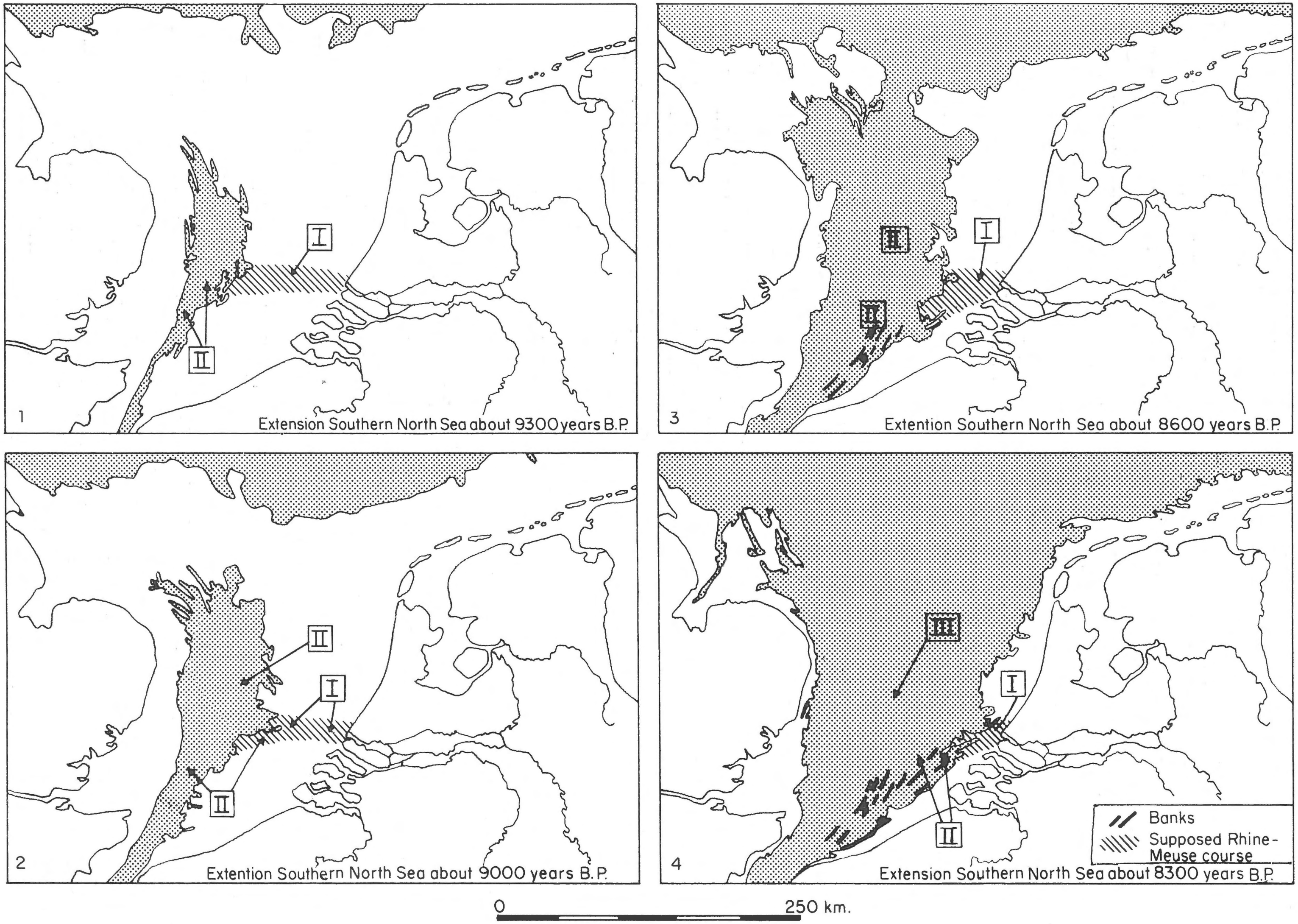

Fig. 14-A
Hypothetical maps, showing the extension of the southern North Sea during the different transgressive periods of the early Holocene.

