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Assessment of Ower Bank stability

M A Johnson & G F Caston

1984

Natural Environment Research Council

INSTITUTE OF OCEANOGRAPHIC SCIENCES

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ASSESSMENT OF OWER BANK STABILITY

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ASSESSMENT OF OWER BANK STABILITY

Background

Shell U.K. Exploration and Production plan to install a piled steel jacket on the south easterly end portion of the Ower Bank at -10m (53°07'26"N, 2°06'39"E), a position later moved downslope SW to -20m. The company required an assessment of the potential mobility of sediment and migration of the bank under the the following headings:-

1. Long term average stability
2. Short term single storm profile changes.
3. Expected heights of sand waves.
4. Monitoring procedures.

A draft report was required by the end of March 1984 which limited the time available for the assessment, and allowed only a cursory look at the available data and some brief calculations to be made. A more exhaustive study could be carried out should Shell require it.

CONTENTS

EXECUTIVE SUMMARY AND CONCLUSION

The construction of a platform in 20m chart depth of water on the SW flank of the south east portion of Ower Bank required information on the probable changes of bed level at the site. The Ower Bank is fairly central in the group of sub-parallel banks extending from active inshore banks near the Norfolk coast to the moribund offshore ones approaching the middle of the Southern Bight. The south east end portion (head) of the Ower Bank has a steep face on its NE side with a maximum inclination of about 3.5° and a gentle slope to the SW at an angle of about 0.8° (Fig. 12). It is mainly composed of medium/fine sand and sand transport paths on both slopes converge at the bank crest. The sand transport path up the gentle SW flank is the dominant direction and internal layers parallel to the steep NE slopes of adjacent banks imply that the banks migrate in a NE direction.

To investigate the long term regional and local changes a series of charts and echo sounding surveys were compared for time periods from less than 20 to greater than 100 years. All comparisons for the Ower Bank head demonstrated that the bank has extended in a south easterly direction and the steep slope has migrated to the NE at a rate equivalent to the regional estimate for long term average bank movement; 1.1km per 100 years. Because Ower Bank head is widening, however, there has been no detectable change in elevation at the site. Elsewhere on the SW flank repeat soundings over 18 years measured bed level change to be less than a metre in all cases down to the 25m isobath.

Regional charts show that bank movement varies along the axis of a bank, between different banks in the Norfolk bank series, and in time. Local bank movements over 10 and 20 years are considerably in excess of the long term average bank movement, but the Ower Bank head remained relatively stable. Despite the significant movements of the adjacent Well Bank internal layers recently observed in Well Bank head and tail are distinct to within 1m of the bank surface, implying that only the top metre is mobile in the short term.

Examination of side-scan sonar surveys has shown the presence of small sand waves of height about 1m and wavelength about 10-20m, diminishing upslope. These features will migrate fairly rapidly across the bed, perhaps up to 40m per tide. This would cause temporary elevation changes of up to 1m, as would also occur when the sand waves were smoothed out by extreme conditions. Greater changes could occur if larger sand waves were generated. Large sand waves occur between the banks and they have occasionally been found on adjacent banks. They may occur on Ower Bank under exceptional circumstances, most likely in summer and early autumn and would involve, at most, a bed level reduction of 2m in the troughs. This would be a short term effect until the large sand waves were smoothed out.

Maximum erosion/deposition rates were calculated using current velocities for estimated 50-year extreme tides plus storm currents, then with 50-year extreme waves superimposed. Using appropriate values for the bed roughness and the estimated changes in the current towards the crest of the bank, the sand transport rates were calculated using a variety of published methods. The calculated erosion/deposition reached maximum values of only a few centimetres in the few days duration of the stormy conditions. No consideration was given to local scour around the platform.

Taking all the different components of bed level change into consideration, it is concluded that the most likely change of bed level at the site would be of the order of a metre in the 20-25 year life of the platform.

Monitoring procedures are recommended to ensure that these predictions are verified. The most important priority is a programme of repeat echo-sounding and side scan sonar surveys.

