Accumulation and Abrasion in a Tidal Area

Cartographical Methods and Results

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Abstract

A cartographical account of accumulation and abrasion in a Danish tidal area at the southwestern coast of Jutland. The maps are based on surveyings executed during 1941 and 1959–62 on the scale 1:10.000 and give a quantitative explanation of the changes undergone. The examination method is described and the maps are analysed. Furthermore a description of a few changes in the same area within a shorter period.

Institutions

The Geographical Institute of the University of Copenhagen under the leadership of professor, dr. phil. *Niels Nielsen* has on behalf of *De Danske Vade- og Marskundersøgelser* (The Danish Wadden and Salt-Marsh Investigations) surveyed the tidal flats near the coast from the Danish-German border in the south to a point west of Ribe in the north on the scale 1:10 000, and furthermore carried out hydropraphical, sedimentological and ecological investigations in the Danish tidal areas. *De Danske Vade- og Marskundersøgelser* continues a research work of long standing, institutet by *Niels Nielsen* at *Skalling-Laboratoriet* (Skallingen being the peninsula north west of Esbjerg, fig. 1) in the early thirties. These investigations served to a great extent practical purposes, first of all with a view to the utilization of the salt-marsh, landreclamation and protection of already reclaimed areas.

Previous Investigations

In the research work on the tidal flats one of the problems has been to examine the material drift and its consequences, as the understanding of this is essential for the planning of possible landreclamation plants in the area. As a part of a bigger investigation in 1938 the contents of sediment in the water of Grådyb (the tidal inlet west of Esbjerg, fig. 1) was measured. A result of this investigation was a stating of a considerable loss of sediment — anyway at this place—as the measurings showed that the amount of water and sediment at outflowing water passed the corresponding amounts at inflowing water *(H. Gry* 1942). The consequences of the results of this investigation have later been discussed by *B. Jakobsen* (1961). Furthermore, through his own investigations the lastmentioned author has proved that the surplus of outflowing water (and sediment) was due to the fact that the investigation in 1938 was made in the channels of the outflowing water (ebb-channels, *J. van Veen* 1950) as these usually coincide with the deepest part of the tidal channels. Later *B. Jakobsen* (1962) demonstrates through measurings in the channels of the outflowing and the inflowing water (flood-channels) that there must be a loss of sediment in the Wadden Sea during quiet weather conditions. During the heavy western storm in connection with the inflowing water a surplus of sediment is carried toward east. So on a long view there is a surplus of sediment supply to the Wadden Sea from the North Sea. — Thus it is also demonstrated that many important processes mainly take place during extreme weather conditions, for which reason it is by no means permissable to confine the measurings to more quiet and consequently convinient weathers.

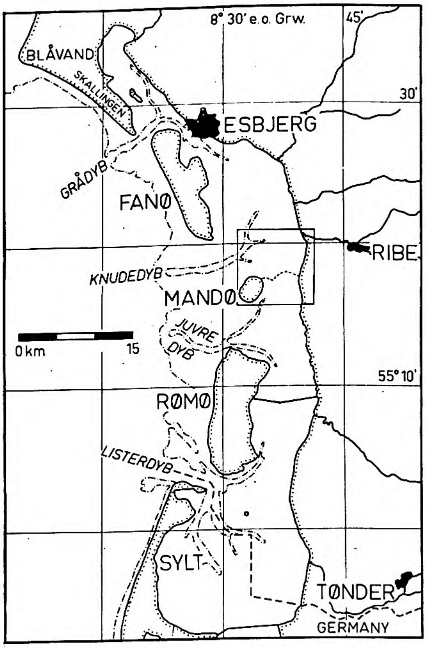

Fig. 1. The southwestern Jutland with the Danish part of the Wadden Sea. The depths are shown by the ÷ 4 m contour line (DNN = Danish Ordnance Datum). The framed area west of Ribe is the limits of fig. 2. Dyb = a great tidal channel. Ø = island.

Fig. 1. Det sydvestlige Jylland med den danske del af Vadehavet. Dybdeforholdene er angivet ved ÷ 4 m kurven (DNN, Dansk Normal Nul). Det indrammede område vest for Ribe er begrænsningen af fig. 2.

Previous investigations of the material drift have as a rule as object had the changes along some cross-sections — remeasured at intervals. That means that the measurings have been limited to a certain vertical section. *A. Sundborg* (1957) and *L. Arnborg* (1958)

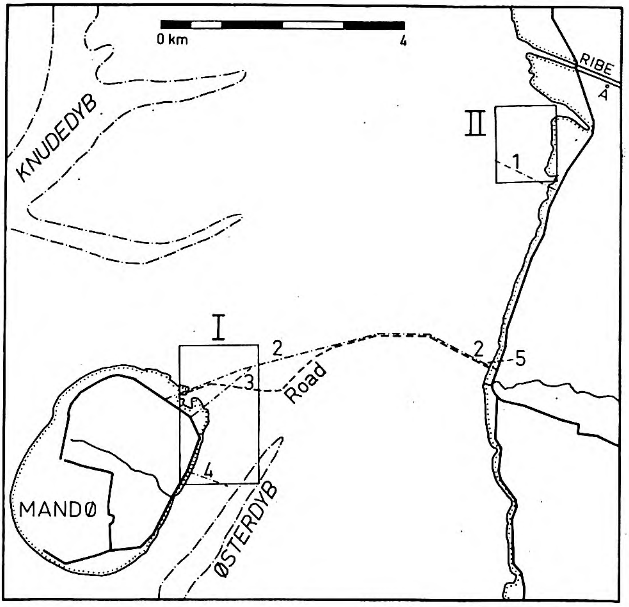

Fig. 2. The Wadden Sea between the western coast of Jutland south of the outlet of Ribe Å and Mandø. The depth contours indicate the ÷ 4 m DNN. The indentation in the coast south of the outlet of Ribe Å is the old outlet of this. The present route of the ebb-road to Mandø is indicated by the fat, dotted line. The sea-dikes are marked by fat full-drawn lines. The framed areas I and II show the limits for pl. I and II, respectively, whereas the numbered lines indicate the situation of the profiles 1—5. The length of the last one is in the figure greatly exaggerated, however, as it is only 50 m long. Å = river. Østerdyb = the eastern tidal channel.

Fig. 2. Vadehavet mellem vestkysten af Jylland syd for mundingen af Ribe Å og Mandø. Dybdekurverne angiver ÷ 4 m DNN. Indskæringen i kysten syd for mundingen af Ribe Å er dennes gamle udløb. Den nuværende rute for ebbevejen til Mandø er vist med fed, punkteret linie. Havdigerne er markeret med fede, fuldt optrukne linier. De indrammede områder I og II viser begrænsningerne for henholdsvis pl. I og II, mens de nummererede linier viser beliggenheden af profilerne 1—5. Længden af den sidste er dog stærkt overdrevet på figuren, idet profilet kun er 50 m langt.

have in their papers about Swedish rivers worked on similar problems. The latter has a.i. outlined the Ångermanälv's (älv = river) erosion and accumulation by cross-sections of the river-bed. For a separate river section the nett erosion and -accumulation over 0,5 m is shown by signatures of area. *A. Sundborg* has in a similar map of a part of the Klarälv distinguished between three different values of abrasion and accumulation, relatively, indicated by black/white signatures. However, these are very difficult to distinguish on account of the growing intensity above and below the zero. Maps of a similar type for inside use were in certain cases executed for the landreclamation works along the Rømø Dam facilitating the projecting of soil-movements (*H. A. Olsen*, personal information).

