CHAPTER 130

DEFORMATION OF ROTATIONAL TIDAL CURRENTS IN SHALLOW COASTAL WATER

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Abstract

Along gently sloping coasts of seas having rotary tidal currents, the symmetry of the rotary current is interrupted where the water is shallow As a result, residual counter currents are formed The dynamics of such a current system are described based on current measurements in the Elbe Estuary (southeastern North Sea) The residual currents of this area result in the movement of bottom sediment and are most likely responsible for a series of similar appearing morphologic features.

1 Rotary Tidal Waves

A typical effect of tidal motion in oceans as well as in bays is the formation of rotary tidal waves They are characterized by cotidal lines radiating out from a nodal or amphidromic point, where the tide vanishes to zero Amphidromic regions can be developed through the superposition of longitudinal and transverse oscillations Normally, however, they form as a result of the Coriolis

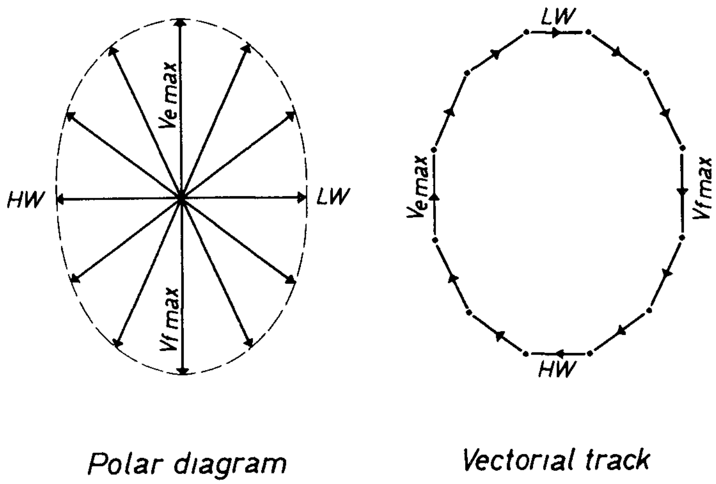

Fig 1
Pattern of a rotational tidal current (shematic)

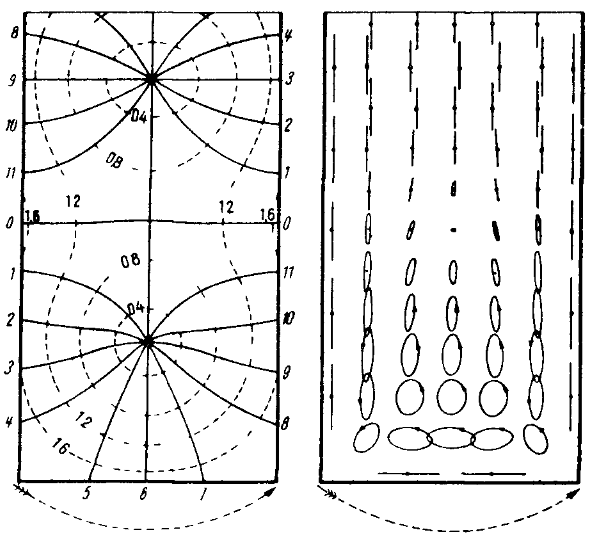

Fig 2
Reflection of a Kelvin Wave in a basin open at one end (from Dietrich, 1957)
Left cotidal lines and tide range
Right currents

force acting on progressive or on standing long-period waves This effect was described by W Thomson (Lord Kelvin) in 1879 (Kelvin Waves)

Observations of tidal currents within an amphidromic system show characteristic circular or elliptical current patterns when the measurements from a complete tidal phase are plotted in vector form (Fig 1) Figure 2 shows Taylor's (1920) mathematical description of a Kelvin Wave in a basin open at one end The dimensions of his theoretical basin are comparable to the North Sea Two counterclockwise-rotating amphidromic systems are developed, the southernmost of which has rotating currents The general pattern of this example corresponds to the actual tidal motion found in the North Sea