INTRODUCTION

The Norfolk banks form a complex within 65 miles of the East Anglian coast (Fig. 1). All are composed of Holocene and Recent sand and are underlain by a Pleistocene surface. The Pleistocene sands and gravels are exposed at the surface between the Leman and Swarte banks and may at times be subject to erosion by the strong currents (Houbolt, 1968, Caston, 1968 - SMSG report). The innermost banks are sinuous (Hewett ridges) or of the parabolic type (the Haisborough-Winterton-Hearty Knoll complex). These give way seaward to linear asymmetric banks (Leman, Ower, Well, Broken, Swarte) which are asymmetric in cross section, with steep slopes up to a maximum of 7° facing NE. They average 35m in height relative to the seabed. Further offshore lie the Viking and Indefatigable banks, lower and more rounded with slopes only about 1°. Peak tidal current strengths are strongest near the coast - weakening across the line of banks (see Section 2 below). There is a corresponding transition in the banks from the inner active sand banks with large sand waves to the outer moribund banks with degraded profiles and an absence of sand waves. The Ower Bank is in the centre of the linear group of banks and is thus expected to be intermediate in state between the very active highly mobile banks and the stationary moribund banks.

The sand transport paths have been shown by Caston (1970) for the banks from Hewett ridges to Well bank. Fig. 2, taken from the SMSG report shows these transport paths and all data examined in the present study confirms this pattern. Fig. 3 is a model of an active sand bank (after Stride 1982) showing the relationship between the regional dominant net sand transport direction and the sand bank asymmetry. For most of the Norfolk banks the regional net sand transport direction is to the NW, and is to the SE only on the steep flanks of the sandbanks. The rounded SE ends of the banks point "upstream" and are the heads of the banks, the narrower tails are the northern ends of the banks (Caston, 1981). The presence of aprons of sand waves south of some of the bank heads is confirmed by pre-1968 IOS sidescan data (Fig. 11). The internal structure has been observed on the Well Bank and Smiths Knoll by Houbolt (1968) and on the Well Bank in 1981 (IOS unpublished data). The implications of the internal structure (master bedding) are that the sand bank migrates in the regional direction of net sand transport by a process of gradual erosion on the gentle flank and deposition on the steep slope. Consequently Ower Bank is likely to have the tendency to move towards the NE except for that part of the bank which bends towards the SW. At the SW bend the asymmetry of the bank is reversed and the bank will tend to move towards the steeper SW side, thus accentuating the bend (Caston, 1972).

SAND BANK STABILITY

1.1 ESTIMATES OF LONG TERM AVERAGE STABILITY - Norfolk banks.

The inundation of the area of the Norfolk banks began at about 8,000 years B.P. (Jelgersma, 1979), and the reshaping of the Pleistocene sands into the present day series of sand banks may have begun at the same time. The internal structure observed demonstrates the growth pattern and implies an average migration to the NE during this geological time scale, but there have been few attempts to quantify the rate of movement of sand banks.

Houbolt (1968) compared the positions of the banks on hydrographic charts compiled at around 1900 by ship to ship triangulation with the latest charts available in 1968. The apparent movement of the banks was 1n mile to the NE but Houbolt explained this shift was possibly due to the inaccuracy of the earlier charts.

Caston (1972) compared charts of 1851 with charts of 1966 and 1967 but counteracted any regional shift in navigation by superimposing bank isobaths and only looking for local changes. Local bank movement varied from 350m to 750m over limited areas, in all cases in the direction of the steep bank slope. For the Ower Bank the measured change was 762m to the SW at the SW kink in mid-bank where the bank asymmetry is reversed. Caston's estimate (SMSG report) for average bank movement is slow - not exceeding 1.1 km for 100 years.

1.2 STABILITY OVER A 25 YEAR PERIOD

I.A. Pravotorov (1983) has compared isobaths from a 1:200,000 series of charts with good navigational control published from 1956 to 1980 for the Norfolk banks area. In transferring the isobaths Pravotorov allowed for a mean square positional error of 0.3mm and for paper distortion. His isobaths are shown in Figures 4-6. These figures were used to assess both regional and local bank movements. Despite the small scale of his charts many significant changes are apparent.