Measurings of the quantities of sedimentation in a tidal area were one of the first problems solved by the *Skalling-Laboratorium* through experiments with laying out of red-coloured sand (*Niels Nielsen* 1935 and 1941). These early experiments are actually still going on as the red sand in the old sample-areas is still to be recognized. This pioneer work has later been followed up by *B. Jakobsen* (1953) who in an examination of the development of the morphology and vegetation of Skallingen has shown a sedimentation of nearly 2 mm per year. At other places is found a considerable bigger sedimentation. On the southern side of the Rømø Dam f. i. measurings through a number of years have shown a sedimentation of 25 mm a year (*H. A. Olsen* 1959).

As previously mentioned there exists a considerable collection of large scaled maps — surveyed since 1954 — of the tidal flats near the south western coast of Jutland. As there also exist some maps of the Wadden Sea from a big investigation in 1941 (executed by the *Skalling-Laboratorium)*, when selected tidal areas were measured on the scale 1:10 000, the maps mentioned above have been tried utilized in a cartographical description of the development of the wadden surface during the period 1941—1959/62. The following discussion is about two maps of the changes in the tidal flats within the areas I and II in fig. 2 with an account of the measuring methods, an interpretation of the results of the measurings and an examination of similar changes during a short term of years — the last mentioned, however, only illustrated by profiles.

The Landscape

Since 1958 a research work has been concentrated in the Wadden Sea between the western coast of Jutland southeast of Ribe and the small island of Mandø (fig. 1 and 2). While the traffic to Fanø is accomplished by ferryboat and to Rømø along a dam, it is only possible ot reach Mandø by driving on the sea floor, where the traffic period is limited to two hours at the most before and after the low water stage. During storms and ice periods, the island can be isolated more days on end. Fanø and Rømø have steadily increasing importance as seaside resorts, whereas the agriculture is negligible. Mandø on the contrary consists practically solely of arable areas and the inhabitants are to a higher degree than on the neighbouring islands still living as farmers. In order to give Mandø better possibilities for transport of agricultural products and on the whole procure the island a safer communication with the surrounding world, proposals of a dam from Mandø to Jutland have been made. The research work mentioned here has, therefore, mainly been directed at problems like deciding the optimum situation of a dam, examine the effects a dam may have on the surroundings, procure informations about the sedimental contents of the water in the area, and furthermore to outline the morphological development during recent years, and possibly to suggest the lines in the future development as influenced by a dam.

The primitive ebb-road to Mandø follows to a certain degree the water shed between the two tidal areas drained through the tidal outlets Knudedyb and Juvre Dyb (dyb = tidal outlet), respectively. The eastern part the ebb-road cuts off an area south of the water shed in order to make the length of the road as short as possible. The surroundings of the ebb-road are in a belt of nearly 1 km surveyed on the scale 1:10 000, as it is the case with the tidal areas near the coast (*J. T. Møller* 1960 and 1963). The tidal area lying north of the ebb-road, but south of the water shed is part of an old navigable channel, before the middle of the 17th century leading to the town of Ribe from the northern branch of Juvre Dyb, Østerdyb (fig. 2). In the lowest part of this channel lies the ebb-road about 1 m below average high-water level (+0.9 m DNN, Danish Normal Nul = Danish Ordnance Datum). Longer westwards the ebb-road passes a big tidal flat, 0.5 m below average high-water level. Then one more tidal channel is crossed before the road arrives at the high-lying tidal flat stretching north eastwards from Mandø. This tidal flat, which near the island gradually passes into the steadily increasing salt-marsh foreland outside the sea-dike, lies 0.0—0.4 m below average high-water level. This north eastern foreland has since the late thirties been subject to careful supervision, as the dike at this place was constructed on the uncovered tidal flat below the high-water level. The natural accretion of land proceeded, however, very quickly and in 1941 the area (fig. 2, I and fig. 3) as mentioned was measured on the scale 1:10 000. This map is incorporated in pl. I.

A corresponding map from 1941 of the area south of the outlet of Ribe Å (Å = river) (fig. 2, II) includes an area which has been tried reclaimed by means of fascine fences. In the same way as is the case at the north eastern corner of Mandø considerable interests have been attached to the coast around the outlet of Ribe Å. The

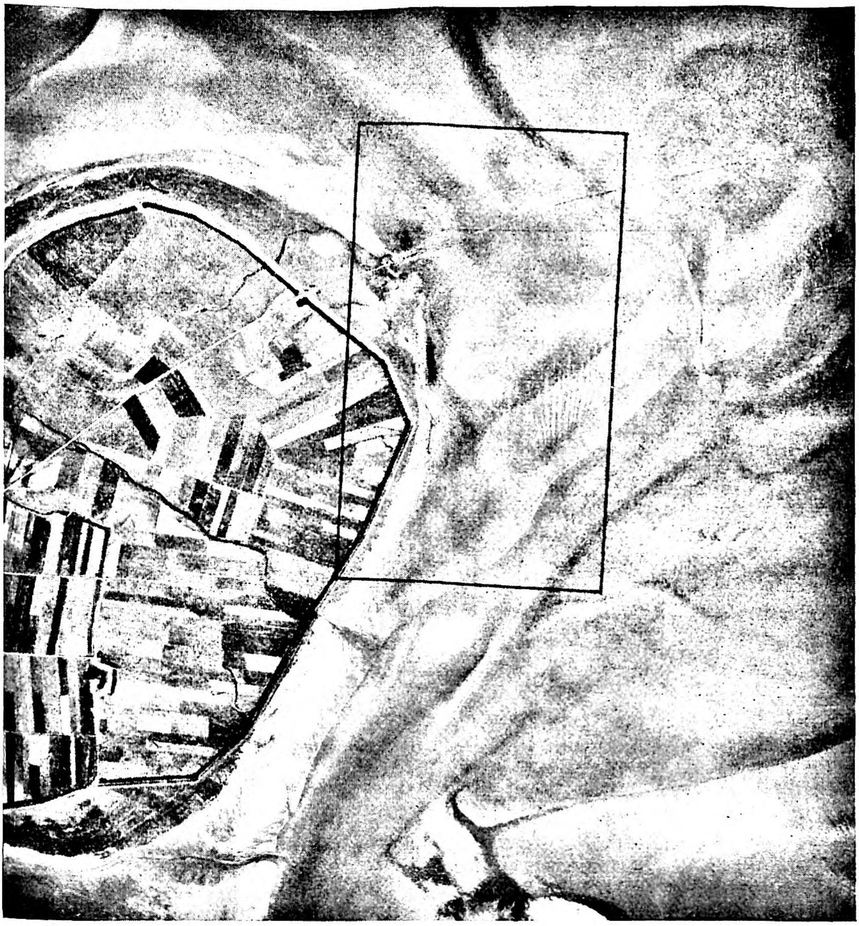

Fig. 3. Vertical aerial photo from 1954 of the Wadden Sea around Mandø. The frame indicates the limits of pl. I. Dikes and roads are light-coloured and the ebb-road is seen dimly as an elongation of the road across the island to the north. The photo is taken at low water and it is possible to get an impression of the size of Østerdyb and Thues Rende. The latter cuts the northern side of the frame. It must be noted that the ebb-road is not crossed by any sharp-cut channel. Royal Danish Airforce photo.