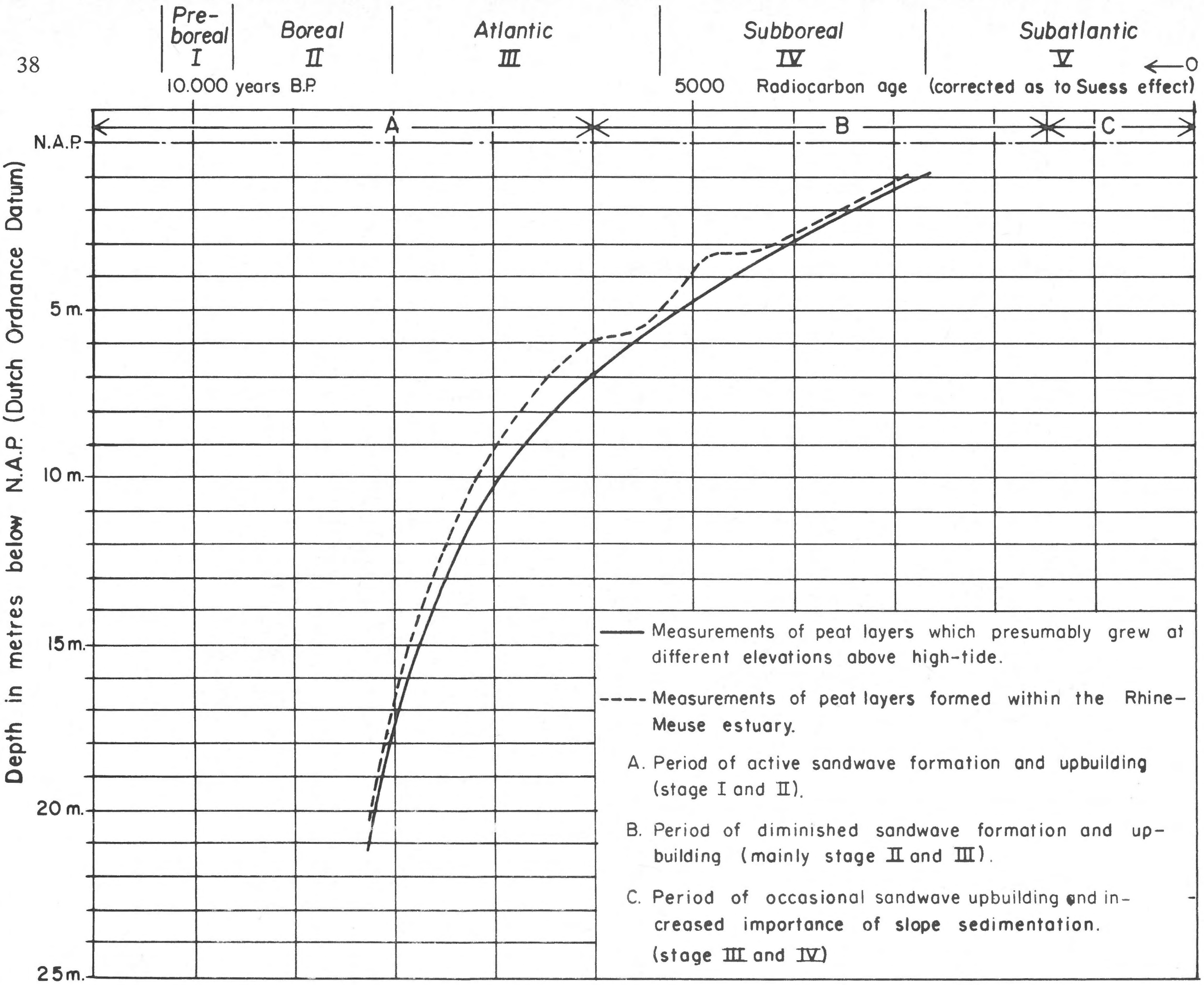

Fig. 14-B
Time-depth graph with curves of relative changes in sea-level and their relation to the different stages of sandwave formation during the Holocene of the North Sea basin.

conditions are such that processes which tend to modify the original sandwave morphology are dominant; slope facies sedimentation will occur. Under certain conditions (e.g. during heavy storms) substantial upbuilding of the sandwaves can still take place (comparable with the transitional period of stage III and IV in fig. 12). The existence of this delicate balance of erosional and accretional processes may explain the preserved asymmetry of certain sandwaves.

5. Occurrence of sandwave fields seems to be localized by the topography of the basin (Caston & Stride, 1973).

One of the consequences of the previous discussion, is that part of the sandwaves should belong to the Boreal or even pre-Boreal stage; others, the more northern sandwaves, however, should be younger. Another aspect of these North Sea sandwaves, which still needs further investigation, is the nature of the underlying sediments (such as for instance the genesis of the Flemish Banks).

A well accepted and more detailed model of sandwave formation for the sandwaves in the North Sea basin must await further data.

CONCLUSIONS

1. Studies of ancient sandwave complexes show that their occurrence is in relation with marine transgressions in association with strong tidal currents. Another pre-requisite for the formation of ancient sandwaves seems the configuration of the basin topography during the initial stage of the transgression and also a sufficient sediment supply.