Regional

During the first decade two banks combined to form the Viking Bank. The heads of Swarte, Well, Leman banks were all eroded but the Inner extended by 900m. The southern parts of the steep slopes of the banks showed deepening, with some shoaling on the opposite gentle flank. This apparent backward movement of the banks is especially obvious in the inshore group of banks. For all the banks local shoaling or deepening caused an increase in the sinuosity of the isobaths.

During the second decade the erosion at the heads of Leman, Swarte and Well banks stopped and the heads of Swarte and Well banks extended southwards. Extension also occurred at the heads of the Viking, Broken, Ower, Hewett and Haisborough (up to 4km for Broken bank). The tails of Broken, Well, Ower, Leman and Haisborough banks also extended (1500m for Broken Bank). Overall the isobaths have straightened again., Large sections of the Swarte and Broken banks show an apparent movement to the SW and a large shoal area extending SW from an eroded area on Swarte Bank implies considerable local sand transport. The southern half of Well Bank is the only large area showing an apparent migration to the NE, so that the bank axis is straightened.

The two decades show considerable changes. For a particular bank a decade of bank shortening may be followed by one of bank extension, part of the bank may move to SW in one decade, to NE during the next. Over the 20 years the net movements are summarised as follows: All the banks extended at their tails, to NW. The heads of Swarte, Broken, Well, Ower and Inner banks extended to the SE. The Viking Bank shoaled extensively. The Swarte and Broken banks have apparently moved to the SW. The southern half of the Well bank and the northern parts of the Inner, Ower and Leman banks have moved to the NE.

Ower Bank

A comparison of the isobaths from Pravotorov (1983) shows less change on the Ower Bank than the other banks. Over the first decade erosion occurred at the head (<300m) and tail (<1km). The tail end of the bank narrowed and the kink in the bank became more pronounced. The SE end of the bank apparently moved <0.5km to the NE. During the second decade the bank extended at the head (1.5km) and at the tail (3.8km) by annexing a separate shoal. The kink became more pronounced. The SE part of the bank straightened, involving local movements of the isobaths to NE and SW of up to 800m. Over the twenty year period there was a net extension at head and tail, a net movement of the tail end to the NE; the development of a more pronounced kink in the centre of the bank and a net movement of the head of the bank to the NE by up to 500m. However, the measurements of the horizontal excursions of the 20m isobaths are very approximate from such a small scale and should be regarded with caution. On the gentle flanks large areas exist with depths close to each isobath. Thus small movements in bed level may cause large movements of the isobaths and imply large apparent bank movements. This is also true for the isobaths at head and tail, where extension may represent slight shoaling over the aprons of sand waves.

1.3 STABILITY OF OWER BANK HEAD

Long term

For the present study charts for 1826, 1874, 1914 and 1915 were obtained, with the intention of comparing isobaths with those of a 1967 H.D. survey. The latter was done using hifix and positions are accurate to 20m. The 1915 survey was a beacon survey with longitudinal accuracy only good to 500m whereas no reports at all exist for the earlier surveys and the survey methods are unknown (G.S. Shimmin, Hydrographic Department, pers. comm.). The surveys were done at different scales and the soundings on the earlier surveys were sparse. Isobaths for 3, 5, 10fm were compared for the south eastern part of the Ower Bank but there was not time to extend this excercise to the northern end or to the adjacent banks.

Superimposing the isobaths for the 1874, 1914 and 1967 surveys (accuracy ±500m) demonstrates the lengthening of the head of the Ower Bank by 3.9km, 3.1km in the first 40 years, 0.7km in the latter period of 53 years. The axis of the head of the bank moved to the NE by approximately 1km. Again the maximum apparent movement was during the first 40 years, with some local retreat 1914-1967. There is no change of the position of the 10fm isobath near the proposed platform site but in 1874 this position was right at the tip of the bank and is now on the shallow slope of the bank almost 4km from the tip.