Fig. 3. Lodret luftfotografi af Vadehavet omkring Mandø optaget 1954. Rammen viser begrænsningen af pl. I. Diger og veje er lyse, og ebbevejen skimtes som forlængelsen af vejen tværs over øen mod nordøst. Billedet er taget ved lavvande, og det er muligt at få indtryk af størrelsen af Østerdyb og Thues Rende. Den sidstnævnte skærer nordkanten af rammen. Det bemærkes, at ebbevejen ikke skæres af nogen skarpt udformet rende. Luftvåbnet fot.

town of Ribe has old priviligies as a port and has as such been of great importance until about the beginning of the 17th century, when the navigation conditions grew so much worse that the harbour of the town now only is to be considered as a curiosity, even it still is maintained. This downward trend is due partly to the use of bigger ships, partly to a growing sedimentation. The old fairway to Ribe was, as previously mentioned, east of Mandø towards north to the outlet Ribe Å. The original outlet of this was situated a little longer south-wards than the present one (fig. 2). During the years 1855—56 a last serious attempt to save the harbour of Ribe was made, the river was dredged and canalized and got by these means the present course with an outlet some hundred metres longer to the north. The old riverbed was since then as a dead river branch up to 1911—15, when the now existing sea dike was built with a lock at the place where the dike cuts the canalized river. The old outlet of the river lies still in its full extent without any vegetation, although some sedimentation naturally has taken place during the 110 years passed since it was put out of action (fig. 5). This old river outlet has in connection with a deep off-shore channel (tidal creek between the old shoreline and the high-lying tidal flats outside), here stretching close to the shore towards the south from the present river outlet, caused the foreland to be threathened by erosion, aganist which the previously mentioned landreclamation is a countermeasure. Owing to the two said surveyings from 1941 it is now possible together with the surveyings of *De Danske Vade- og Marskundersøgelser* from 1958 to work out a map of the nett changes in the level of the wadden within the twice measured areas.

Basis for the Survey

The basis for the survey on the scale 1:10 000 is a system of lines (along which the levelling is executed) marked out perpendicular to a base line, normally placed nearly parallel to the coast line, aiming at having the network of levelling lines cutting the contour lines at nearly right angles. As the contours are normally rather uniform and lie more or less parallel to the coast line, it has been enough to place the lines of the network at intervals of 300 metres. At places where the topography has been more complicated the line distance has been diminished, and it is also supplemented with cross-lines where the contours have not been parallel to the coast line. The levelling is executed along the thus marked out lines with determination of levels for every 25 m. The network of levellings is marked in such a way that it will later be possible to be re-established and to repeat the levelling. As an example are shown the networks of levelling lines (1941 and 1959/62, fig. 4) lying within the frame I in fig. 2. All the here mentioned levellings are connected with the network of levellings executed by the *Danish Geodetic Institute* and thus based on the same reference level DNN = Danish Ordnance Datum. The mapping from 1941 has a similar system of levelling lines as a base (the dot-and-dash line in fig. 5), but this is displaced compared to later networks. Furthermore, the distances between the levelling lines were at that time only 200 metres, but then levels were only measured for every 100 metre.

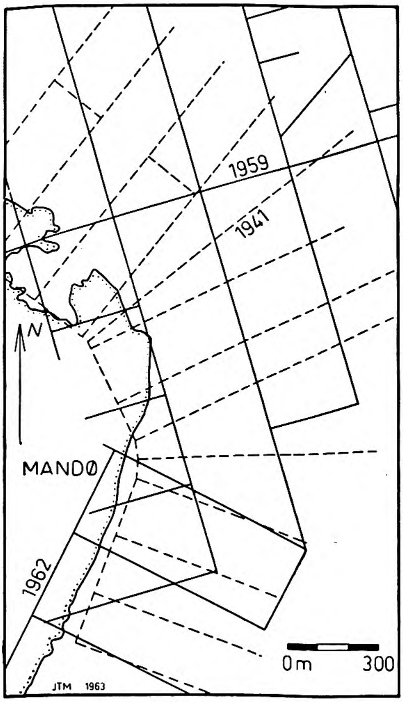

Fig. 4. The networks of levellings at Mandø. The networks from 1941 is the dotted line, the network from 1959/62 the full-drawn one. Of the network from the last mentioned year is only seen a part of the base line and three levelling lines perpendicular to this. Double profiles (fig. 6) are drawn along all levelling lines from 1941 and along the north/south going crosslines from 1959.

Fig. 4. Nivellementsnettene ved Mandø. Nettet fra 1941 er stiplet, nettet fra 1959/62 er fuldt optrukket. Af nettet fra det sidstnævnte år ses kun en del af basislinien og tre nivellementslinier vinkelret på denne. Dobbeltprofiler (ex. fig. 6) er tegnet langs alle nivellementslinier fra 1941 samt de nord/sydgående tværlinier fra 1959.

Method

By the construction of pl. I and II the method has been as follows: Profiles of the surface of the tidal flats have been drawn along every levelling line from 1941 with the levellings from 1941 and 1959/62. The reason why the profiles are placed along the lines from 1941 is primarily that the knowledge of the levels at that time solely exists in the measured levels along these lines. The contour map from 1959/62 has been executed on the spot viewing the landscape, and the maps were finished completely in the field to make sure that all information necessary for the mapping were at hand. For supplementing the profiles mentioned here, similar profiles have been drawn along all the crosslines in fig. 4 within the areas, from which it has been possible to procure information about the levels in both 1941 and 1959/62. The mapping executed during the last period is in this connection considered as one survey. The difference between the period of 18 and the period of 21 years is so small that the so resulting uncertainty hardly impair the method. This must of course be defective in more unverifiable ways, among other things the poor knowledge of the topography in 1941 outside the measured levels. Concerning these, now unknown places, it is necessary to rely on the surveyor's reaction at that time, were considerable deviations from the rest of the wadden level found. Examples on the practice followed in the sectional drawing are shown in fig. 6, in which the upper diagram comes from pl. II (line 1 in fig. 2 and 4), whereas the two lower profiles are from pl. I (line 3 and 4).

On account of the scale of the changes it has been necessary — and possible — in the investigations of the level changes in the Wadden Sea at Ribe and Mandø to divide the changes into small intervals. Thus the faintest yellow colour in pl. I and II indicates a nett accumulation of 5 cm, this interval being defined as an accumulation between 2,5 and 7,5 cm. Along the profiles the uncertainty of the size of the changes may be put to ± 1 cm. The area from + 2,5 cm to ÷ 2,5 cm is considered the O-area. This means the area within which the changes — positive or negative ones — must be considered smaller than what it is reasonable to attach importance to by this method. After having made similar profiles for all the levelling lines from 1941 and the cross lines, are lines of constant abrasion or accumulation united by contours. These isolines are interpolated lineary between the levelling lines, but these are only intersected by contours in the interval termini. In this way it has been possible to investigate the two localities; 46 hectares south of the outlet of Ribe Å (pl. II) and 169 hectares east of the easternmost part of Mandø (pl. I and fig. 2). Both maps have the last surveyed map of the level conditions incorporated (at Ribe from 1961, at Mandø from 1959 and 1962 for the northern and southern part, respectively), partly in consideration of the orientation, partly for diminishing the possibility of confusing the isolines of level change with the contour lines. Without contour lines pl. I and II will look just like a physical map. For similar reason crude colours normally not used for illustrating elevations have been chosen. All information about height conditions in pl. I and II are proportional to DNN.