2 Deformation of Rotational Current in Shallow Coastal Water

In the theoretical model of Fig 2, simplified marginal conditions result in the formation of reversing currents along the coastline On natural coasts the relationships are much more complex The deformation of the rotary current flow along the shallow coasts of the southern North Sea results in an interesting effect which can be of consequence for sand transport Large parts of this coast are composed of tidal flats ("Wattenmeere") (Fig 3), which are covered with water at high tide and fall dry at low tide Even further away from the coast the southern North Sea remains quite shallow, seldom reaching depths of over 30 or 40 m

If symmetrical rotary currents with elliptical current patterns exist in deep water off such a shallow coast, then this symmetry will be altered in the shallower water zones This is illustrated in schematic form in Figure 4 The left drawing shows the symmetrical rotary current in deep water. The pattern is based on a counterclockwise current flow whose maximum velocity (reached during flood an ebb) is

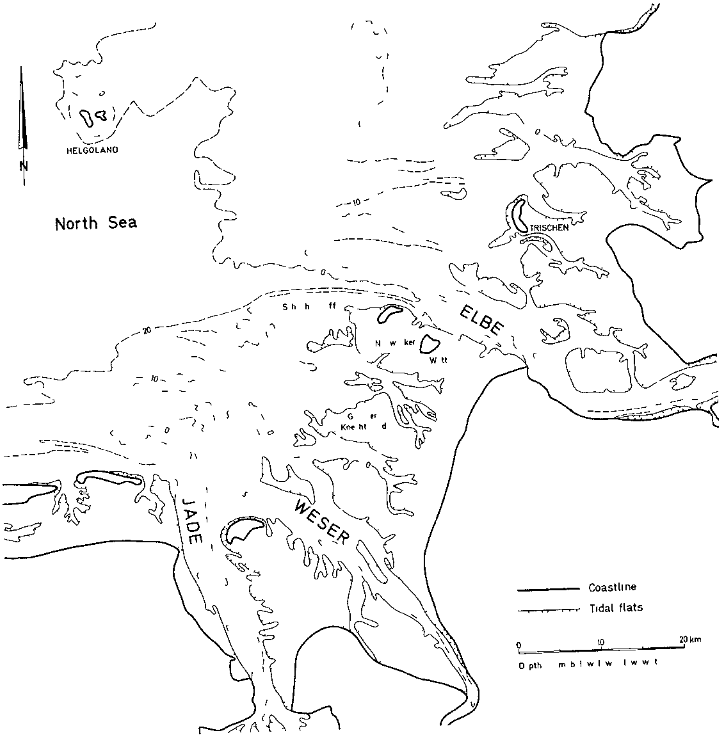

Fig 3
Map of the coastal area in the southeastern North Sea

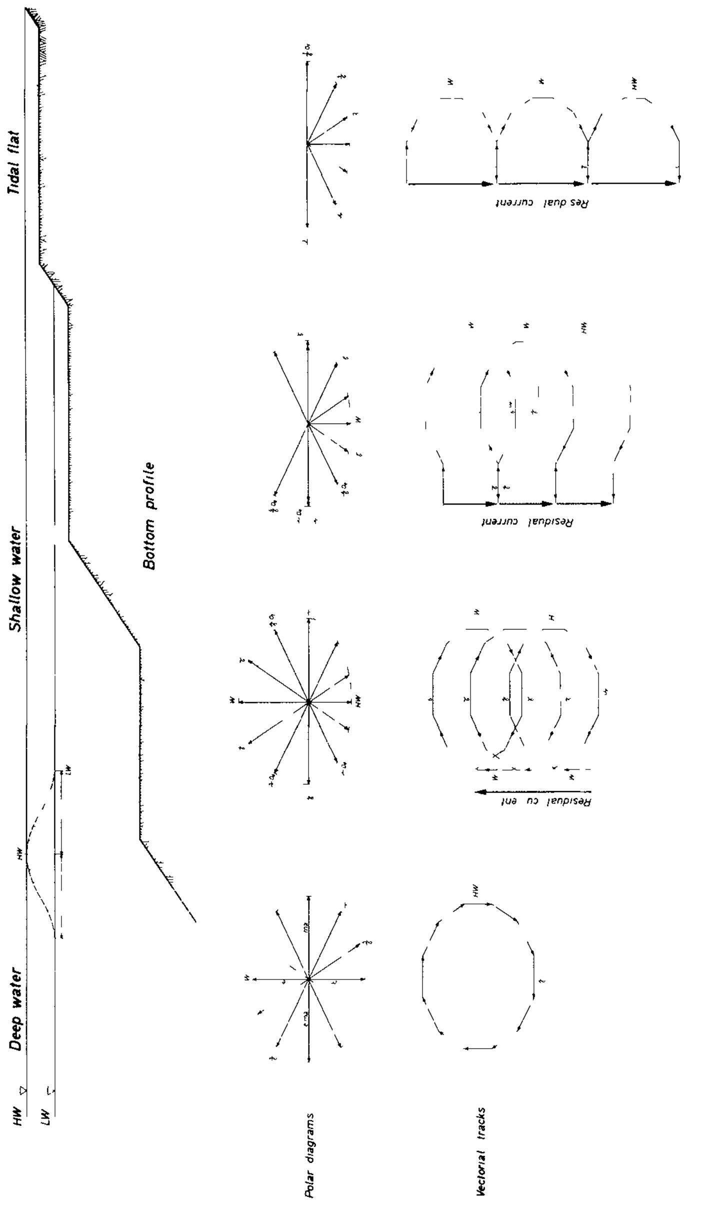

Fig 4
Deformation of rotational currents in shallow coastal water (shematic)

developed normal to the coast, and whose minimum velocity (at high and low water) runs parallel to the coast In general this compares to the relationships in the southern Elbe Estuary.

On the tidal flat (right in Fig 4) only the high water phase of the tidal current ellipse can be effective The current vectors yield a garland pattern with a strong residual current developed in the current direction which prevails at high tide

Two factors lead to the conclusion that opposing residual currents, like those on the tidal flat, must also develop in the shallow water zone between tidal flat and deep water (middle, Fig. 4) Even without a net transport of water, the current velocities reached during low water are greater because of the decreased water depth in comparison to the tidal range Consequently, the vectorial plot takes the form of a series of elongated loops showing a shift in the direction of flow at low water. This shift is intensified through an actual transport of water in the same direction; the total movement counterbalances the residual flow in the tidal flat

The combination of these two factors changes the tidal ellipse into a spiraling current pattern which has a residual flow corresponding to the current direction found at low tide In this way a system of opposing residual currents is developed which can influence both bottom morphology and sediment movement

3. Data from the Elbe Estuary (southeastern North Sea)

The Elbe Estuary is presently the site of a wide-ranging scientific program concerned with harbor planning (Laucht, 1968) Figure 5 shows the "Scharhornriff" portion of the investigation area (cf Fig. 3), a broad shallow-