18 year period

A comparison was made of 3 detailed bathymetric surveys of part of the Ower Bank. These surveys were all executed by Decca for Shell U.K. and copies are included as Figs. 7, 8 and 9. All 3 surveys have a high degree of positional accuracy, to 30m. Figure 7 is a compilation of surveys done in 1965 and 1966 with soundings and isobaths in feet. The soundings were converted to metres and isobaths were drawn at 5m intervals to compare with those of 1981 (Fig. 8). The isobaths for both surveys are shown on Fig. 9. Where soundings of both surveys coincide differences in bedlevel of 1m have been shown on the figure. Some quite large excursions of the isobaths represent changes of less than a metre, e.g. the movement of the 10m isobath on the SW side of the head. There is little change in bed level on the gentle slope of the bank and only a few of the coincident soundings show deepening or shoaling of a metre or more. However on the steep slope of the bank all the isobaths have moved to the NE and this change represents a real shoaling. Sand accumulation is locally up to 8m for the 15 year period. The region of maximum sand accretion appears to be high up the steep slope, at the 10-15m level and the amount of shoaling varies along the axis of the bank. The sand accumulating on the steeper NE slope has not necessarily all been transferred from the SW slope.

Figure 11 compares isobaths and soundings from the 1981 and 1984 surveys. Changes less than 0.5m have been ignored. Sounding coverage is more extensive on the SW slope for these two surveys but there are still large areas of no bed level change. Changes do not exceed 1m except for deeper than 25m where sand waves are known to be larger. The bank top has been eroded by approximately 1m (Fig. 11) between 7.11.81 and 28.1.84. This change may be due to storm wave action during the winter. The greatest bed level changes are again on the steep slope of the bank, near the head end. Movements of the isobaths on the gentle slope (of up to 190m) represent bed level changes of 1m or less whereas a smaller movement of 120m of the 10m isobath on the NE side represents a 4m bed level change, in only 3 years. Exceptionally, a maximum of 6m sand accretion was measured at one spot near the head of the bank.
A cross-section of the Ower Bank has been drawn from the 1981 survey, through the position of the proposed platform to illustrate the relative slopes of the bank in this region (Fig. 12). Using Caston's estimate for long term bank migration of 1.1 in 100 years the expected migration of the Ower Bank would be 165m in 15 years, or 30m in less than 3 years. Assuming that the bank would maintain the shape and slope angles illustrated in Fig. 12 some rough estimates of bed level changes can be made for these time periods. For a position at the bottom of the steepest part of the NE slope bed level changes would be +9.5m (to bank top level) and +2.5m respectively. For the proposed platform site the estimates would be -3m and -0.5m respectively. This estimate is greater than the values measured from the comparison of surveys, because the Ower Bank movement has involved a change in width.

1.4 SUMMARY AND CONCLUSIONS

Longterm studies of bank movement are hampered by the paucity of soundings and poor navigational control of earlier charts. Nevertheless there remains a significant movement of the isobaths after allowing for the possible inaccuracy of 500m. For the SE end of the Ower Bank this movement is in the expected direction i.e. the bank has lengthened at its head and the axis of the head has moved to the NE.

The three Shell surveys also show a movement of the steep slope to the NE, the amount of movement varying from 120 to 260m from top to bottom of the slope in the first 15 years, from 70 to 120m for the following 3 years. The comparison of soundings show that this slope is built out to the NE unevenly. Local regions of sand accumulation reach a maximum of 8m in the 15 years 1966-1981, 6m in less than 3 years between the 1981 and 1984 surveys - a very rapid sand accumulation. These findings are again in agreement with the expected growth and migration of sand banks suggested by the internal structure observed on Well Bank and Smiths Knoll.

At the 20m level on the shallow slope little change in bed level has occurred. The positions of the 10fm and 20m isobaths on charts and detailed surveys has been stable. Bed level changes over the last 20 years have been generally less than 1m and this change can be accounted for by the expected migration of the 1m sand waves known to occur at this depth on the shallow slope of the Ower bank.

For the steep NE slope the estimates of bed level changes are reasonably consistent with the measured changes (Figs. 10 and 11) but for the proposed platform site the measured changes of less than a metre compare with estimates of -3m. The implication is that the bank has been increasing in width during the last 18 years, with the steep slope migrating to the NE but with the gentle flank remaining relatively stable.

Thus the proposed platform site has been a relatively stable area but the regional work of Pravotorov strikes a cautionary note. A period of sand erosion at heads and tails may be succeeded by a period of sand accumulation and bank extension. His charts show wholesale movements of banks to NE and to SW as well as delineating local areas of sand accumulation and removal. The Ower Bank showed less change than most banks but it may not continue to do so, although it lies in a relatively sheltered position between Leman and Well banks.