The Material Drift at Mandø

It comes naturally to divide the map of the changes of the surface of the tidal flats at Mandø (pl. I) in a northern and a southern part, characterized by accumulation and abrasion, respectively. By comparence of the isolines of level change with the contour lines in this

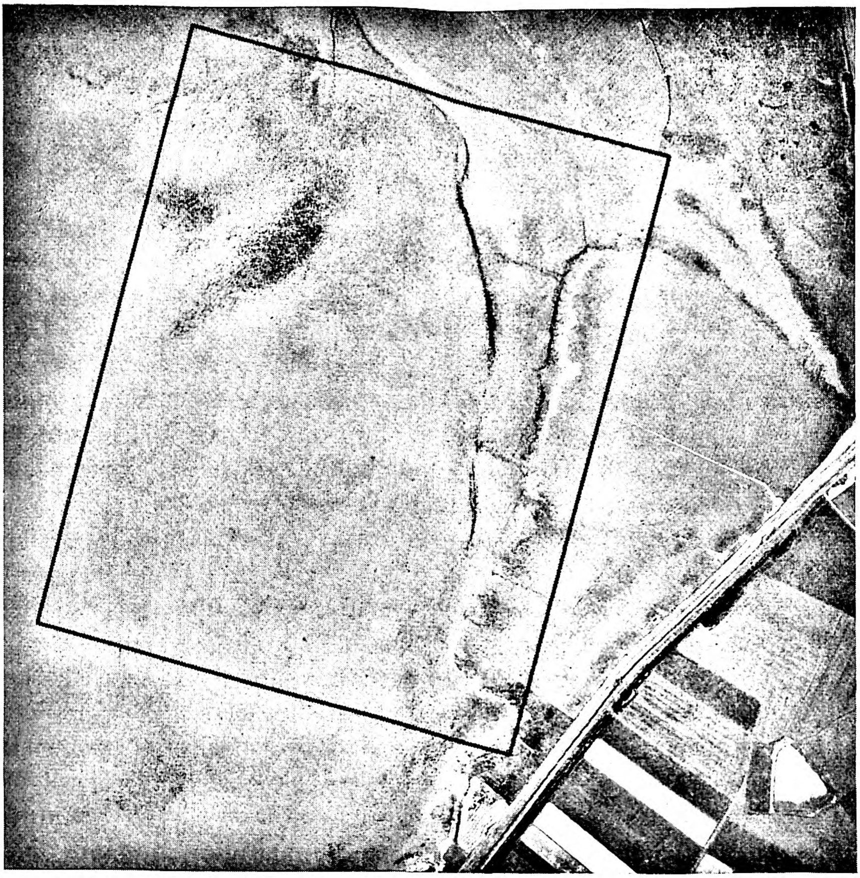

Fig. 5. Vertical aeriel photo from 1961 of the salt-marsh and tidal flats south of the old outlet of Ribe Å (seen uppermost to the right in the photo). The frame indicates the limits of pl. II. The off-shore channel is seen as a dark outline within the frame and cuts the northern side of this in the middle. The dark tone in the off-shore channel is due to the vegetation. Along the coast it is possible dimly to see three fascine fences perpendicular to the foreland. The sea-dike is seen eastwards on the photo as a light-toned outline limiting the cultivated fields. Danish Geodetic Institute phot.

Fig. 5. Lodret luftfotografi fra 1961 af marsk og vade syd for det gamle udløb af Ribe Å (ses øverst til højre i billedet). Rammen viser begrænsningen af pl. II. Landprielen ses som en mørk kontur inden for rammen og skærer midten af dennes nordlige kant. Den mørke tone i landprielen skyldes vegetation. Langs kysten er det muligt at skimte tre faskinlåninger vinkelret på forlandet. Havdiget ses mod øst i billedet som en lys kontur, der afgrænser de dyrkede marker. Geodætisk Institut fot.

map, a pattern stand out distinctly. If the isolines for accumulation or abrasion run parallel to the contour lines, it means that the change has resulted in an alteration of the topography of the tidal flat. If on the other hand the isolines run at right angles to the contour lines, it indicates an even change of the tidal flats, the previous relief of which must have been more or less in conformity with the present one. A general raising or lowering of the surface has occured. The development in the northwestern part of pl. I may consequently be explained in this way: Already in 1941 there was a belt of very high-lying tidal flats — all up to the average high-water level (+ 0.9 — + 1.0 m DNN) — along the northern part of Mandø. This zone of high-lying tidal flats has, in the time passed, grown in a zone around the 0.8 m contour. Within the same period all the wadden in the northern part of pl. I has been raised about 0.1 m. Only very near the shore in the north westernmost part of the examined area is seen some of a wadden, characterized by equilibrium. The hollow, especially standing out at the 0.7 m contour just south of the ebb-road, seems to be stable. North east of the extension of this hollow is an area, which has not been subject to changes. The ridges stretching from Mandø towards northeast show clearly both in the map from 1941 and in the latest map. There has been, then, a rather uniform accumulation all over this part of the area. Beside the mentioned extension of the very high tidal flat north of Mandø ebb-road, the areas in the northern part of pl. I are characterized by a uniform raising within the last 20 years.

In the southern part of pl. I (left of the arrowhead of the north point) a rather considerable abrasion has taken place. This can for that matter be stated within a shorter span of years, as the map of the eastcoast of Mandø partly overlaps the map of Mandø ebb-road. In the period 1959—62 the vegetation limit has moved just under 100 m shorewards. Furthermore, the inhabitants of Mandø have complained about an increased erosion on the eastcoast of the island, where the distance from the dike to the vegetation limit is still falling. The southern part of pl. I shows that besides a general abrasion, a stronger erosion has occured in a zone parallel to the contour lines, strongest in a distance of 200—300 m from the shore. The contour lines in the interval 0.1—0.2 m seem to move swifter westwards than the other contours. So there is a tendency for the tidal flats lying in a distance of 200—300 m from the shore to become more steep. Longer to the east the abrasion declines again, and just left of the arrowhead of the north point even an accumulation has taken place (fig. 6,4).