2. The Lower Tertiary sandwave complex within the southern Pyrenean basin is an example where sandwaves were

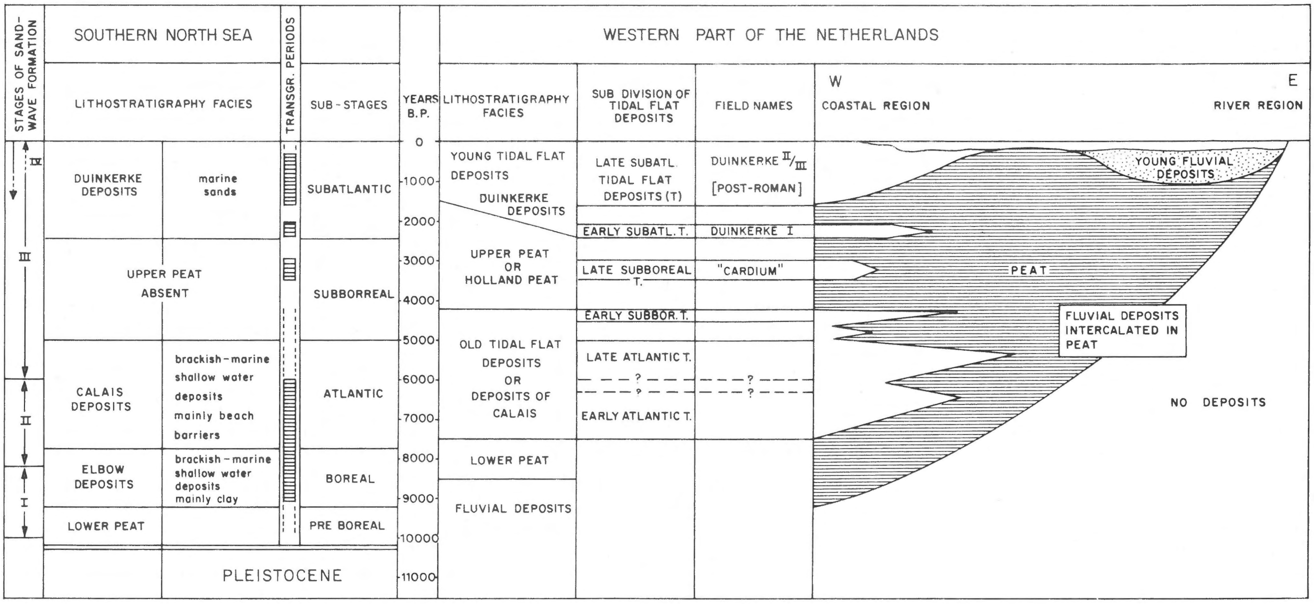

Fig. 15
Schematical section through the Holocene of the western part of the Netherlands and a stratigraphical scheme of the southern North Sea.

formed within a tectonically unstable basin. Local subsidence of the basin floor caused local marine transgressions to which the formation of several sandwave intervals are related.

3. The formation of the Lower Greensand sandwave complex is related to the world-wide mid-Cretaceous transgression, the first major pulse of which was during Aptian-Albian. Its position within the basin seems to be localized by the trough-like topography of the basin.

4. The Miocene sandwave complex of the Swiss Molasse is situated within a narrow, elongated and tectonically unstable basin; the sandwave facies is formed during the Burdigalian transgression.

5. The organization of the sedimentary structures seems to indicate the presence of strong fluctuating current conditions, which are obviously produced by strong tidal currents.

6. The vertical and lateral sequential order of ancient sandwave complexes shows a distinct organization. The lower part of the sequence is characterized by a vertical as well as a downcurrent lateral thickening (initial sandwave to sandwave facies), showing a lower aggrading sandwave sequence. This is followed by an overall thinning (sandwave to slope facies), showing an upper degrading sandwave sequence.

7. Measurements within the (initial)-sandwave facies show a narrow spread of current directions; measured current directions within the slope facies, however, show a much wider spread.

8. Preliminary studies of the modern sandwaves in the southern North Sea also suggest that sea-level rise related to the Holocene transgression was responsible for their formation. The present-day energy conditions are in general not high enough to induce large-scale migration and upbuilding of these sandwaves. More data are needed, however, to confirm this assumption.

9. Occurrences of sandwave complexes within regressive sequences are not discussed here. Such sandwave complexes, when they exist, should have another mechanism for their formation and will therefore not show the same sequential order as those related with marine transgressions.

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