Although the isobaths of Pravotorov's charts show a tendency for the tail of Well Bank to 'wag', the internal layers (IOS unpublished data) within the tail give no indication of periods of erosion or of reversal of the direction of sand movement and these layers are distinct to within 1m of the bank surface. The implications are that only the top metre of the sand is mobile in the short term.

Conclusions based on all the original data examined in the course of this study are as follows. The bed level of the proposed platform site at 20m on the gentle flank of the SE part of the Ower Bank has not varied by more than a metre during the last 20 years. It is the most stable part of a bank and for the Ower Bank the 10fm (20m) isobath has remained near the proposed platform site since 1826. It is most likely that bed level changes over the next 20 years will be similar to the last 20 years, but this does notpreclude short term changes of a greater magnitude under exceptional conditions. (See predicted occurrence of large sand waves, Section 2).

SECTION 2

SHORT-TERM EXTREME BED LEVEL CHANGES

2.1 Scope of the study

To complement the analysis of historical changes in the bank topography, and of sandwave distributions, an attempt is made here to calculate the possible short-term changes in bed level caused by sand erosion or deposition. The Norfolk banks area is one of great topographic complexity, and, in view of the limited field data available, the calculations can only be considered as of order of magnitude accuracy.

Deposition or erosion of sand results from a change in space or in time of the sand transport rate. A current slowing down will deposit its sand load, and conversely a current speeding up will cause erosion. Consequently it is necessary to calculate the gradient of the sand transport rate. We need to estimate values for extreme current conditions, having considered how the current velocities change over the slopes of the bank. Then one can use methods based on laboratory flume and river sand transport data and the limited shelf information to make approximate predictions of the sand transport rates.

Surface waves will enhance the sand transport. Since no local measurements are available wave significant height and period have to be estimated from outside the bank area and adjusted to take into account the attenuation caused by shallow water over the banks. For practical reasons, field studies measuring shallow-sea sand transport rates and the currents and waves responsible have rarely included very strong currents and waves, and for that case no suggested method for predicting sand transport rates under simultaneous currents and waves can be remotely considered proved. However, Bijker's (1967) method has commonly been found to give predictions agreeing reasonably well with field and laboratory data for weaker currents and waves. The methods are applied to estimated extreme storm conditions superimposed on the regular tidal currents. The input, numerical values of current (Secs. 2.2, 2.3) and wave (Sec. 2.4) parameters, has to be predicted, first regional values and their modifications on the Ower Bank near the proposed installation site ("the site").

Storms will also influence the effects of the structure itself on the adjacent sea bed. In particular, the scour pattern in the sand bed near the legs may be temporarily altered from the probably steady pattern formed under the regular tidal currents. These effects and the remote possibility of a sediment failure (liquefaction) adjacent to a leg under waves of extreme height should be assessed. They are outside the experience of IOS, and are excluded from this study.

2.2 Regional tidal currents and 50-year 'storm' currents

2.2.1 Regional tidal current charts

These (Sager and Sammler, 1975; Howarth, 1982) were derived by contouring plots of observational mean springs tidal current speeds ('peak' values, i.e. over a 12.4 hour tidal period). The data used relates to positions between banks, only a very few and short-term measurements having been made on banks (Sec. 2.3). Sager and Sammler also analysed directions. Their charts, derived mainly from observations at 5-10m below the surface, lead to a regional speed value of about 1.08m/s and a regional direction 329° for the site position. Howarth's analysis of speeds took particularly into account the available off-shore current recordings up to 1980 by IOS and by co-operative programmes involving IOS. The MIAS data bank at IOS has not received any subsequent current measurements within 20km of our area. Howarth's chart gives just over 1m/s for the site position. Since it relates to depth-mean speed there (current speed averaged from bed to surface) the results are about 5-10% less than Sager's and Sammler's value, using the velocity profile discussed in Sec. 2.2.5, in these 30-40m depths. Both charts agree with a depth-mean regional speed value of 1.02m/s which will be adopted.