The map in the southern part of pl. I reveals that Østerdyb (the northern branch of Juvre Dyb, fig. 2) moves nearer the east coast of Mandø in the area where the big tidal channel bends, thus get-

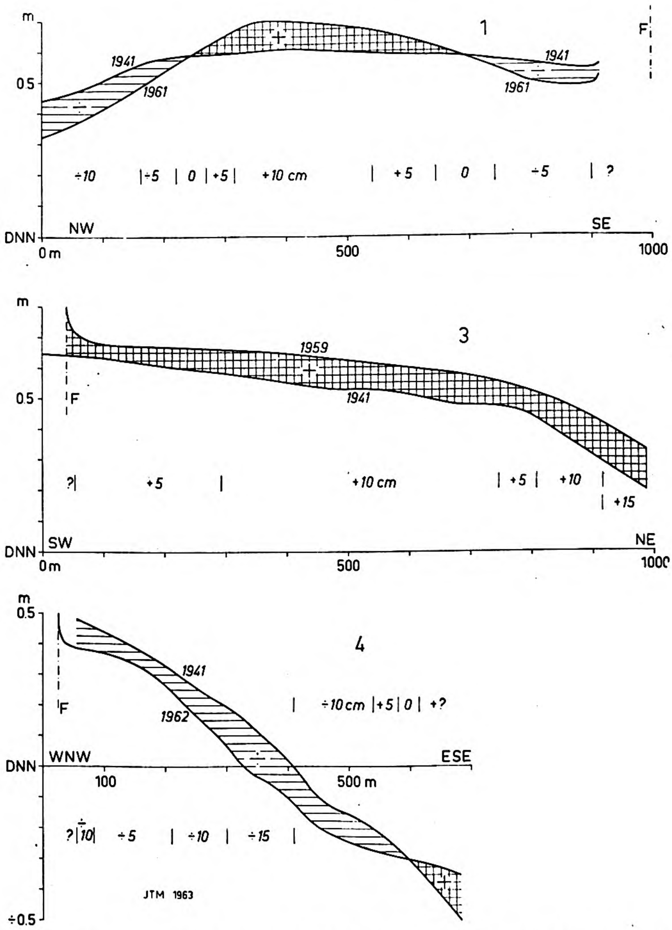

Fig. 6. Examples of double profiles. The numbers refer to the position of the profiles in fig. 2. No. 1 shows the accumulation flat with the more eastern lying off-shore channel in the southern part of pl. II. No. 3 is a profile from the accumulation area, and no. 4 a profile from the abrasion area within pl. I. The size in centimeter of the changes appears from the slanting figures between the vertical lines. ? means doubtful parts of the profiles. F: The situation of the vegetation border of the salt-marsh foreland.

Fig. 6. Eksempler på dobbeltprofiler. Numrene henviser til profilernes beliggenhed på fig. 2. No. 1 viser akkumulationsflakket med den østligere liggende landpriel i den sydlige del af pl. II. No. 3 er et profil fra akkumulationsområdet, og no. 4 et profil fra abrasionsområdet inden for pl. I. Forandringernes størrelse i centimeter fremgår af de skrå tal mellem de lodrette linier. ? står for tvivlsomme dele af profilerne. F: beliggenheden af forlandskanten.

ting a more south going direction. The investigated area involves only the most western border of Østerdyb, but it is revealed that the tidal flats of a certain level get steeper as a general lowering of all the area occur. It is this which explains the withdrawal of the vegetation limit towards Mandø. It seems to be characteristic of the development along a big tidal channel when this as a consequence of meandering comes closer to the shore, that not only is the coast threathened by the deep channel itself, but the tidal flats between this and the coast decline in height and get at the same time in a certain area steeper and consequently more vulnerable for erosion. The same development is seen at a big tidal channel on the east-coast of Rømø north of the dam (*B. Jakobsen* 1962). The abrasion in the southern part of pl. I declines towards north for changing to accumulation at the place, where the contour lines turn strongly away from the coast of Mandø. The accumulation area lying within the abrasion zone's northern part is difficult to explain. It will only be mentioned, that it is here a question about a filling of a deep hollow located here in 1941. As to the size of abrasion and accumulation within pl. I it can be said that the abrasion in the southern area (west of the arrowhead of the north point) amounts to 23.000 m^3, whereas the accumulation in the northern part of the map is 89.000 m^3, so that the gross transport within the examined area at least has been about 122.000 m^3 in the period 1941—1959/62.

The causes for the above mentioned development must be divided into two principal groups partly a material drift around the north west of Mandø primarily caused by waves, partly a predominating south eastern bound material drift in Østerdyb brought about by the strong ebb-current here.The high-lying tidal flats northeast of Mandø are to a great degree marked by a wave produced material drift from the section west-north during winds from western directions (*J. T. Møller* 1960). Close connected with Mandø proper, wide tidal flats are situated at the western, north western and north eastern coast of the island, though at certain places separated from this by an off-shore channel. Actually, relatively deep water near the shore is only found on the south eastern coast. Compared with the broad foreshores on the western coasts of Fanø and Rømø, the tidal flats of Mandø are low-lying and flooded by all high-tides, so the vegetation limit is the shoreline at high-tide. However, the tidal flats on the north and east coast of the island reach such a level that they during periods with eastern winds and low high-tide levels may remain dry for quite a long time. At such occasions sand drift leading to formation of small dunes may be observed here. The dunes will disappear immidiately at normal tide conditions. Only this northern part of Mandø may be compared to the wide western beaches of Fanø and Rømø.

The eastward material drift must be considered as a result of the interplay between tide- and wave currents. The sand drifts towards Mandø in the same way as is the case at Fanø and Rømø, and is deposited on the big tidal flats west of the island. Part of the material drift to the south or to the north — according to the wind direction — until reaching the tidal outlets of Juvre Dyb or Knudedyb, respectively, for there to be removed by the tidal currents. The amounts of sand, however, which come far enough into the north coast of Mandø take part in the formation of the big tidal flats here. It will furthermore during storms from west and north drift farther eastwards towards the tidal flats between Mandø and Jutland. So a constant accumulation will take place here, even if they apparantly lie sheltered by the island. The material drift from north west can also be observed in areas with tussocks of *Spartina townsendii* sheltering big sedimentation fans pointing away from the wind direction.

This material drift may naturally be strongly impeded by transversing channels with a water-bearing sufficient for removing the transported material. However, the only transversing channel is Thues Rende (rende = creek) (fig. 3 and 7). The water-bearing of this is so small that it is now without any of the importance earlier so considerable. Probably the process has been that the creek gradually has been filled with sand from the north western material drift. By this the water-bearing has been reduced which results in a further accelerated sedimentation, so the depth on the water shed now as mentioned only is 0.6—0.7 m at the average high water level. Actually it is only the northern part which is formed as a creek draining the surrounding tidal flats to Knudedyb. Only during storm periods big amounts of water may be driven beyond the water shed between Mandø and Jutland, as the tidal area at the lee-side of the water shed cannot be filled up at the same time as that on the windward side.

While the northern part of Mandø and the surrounding tidal flats are a long way from the big tide channels, it is quite different as to the south eastern part of the island. Here runs close to the coast the big channel Østerdyb (fig. 3), a remainder of the old channel from Ribe Å to Juvre Dyb, which must have been very important at a time, before Knudedyb was a great tidal outlet (*J. T. Møller* 1960). The tidal area of Juvre Dyb is the most regular of the Danish tidal areas. Nearly rectangular it stretches inside the outlet to the North Sea. In a rectangular basin like the tidal area of Juvre

Dyb the main tidal current's division into two branches pointing at the most distant corner of the basin will be equilibrium form (*A. Lundbak* 1941 and *J. T. Møller* 1956). The same applies to the angular tidal flats, the head of which lies directly east of the tidal outlet and which — even of very different appearances — may be refound east of all the big tidal outlets in the Wadden Sea (fig. 1).