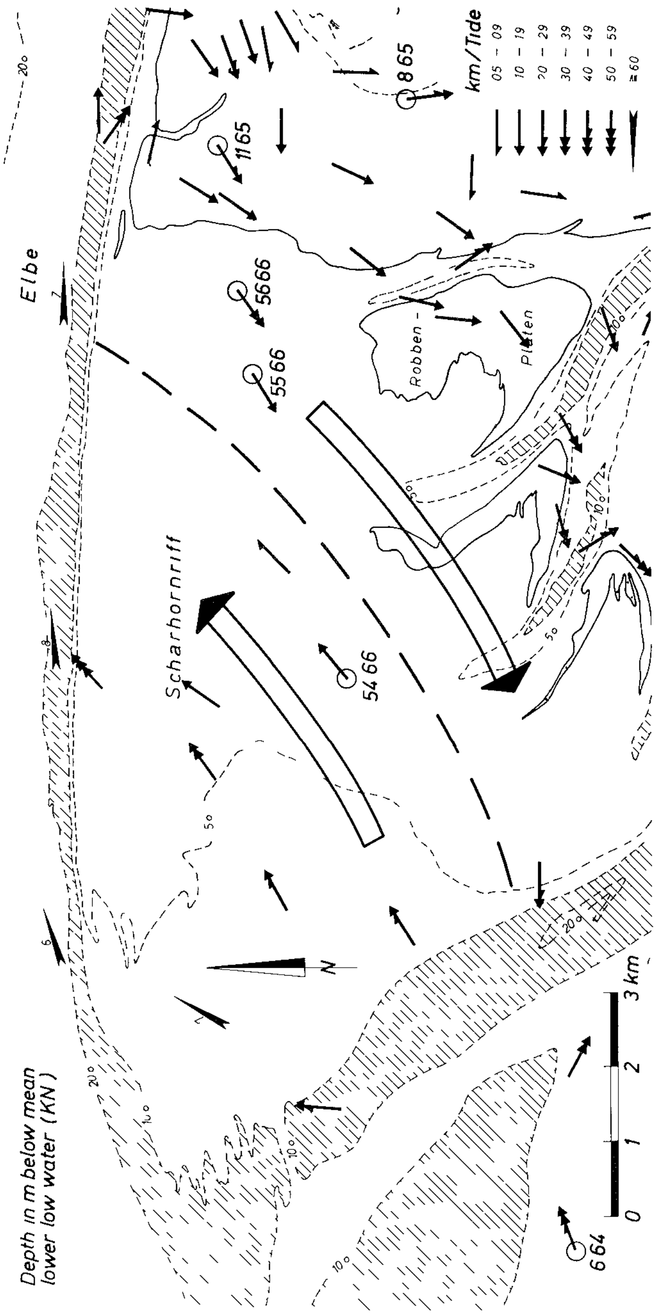

Fig 5
Residual counter currents on the "Scharhornriff" (Elbe Estuary, southern North Sea, cf Fig 3)

water zone bordering the Neuwerk tidal flat. Using the continuous recording current meters pictured in Figs. 10 and 11, current measurements have been made at numerous points throughout the zone (Gohren, 1969) Each recording lasted approximately two weeks Calculations based on these records show a uniform residual current toward the northeast in the outer portion of the zone and an opposing southwest residual current in the inner portion and on the tidal flat. A sharp boundary line can be drawn between these two residual current systems

Plots of current velocity and direction for several stations are given in Fig. 6 The rotary nature of the current can be clearly seen, especially at the outermost stations (6 64 and 54 66).

At stations 55 66 and 56.66 the decreased water depth is reflected in a disturbance of the rotary current pattern. On the tidal flat itself (stations 11.65 and 8.65) the motion is interrupted during the low tide period, however, during the time when the flat is covered with water, the rotary nature of the current is clearly present, especially at station 11.65

Figure 7 presents further substantiation that the residual counter currents illustrated in Fig 5 are actually caused by the distortion of the rotary current in shallow water Here, the measurements from several stations are presented as vector tracks The closely spaced measurement intervals (5 min) result in nearly continuous curves. The loop-shaped current paths correspond exactly to the theoretical picture presented in Fig. 4. This seems to be confirmation that the residual current system in Fig 5 is not an isolated occurrence but rather a hydrodynamic process, which may be expected on any shallow coast where rotary tidal waves are developed Similar measurements are not yet available for other coastal sections in the