2.2.2 Tidal current values from numerical models

Numerical models give regional values of depth-mean tidal current speed and direction for each computational grid rectangle. Each pair of speed and direction values represents averages over the rectangle concerned and has to be assigned to its centre. Also the computations necessarily use mean water depths over each rectangle, so that the banks are only included in that they reduce mean water depth by a few per cent, since their width is small in relation to grid rectangle length and width (30 minutes of latitude, 20 minutes of longitude for model whose results will be quoted). Values at positions not at a grid rectangle centre are obtained by interpolation. However, the agreement with charts (Sec. 2.2.1) derived from the relatively numerous observations is generally good.

An extreme (50-year approximately) springs peak speed value of 1.20m/s compared to about 0.95m/s at mean springs, has been computed by R.A. Flather (pers. comm.) for a grid rectangle centre 53°10'N, 2°15'E. This would correspond to a value of 1.29m/s as a regional extreme tidal value for the site position. These computed peak currents are directed to 335°, both at the above rectangle centre, and, by interpolation with neighbouring rectangle centres, for the site position. The numerical model value will have been affected by the grid rectangle representation of the topography, especially of the coastline. However, this value is very close to the direction obtained from current measurements.

2.2.3 50-year storm current values from numerical models

In contrast to regular and predictable tidal currents, non-tidal storm currents depend on numerous variables, and even regional values cannot be reliably predicted in shelf seas of other than very simple topography, from analytical theory or analysis of the relatively few observations. Thus only the results of numerical modelling of storm surges and currents are reasonably reliable. The procedure is to compute depth-mean currents caused by surface wind stress and atmospheric pressure distribution as well as tidal forces, and to subtract from them computed currents for the same times caused solely by the tidal forces. The quite good agreement (Sec. 2.2.2) of these latter numerically-modelled tidal currents with observations supports the use of Dr. Flather's numerical modelling procedure (the most recent developed by IOS) whose results will be quoted. Wind speed recordings at coastal sites over many years enable the wind speeds during these storms to be related to 50-year maximum wind speeds, thus making derivation of 50-year maximum storm currents possible. For the grid rectangle centre 53°10'N, 2°15'E, R.A. Flather has communicated a 50-year extreme of tidal plus storm current of 1.72m/s to about 151°, corresponding to 1.84m/s at the site. This figure is made up of the computed 50-year maximum storm contribution of 0.82m/s (depth-mean), corresponding to 0.88m/s at the site, plus the computed peak tidal current speed at mean springs to the SE quadrant of 0.96 m/s at the site. The stronger tidal current is to the NW quadrant, equal to 1.02m/s as already mentioned, but the computed 50-year maximum storm contribution in this direction is only 0.44m/s (depth-mean), corresponding to 0.47m/s at the site, total 1.49m/s.

2.2.4 Observed storm current speeds

The few observed current speeds produced by extreme winds support the general magnitudes discussed above of numerically-modelled storm currents, bearing in mind that the latter are depth-mean current speeds which would be higher than near-bed speeds, and are extreme (50-year maxima). In one North Sea storm (2.11.65) speeds 2m above the bed exceeded 0.7m/s at various German Bight stations (Gienapp, 1973). The highest accurate observational near-bed wind-driven current speed reported for British waters away from straits is thought to be 0.36m/s (Caston, 1976) at about 53°05'N, 2°8'E, at 4.6m above the bed in response to a (bank-parallel) NW gale during 7 to 9.12.67, twice reaching 25m/s (hourly averages). This wind speed was measured at 30m and is equivalent to about 22m/s at the standard exposure height of 10m, at which the 50-year 1-hourly maximum speed is much higher, 32m/s (all directions combined) (Dept. of Energy, 1977). Unfortunately, no storm current numerical modelling predictions for comparison seem to be available for these dates.