In this way the great northern branch of Juvre Dyb, Østerdyb, lies as a very stable channel (stable as to existence, not to the exact position) very near the south eastern coast of Mandø. Like the southern part of the branches of Juvre Dyb the water-bearing is very considerable, because it must drain all the northern part of the tidal area of Juvre Dyb. There is, however, an essentiel difference in the character of the activity of the tidal currents of ebb and flood. In a basin, filled and draind through an outlet in one side, the velocity of flow decreases as the water runs into basin. The decreasing velocity causes the waters to diverge and move away from the channel. By outflowing water, however, the waters converge as a consequence of the increasing velocity and seek the shortest way to the channels (*S. Leliavsky* 1959). In the big tidal channels the ebb current will on account of its greater velocity and bigger water-bearing (*B. Jakobsen* 1962) have the biggest eroding capacity and thereby a dominating importance for the forming of the channel. Even if Østerdyb on account of the development has had a still smaller area to drain, its water-bearing is, however very big. It can only be reduced by a cutting-off of the tidal area by means of a dam between Mandø and Jutland. All water-bearing beyond the water shed will hereby practically finish, for even if the daily water-bearing now only is of a small dimension, it may during storm periods grow to a considerable size.

The short distance from the east side of Mandø to the big tidal channel of Østerdyb is a reason for the loss of material happening now on this coast, as also indicated by pl. I. The surveyed area, only embracing the nothern part of the abrasion area, as all the south eastern coast of Mandø is affected by the erosion, lies just outside a bend of the tidal channel, which here works its way towards west. Therefore, if the connection with the tidal area of Knudedyb is not closed and maybe also at the same time the drainage area of Østerdyb is tried reduced through land reclamation works, it must be expected that the erosion will continue, perhaps occur even at an increasing speed.

Material Drift at the Ribe Marsh

The area within pl. II south of the old outlet of Ribe Å (fig. 2 and 5) has quite another character than the area at Mandø. The conditions are rather particular on account of the situation at the old river outlet, so the map is characterized by the development of an extraordinary big off-shore channel. The size of the erosion, which according to pl. II has been the basis of the formation of the off-shore channel, must be made with certain reservations. This off-shore channel is after all so narrow that the possibility of its having existed in a more weekly developed form in 1941 between two levelled points and so being overlooked, cannot be precluded. Judging from aerial photographs from 1941 the said off-shore channel did exist, but was situated so far from the coast that it lay outside the investigated area seen in pl. II.

The development of the tidal flats within pl. II during the years 1941—61 is an example of the characteristic salt-marsh formation in its first stage (*B. Jakobsen* 1954). The wadden which in 1941 sloped gently outwards, has in some distance from the old marsh border grown steeper and higher. At the same time an off-shore channel has been formed as normally within the highest-lying part. The considerable depth of the off-shore channel is due to the special fact, that it draines a big tidal area south of the investigated area. Furthermore, it just here is quite near its outlet in another big off-shore channel draining the old outlet of Ribe Å (*J. T. Møller* 1963). The two small accumulation areas on both banks of the off-shore channel in the northern part of pl. II are — at any rate as to the most western one — due to the special conditions around an outlet of a current in a bigger basin. It corresponds to the tidal flats flanking the big tidal outlets between the islands Fanø, Mandø and Rømø. Similar formations are incidentally characteristic at passages in narrow waters and exist f. i. on both sides of the bridge crossing Roskilde Fjord at Zealand. The formation of the easternmost accumulation area may possibly be brought about by the presence of a fascine fence at this place. On the other hand, similar fences longer to the south have not been able to prevent the erosion of the off-shore channel. Because of the small scale of the map it has not been possible to make allowance for the conditions just close to the fences, where, anyhow, an accumulation has taken place.

The nett material drift within the investigated area on pl. II is as to the accumulation areas about 10.000 m³. Neither here nor from the investigated area at Mandø has it been possible to procure information about the total material drift. It is only possible to measure what has been the results of the processes through 20 years. However, it cannot be said if it is a question about a uniform development, or if this has taken place intermittently as a result of extreme wind- and water level situation. Neither is anything known whether it is the material from the abrasion areas which has moved to the accumulation areas, or if the processes have been completely independently. At Mandø, as mentioned, it must actually be two different developments. The same goes for the Ribe area probably. Here occurs partly an eastern bound material drift in the form of off-shore bars in the southern part of the area, partly a strong development of an off-shore channel to the north. The latter is due to the special drainage conditions around the old outlet of Ribe Å in connection with the drainage by the off-shore channel of a big area south of pl. II. The consequence of this is that it would be absurd to work out any average numbers of the size of abrasion and accumulation.

The Tidal-flats between Mandø and Jutland

Besides the physical maps from 1941 a line along Mandø ebb-road was levelled by the Danish Geodetic Institute. The levelling was executed just north of the situation of the ebb-road track before 1960 (profile 2, fig. 7), when the route as to its western part was placed somewhat to the south enabling it better to follow the water shed at Thues Rende. Levelling along this road has to be executed in a distance from the road, outside the wadden zone affected by the traffic. The eastern part of the ebb-road lies as a low ridge across the wadden on account of road material supplies. On both sides of this ridge are at more places formed small creeks, because the natural outlet at falling water from the area between the water shed and the road, is barred by the road. The western part of the ebb-road lies on the naked sand flat and is here dug somewhat below the level of the surroundings, because the sand is stirred up by the traffic and washed away by the water left as puddles on the road at falling water (*J. T. Møller* 1960). A comparence between the levellings from 1941 and 1958/59 (the ebb-road area was surveyed during two summer periods) will consequently imply some possibility of errors as the estimation of the distance from the road in which the wadden is affected by the traffic has not been

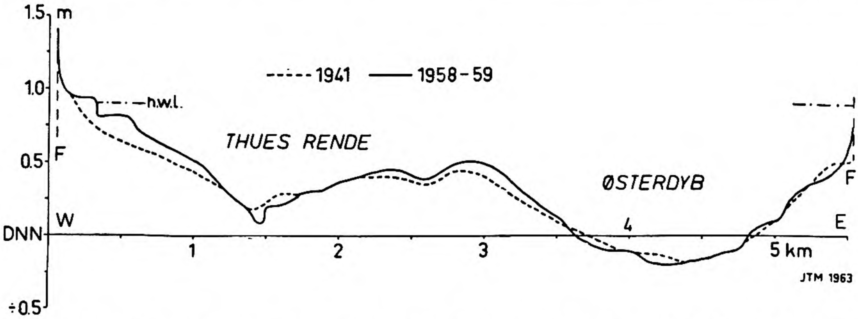

Fig. 7. Profile 2 (fig. 2) of the tidal flats between Mandø and Jutland along the former route of the ebb-road (before 1960). The average low water level is about ÷ 1 m DNN. F: The vegetation border of the salt-marsh foreland. Rende = a small tidal channel.

Fig. 7. Profil 2 (fig. 2) af vaden mellem Mandø og Jylland langs den tidlige rute for ebbevejen (før 1960). Dagligt lavvande er ved ca. ÷ 1 m DNN. F: forlandskant.

the same at the two levellings. The situation of the road itself has not been changed during the period in question.