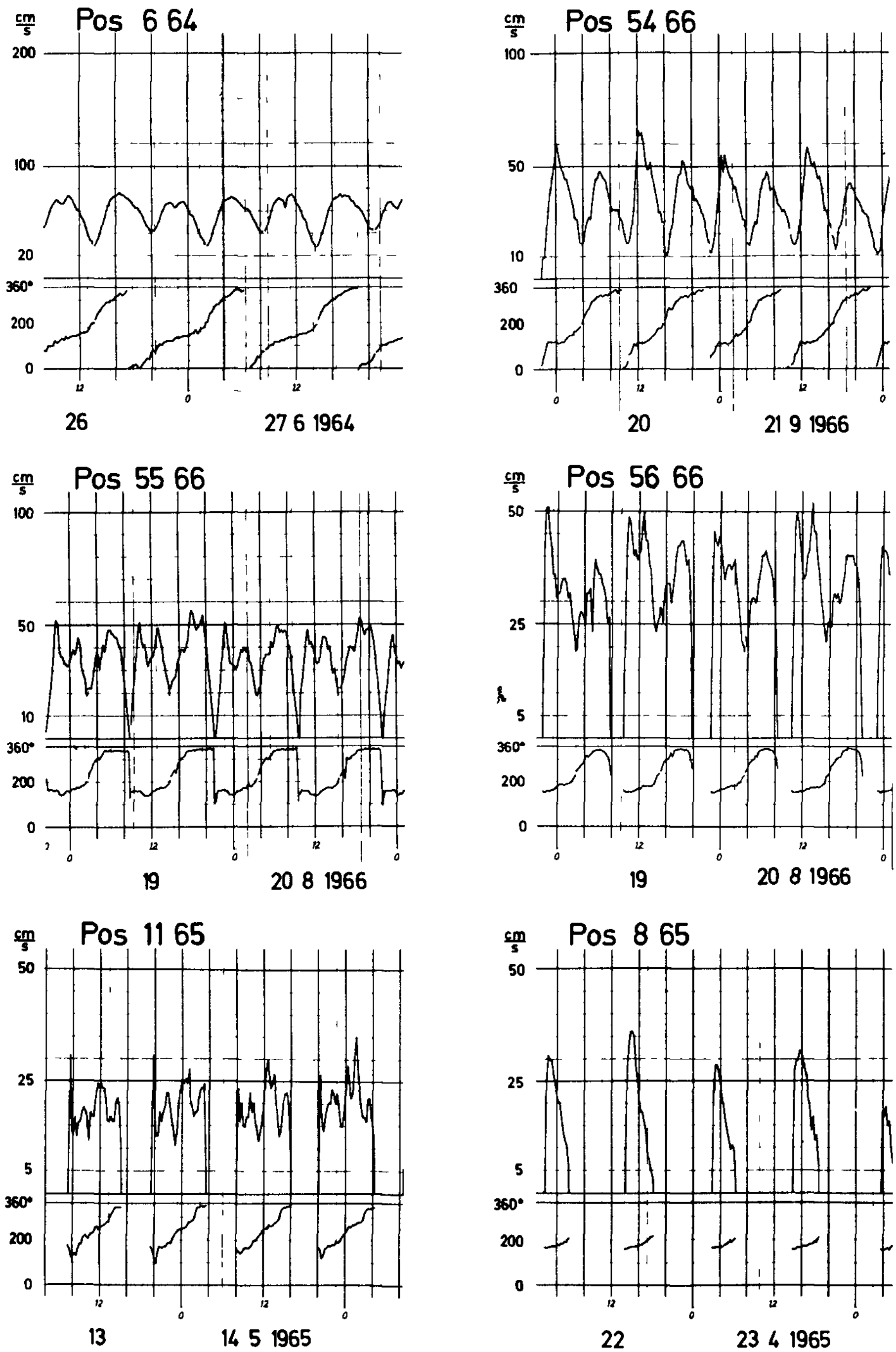

Fig 6

Results of current measurements from several stations on the "Scharhornriff" (cf Fig 5)

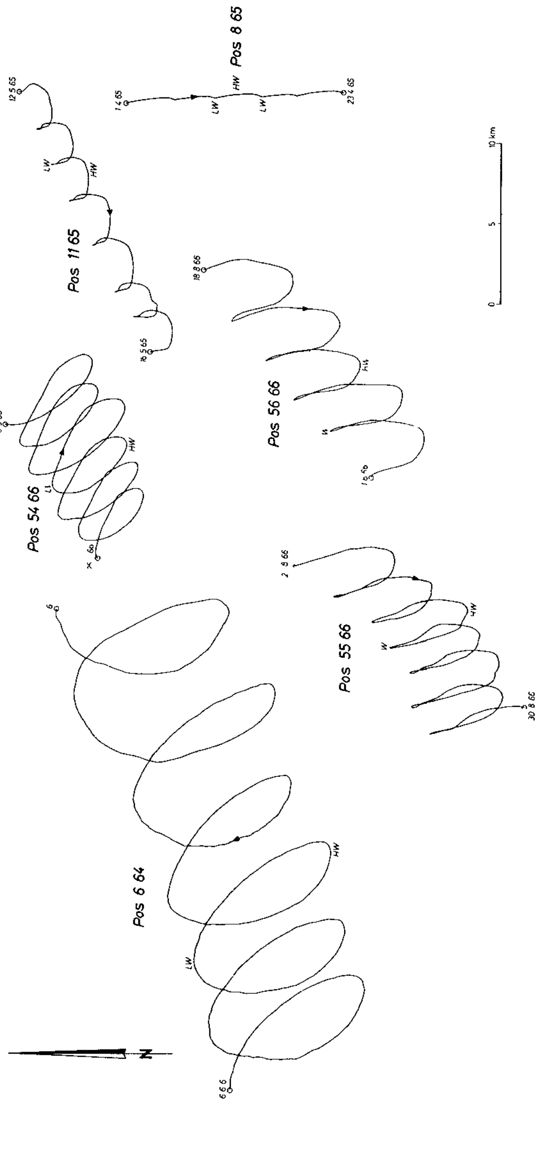

Fig 7

Results of current measurements from the "Scharhornriff", plotted as vectorial tracks (cf Fig 5 and 6) southeastern North Sea This is due to the fact that current measurements in exposed shallow water areas are extremely difficult to obtain and were possible in the Elbe Estuary only after the development of the equipment pictured in Figs 10 and 11

4 Influence of Residual Counter Currents on Sand Movement and Morphology

The direction of sand movement cannot be categorically equated with the residual current direction Figure 6 shows how difficult it is, when rotary tidal currents are present, to single out a dominant sand transport direction However, the maximum velocities developed in the "Scharhornriff" area are sufficient to move sand grains, particularly when one considers the added action of wind generated waves and surf

In order to establish the principal directions of sediment movement within this area of complex currents, a large number of tracer sand experiments were carried out (Gohren, 1969) Figure 8 shows the dispersion of the tracer grains at the conclusion of 5 of these experiments A comparison with Figure 5 shows good agreement between tracer movement and residual current direction The sediment movement on the outer portion of the "Scharhornriff" is toward the northeast or east, on the tidal flat near the island of Scharhorn it is clearly toward the south A circulation of bed material is present which almost certainly exerts an influence on the bottom morphology

Southwest of the "Scharhornriff", the V-form sand banks of the "Robbenplaten" form conspicuous morphologic features bordering the tidal flat Figure 9 shows this area together with the outlying parts of the Trischen and Knechtsand tidal flats, which lie north and south of the Elbe Estuary (cf Fig 3) Isolated measurements

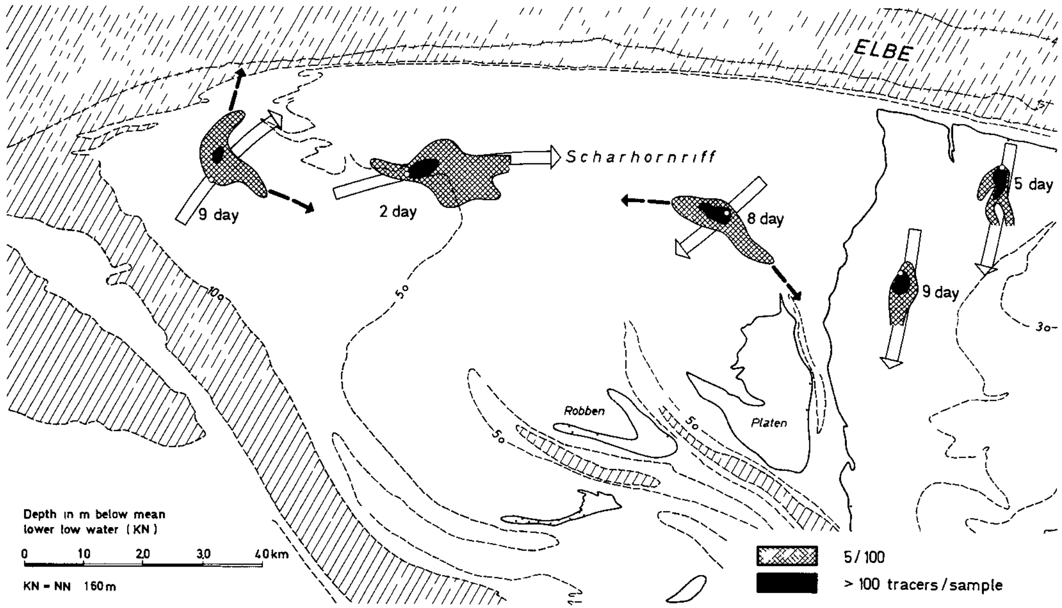

Fig 8

Direction of sand transport on the "Scharhornriff" found by tracer experiments
(Scale of tracer countours = 2,5 x scale of the map)