Assuming that the levellings in 1941 and 1958/59 have been executed along the same line (according to the descriptions 1941 the two lines are identical), the development seems in the main during the 17—18 years to be that the relief has been sharper formed, as there is a tendency for the channels to grow deeper and the tidal flats to grow higher. It is, however, only the tidal flat north east of Mandø and the tidal flat between Thues Rende and Østerdyb which have had so big an accumulation that importance may be attached to it. Where Østerdyb cuts the ebb-road, the lowest part of this is only lowered very little. The deepening of the channel in the middle of Thues Rende has occured within a very narrow area. Such a deepning of a tidal channel may be made during a very short time in ice periods. Even rather thin ice-sheets can be pushed together in big heaps by the tide. If this happens in a tidal channel, the effective width of this is restricted, whereupon the current must cut downwards. The deepening of Thues Rende may only be due to the ice situation during the winter 1958/59, which without being especially severe brought frequent formations of rather thin ice-sheets in Wadden Sea in its train. The accumulation on the tidal flat northeast of Mandø is, as already mentioned, caused by the supply of sand from west. Part of the material is removed by the current in Thues Rende, but a big amount passes this channel and accumulates on the tidal flats east of Thues Rende. It is to be expected that the accumulation here will continue as the Thues Rende gets more and more silted. The continued accumulation has among other things resulted in the development of the vegetation in the area, where tussocks of *Spartina townsendii* now are found all over the high-lying tidal flats between Mandø and Jutland.

It must be considered out of the question that the here mentioned accumulation on the tidal flats between Mandø and Jutland should result in the formation of a stable connection between Mandø and Jutland. During storm periods considerable water amounts are — as mentioned — exchanged between the tidal areas of Juvre Dyb and Knudedyb. As long as there by aid of a dam is not established a very stable water shed between the two tidal areas, there will always be a possibility of formation of new tidal channels or deepening of the existing ones, not least during the rare, but violent catastrophic situations which can arise here. Fig. 7, shows furthermore clearly that the accumulation which has taken place in the area between Mandø and Jutland, in no way has improved the prospects for the traffic on the tidal flats, because channels necessary to pass are found both at the eastern and the western end of the route of the ebb-road, and in these channels no accumulation seems to take place. Furthermore, it can be said that the two channels were surveyed already in the end of the 17th century (*J. Knudsen* 1918) and that their situation then were almost the same as now. They are both still marked as fairways and as such incorporated in the chart, even if it is naturally only a question about traffic with small vessels as the maximum depth (in Thues Rende) only is 0,6 m at average high water. The bottom of the creek is, however, dry nearly 6 hours daily.

Accumulation and Abrasion within a Shorter Time

In a tidal area where the relief on account of the very moderate differences in levels may be very difficult to recognize, a tendency to overestimate level changes is common whether the question is about accumulation or abrasion. This will especially be the case if, at the same time the vegetation's distribution alters in connection with the changes of the heigth conditions. For instance, in that moment a previous naked tidal flat has been covered by vegetation, an impression of a considerable accumulation will be received, not least because it is this alteration which presents the greatest interest. The places giving impression of much accumulation have by control levellings often shown insignificant differences only from the first survey. The divergences are usually so small that no importance

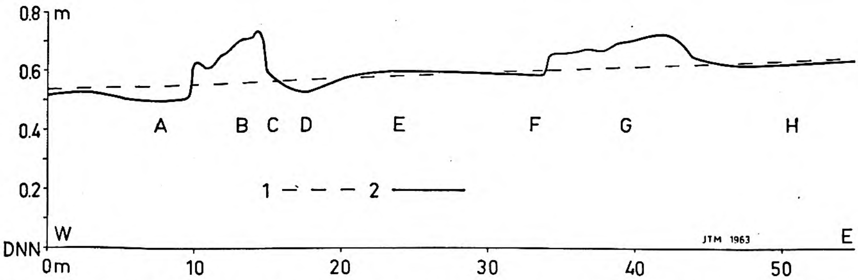

Fig. 8. Profile 5 (fig. 2) shows the development of a tidal flat directly in front of a west-facing salt-marsh under erosion, which has been tried stopped by the planting of Spartina townsendii. 1: The tidal flat 1959; 2. The tidal flat 1962; A, D, F and H: Puddles or channels behind off-shore bars with water unable to run westwards at ebb-tide; correspond in principle to the off-shore channel. B, E and G are bars, of which B and G have grown especially high as a result of a vegetation of Spartina townsendii. At C and half-way between G and H are sedimentation fans due to the shelter of the Spartina townsendii vegetation. As the scales for height and length are as 20:1, all slopes look very steep. The lee-depositions have in reality a slope of 2—5 ‰. Directly east of the profile is the erosion border of the salt-marsh foreland. The marsh surface is here more than 2 m above DNN.

Fig. 8. Profil 5 (fig. 2) viser udviklingen af en vade umiddelbart foran en vestvendt marsk under nedbrydning, som er søgt standset ved udplantning af Spartina townsendii. 1: vaden 1959; 2: vaden 1962. A, D, F og H: pytter eller render bag revledannelserne med vand, som ikke kan strømme mod vest ved faldende vande; modsvarer i princippet landprielen. B, E og G er revler, hvoraf B og G er blevet særligt høje som følge af en vegetation af Spartina townsendii. Ved C og midt mellem G og H ligger aflejringsfaner i læ af Spartina townsendii vegetationen. Da højde- og længdemålestok forholder sig som 20:1 er alle skråninger blevet meget stejle. Læaflejringerne har i virkeligheden et fald på 2—5 ‰. Umiddelbart øst for profilet ligger marskforlandets erosionskant. Marskens overflade ligger her mere end 2 m over DNN.

can be attached to them. As it is the extreme wind- and water level situation as already said, which in the Wadden Sea determines the big changes, and as in any case an even development during longer measuring periods cannot be anticipated as a matter of course, it will just be of great interest to be able to keep certain sample areas under steady control. Such a sample field is chosen just north of the place where the ebb-road to Mandø joins the western coast of Jutland. The area was first measured during the summer 1958 and again in 1962 along the same levelling lines, of which a single one is chosen as an example (profile 5, fig. 2 and 8).

The Wadden Sea coast directly north of the place where the ebb-road joins the western coast of Jutland, was in 1958 a typical abrasion coast, where the salt-marsh foreland was under strong disintegration and rearward movement. At some places the erosion edge lay far into the lowest part of the sea-dike (*J. T. Møller* 1960). Without taking further steps for coast protection the company of dike owners had *Spartina townsendii* planted in this section of the coast, hoping that this plant would spread and thereby stem the erosion. Until that time the qualities of *Spartina townsendii* as a landreclamation plant on a coast as exposed as this, were not found good. During recent years the plant's way of growing and its ability to endure harder conditions than before seem to have altered, possibly because the question in reality is about 2 species, of which the most tough now has spread at the expense of the other one. At any rate *Spartina townsendii* has now spread to coasts strongly exposed to wind, and it accumulates considerable amounts of fine sand. The average grain size of the sediment in the Spartina vegetation being 0,07 mm (*J. T. Møller* 1963).

From 1960 the planted specimen of *Spartina townsendii* began to spread strongly in area in question. Furthermore, it was quite obvious that this vegetation was capable of accumulating material so the wadden surface was raised. In order to obtain information about the size of the accumulation, control levellings were executed during the summer 1962 at places where the accumulation quite subjectively must be characterized as very considerable. In profile 5, fig. 8, the dotted line indicates the wadden 1958, whereas the fulldrawn line is the surface 1962. It must be said that the vertical scale is very big compared to the horizontal scale (20:1) for making the height differences stand out at all, even if this involves that the gradients is greatly exaggerated. Therefore, the profile gives an impression of very steep slopes where it is a question about gently sloping surfaces.

Profile 5 gives a good impression of the development of the tidal flats by a steady formation of sand bars moving towards the coast. The salt-marsh foreland may in many respects be compared to other coasts with bar formations, only are bars which form part of a salt-marsh formation quite flat and low (*B. Jakobsen* 1954 and *J. T. Møller* 1961). In fig. 8 are seen three bars: B, E and G, of which the first and the last are grown with *Spartina townsendii* causing a further increase of the accumulation. Along the investigated levelling lines the accumulation within the *Spartina townsendii* vegetation has been 10—20 cm above the surroundings. An accumulation of this size in an area already lying rather high (less than 0,5 m below the average high water level) will imply so greatly altered biological conditions that other plants can immigrate. It might here especially be *Puccinellia maritima*, the dominating grass in the salt-marsh areas outside the dikes. In this part of the

Wadden Sea *Puccinellia maritima* will normally start immigrating a tidal flat, when the surface lies at a height of 0,6 m DNN, that means 0,2—0,3 m below the average high water level (*B. Jakobsen* and *K. M. Jensen* 1956). Migration-bars together with a vegetation of *Spartina townsendii* and later an immigration of *Puccinellia maritima* may in this result in a regular land development. In the case mentioned here only a rather narrow zone has been raised by sedimentation, but it has been broad enough for stopping the great erosion of the coast, and the border of the salt-marsh foreland has again moved somewhat to the west.

The insignificant width of the zone shows already clearly in fig. 8, where the here mentioned processes actually only have taken place in a zone about 20 m broad, because the westernmost Spartina tussock (B) is too small and isolated for really being able to participate in the process. It does not appear from fig. 8 that all three bars have large north-southwards extension, but the Spartina vegetation on the outermost one covers only a single tussock. The profile shows, however, that no evenly spread accumulation has taken place, but that an abrasion has occured at more places. All the hollows A, D, F and H correspond to the formation of off-shore channels, that means that they carry away the water entered behind the bar. Considering all this collectively, a nett accumulation has taken place, and the material for this has as to the sand come from west in the form of bars, until these have reached a level enabling the vegetation to immigrate. Along the levelling lines at the western coast of Jutland it has been possible to decide the period of some of the processes. In the here mentioned case 2 years have passed (the development of the vegetation started 1960), but even within these 2 years it is possible that the development has happened during shorter periods. It will be difficult to shorten the periods furthermore as so many elements are important for the processes. One of the conditions is f. i. the occurence of a favourable situation as to the seed setting and the germinating conditions for *Spartina townsendii,* as this plant is extremely exacting in that respect (*J. T. Møller* 1963).

RESUME

To områder i Vadehavet vest for Ribe (fig. 1 og 2) opmåltes i 1:10 000 både i 1941 og 1959–62 (*J. T. Møller* 1960–63). På grundlag af disse kort er der langs nivellementslinierne fra 1941 tegnet tværsnit af vadens overflade 1941 og 1959–62, og den lodrette afvigelse mellem de to pro-

filer er udmålt i følgende intervaller: + 15, + 10, + 5, 0, ÷ 5, ÷ 10 og ÷ 15 cm. Nivellementslinierne er indtegnet på et topografisk kort med angivelse af intervalendepunkternes beliggenhed, og disse er indbyrdes forbundet med kurver, som derfor begrænser områder med samme tab eller tilvækst. Den undersøgte vade ved Mandø (pl. I) kan deles i et tabs- og et tilvækstområde. Det førstnævnte, ud for sydøstkysten af Mandø, skyldes en vestgående vandring af Østerdyb, Juvre Dybs nordlige forgrening. Hovedtrækkene i udviklingen er, at vaden her bliver lavere og mere stejl, hvorved kysten trues af en stadig voksende nedbrydning. Kun en effektiv lukning af forbindelsen mellem Knudebys og Juvre Dybs tidevandsområder samtidig med landvinding på den udsatte kyst vil kunne forventes at standse denne udvikling.

Tilvæksten i den nordlige del af pl. I skyldes en, for størstedelens vedkommende vindfremkaldt materialvandring fra vest og nord om Mandø, især i stormperioder. Denne materialvandring kan spores i hele området mellem Mandø og Jylland, men foregår i større omfang kun på flakkene nordøst for Mandø og midtvejs mellem Mandø og Jylland (fig. 7). Denne materialvandring formår ikke at lukke effektivt for forbindelsen mellem de to tidevandsområder, fordi tilsandingen i renderne er meget ringe. Færdslen foregår ved lavvande ad en ebbevej over vaden. Betingelserne for trafiken er forværret i de senere år, ikke mindst på grund af det øgede antal hurtige køretøjer, der passerer vaden.

Syd for mundingen af Ribe Å (fig. 2 og pl. II) er vaden blevet stejlere og højere samtidig med, at der bag ved den herved fremkomne tilvækstrevle er blevet dannet en landpriel. Den kraftige udformning af denne skyldes dog tillige, at den skal afvande et stort område syd for pl. II. I den nordlige del af kortet udmunder landprielen i en større priel, der afvander det gamle udløb af Ribe Å, som har ligget hen som en død flodarm siden 1856 og været lukket af havdiget siden 1911–15. De to tilvækstområder i den nordlige del af pl. II svarer til de flak, som vest for vadehavsøerne flankerer de store dyb. Landprielen eksisterede ved opmåling 1941, men lå så langt mod vest, at den ikke var inden for rammen af pl. II.

De to kort giver kun oplysninger om nettoændringerne i løbet af de cirka 20 år. Der kan på grundlag af dem intet siges om, hvorvidt forandringerne er sket gradvis eller i ryk. Heller ikke vides der noget om, hvorvidt der er tale om de samlede ændringer, eller om disse har været langt større og derefter senere delvist ophævet gennem ændringer med modsat fortegn. Inden for pl. I beløber nettotabet i den sydligste del sig til ca. 20 tus. m^3, mens nettotilvæksten i den nordlige del har været ca. 90 tus. m^3. De tilsvarende tal inden for pl. II er henholdsvis ca. 30 og 10 tus. m^3. Fig. 8 viser to profiler målt henholdsvis 1958 og 1962 som led i en række forsøg på nærmere at undersøge tidsrum og omfang af vadeændringerne. I det pågældende område ved ebbevejens tilslutning til den jyske vestkyst (fig. 2) har tilvæksten i en vegetation af *Spartina townsendii* været 10–20 cm i løbet af 2 år, idet planten først begyndte virkelig at brede sig efter 1960. Figuren giver iøvrigt et eksempel på vadehavskystens opbygning gennem lave, flade indvandingsrevler som det første grundlag for marskdannelsen. Deres overflade er her blevet stærkt hævet på grund af *Spartina townsendii* vegetationen, i hvilken tilvæksten har været så betydelig, at vadeoverfladen er hævet til et sådant niveau, at for eksempel *Puccinellia maritima* kan indvandre og en egentlig marskdannelse begynde.

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