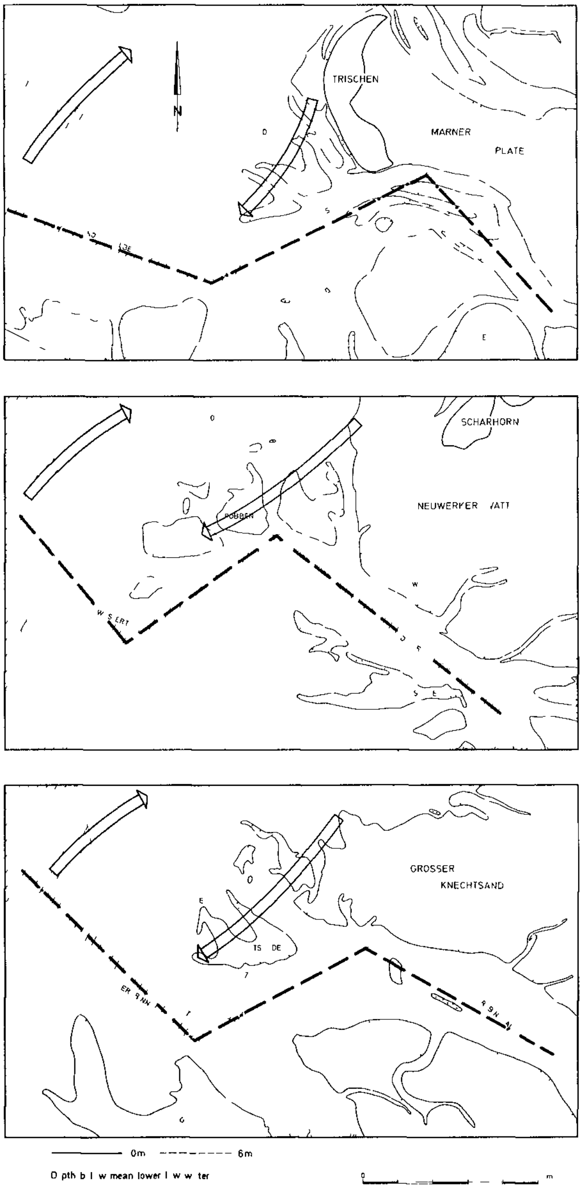

Fig 9

Influence of residual counter currents on the morphology of the outlying parts of the Trischen, Neuwerk and Knechtsand tidal flats (cf Fig 3)

Fig. 10
Recording current meter
for use in tidal flats

Fig. 11
Recording current meter for
use in shallow coastal water

have revealed opposing residual currents similar to those of the "Scharhornriff" in these areas, and it is apparent that the morphologic development in all three areas exhibits great similarity The sand banks seem to be areas of accumulation for the south or southwestward moving sediment This is also apparent from the configuration of the larger tidal channels south of the three flat areas (Neufahrwasser, Till and Robinsbalje). All three exhibit a decided S-form in their channels; the bends opposite the sandbanks reflect the southwestward directed forces. Further seaward the channels revert to a northwesterly course Here, as previously indicated, the sediment transport is directed toward the northeast and most likely exerts a force against the channels in this direction

The morphologic character and general similarity of the three areas mentioned above indicate an analogous mode of development which probably has its basis in comparable hydrodynamic conditions, ie , the generation of residual counter currents caused by the interruption of the rotary tidal current in shallow water

REFERENCES

Dietrich, G and Kalle, H. (1957) Allgemeine Meereskunde

Gohren, H (1969) Die Stromungsverhaltnisse im Elbmundungsgebiet Hamburger Kustenforschung, Heft 6

Gohren, H (1969) Untersuchungen mit fluoreszierenden Leitstoffen im sudlichen Außenelbegebiet Hamburger Kustenforschung, Heft 10

Hansen, W (1952) Gezeiten und Gezeitenstrome der halbtagigen Hauptmondtide M_2 in der Nordsee Deutsche Hydrographische Zeitschrift, Erg Heft 1

Laucht, H. (1968). Ursachen und Ziele der Hamburger Küstenforschung. Hamburger Küstenforschung, Heft 1

Taylor, G.J (1920) Tidal oscillations in gulfs and rectangular basins. Proc. London Math. Soc., 70

Thomson, W. (1879). On gravitational oscillations of rotating Water. Proc. Roy Soc Edinburgh 10