2.2.5 Current velocity profiles in the vertical

For calculation of sand transport rates the near-bed velocity and the bed shear stress need to be estimated from the above depth-mean values. In the vertical, the usual logarithmic velocity profile will be assumed, i.e. the velocity components, u_z, v_z, perpendicular and parallel to the bank crest, of vector velocity $\underline{u}_z = (u_z, v_z)$ at any distance, z, above the bed are given by

$$u_z = 2.5u_* \ln z/z_o, \quad v_z = 2.5v_* \ln z/z_o \qquad (1)$$

When the depth h has to be given, the velocity components are written $u_{z,h}$ and $v_{z,h}$. Also u_*, v_* are friction velocity components and the von Karman constant has been taken as 0.4 (Soulsby, Davies and Wilkinson, 1983), z_o is the bed roughness length and the bed shear stress vector is $(\rho u_*^2, \rho v_*^2)$. Resultant water and friction speeds $(u_z^2 + v_z^2)^{\frac{1}{2}}$ and $(u_*^2 + v_*^2)^{\frac{1}{2}}$ will be required for sand transport predictions and are written $|\underline{u}_z|$, $|\underline{u}_*|$. If the speed profile were logarithmic up to the water surface, as in flumes and rivers, the depth-mean speed would equal the actual speed at z = 0.37h, where h is water depth. Many observations have shown that the profile is closely logarithmic in the lowest few metres but deviations occur further from the bed, due to tidal accelerations and earth rotation forces. However, these deviations are small during the periods when most sand transport takes place, i.e. at and near times of peak ebb and flood current speed. The value of z_o appropriate to a rippled bed, often with small sand waves present, is about 0.5cm (Soulsby, 1983). At very high current speeds the sand waves and ripples are largely smoothed out but z_o may not decrease, on account of an increasing contribution from the effects of sediment suspension. The increase in z_o with moving sediment can be approximately taken as

$$z_o = 26.3\rho \; (u_*^2 + v_*^2)/g(\rho_S - \rho) \; \rho_S - \rho) \qquad (2)$$

where ρ_s, ρ are sand and water densities (Soulsby, Davies and Wilkinson, 1983).

Current velocity profiles can be altered by wind stress on the water surface. However, the main effect may be on the uppermost 10 metres (IOS Annual Report, 1982), the strong tidal currents being little altered below that. Consequently the near-bed velocity and bed shear stress are assumed obtainable from the depth-mean currents and equation 1, with the appropriate z_o value.

2.3 Relation of local to regional currents

2.3.1 Velocity components

The Norfolk and most other offshore active tidal banks have crests at appreciable angles to regional peak tidal current direction (Kenyon et al., 1981). Consequently the obstruction they cause makes the flow (1) divert around the bank and (2) accelerate over the crest. The magnitude of the acceleration (2) depends on the relative effects of shallowing and friction on the flow. The transverse and longitudinal velocity components behave quite differently (Secs. 2.3.2, 2.3.3).

2.3.2 Transverse current component

The tidal current vector, $\underline{u} = (u_z, v_z)$ past the site is directed either as in Fig. 2, obliquely towards between NW and N, or the reverse, except when it and the sand transport rate are weak. A fairly accurate prediction is that, as the transverse current component approaches the bank crest, its depth-mean speed, U_h say, increases in proportion as the local depth h decreases. This "continuity" requirement is negligibly affected by tidal time and space variations (Huthnance, 1982a). Thus the present discussion should also apply to storm currents. THe only current meter recordings with directional information at positions distributed over an offshore tidal bank seem to be those of Venn and d'Olier (1983). These workers had current meters moored at three positions on a transverse line up the western slope of the very long straight South Falls Bank, well away (about 4 bank widths) from bank ends. The current meters were at levels 1, 2 and 10m above the bed at a position with water depth 40m, at 10m above the bed in water depth 20m and at 1m and 2m above the bed in water depth 10m. For 10m above local sea bed transverse current speed, $u_{10,h}$ in water depth h, was nearly doubled from the 40m to the 20m water depth, i.e. $u_{10,20} = 1.95u_{10,40}$. The predicted doubling of depth-mean speed, U_h, i.e. $U_{20} = 2\ U_{40}$, would correspond to doubling of current speed at 0.37 of 20m depth compared to 0.37 of 40m depth, i.e. $u_{7.4,20} = 2u_{14.8,40}$ assuming logarithmic profiles. Taking $z_o = 0.5$cm, this would correspond to a 2.2 instead of 1.95 times speed increase between the bed + 10m positions, i.e. $u_{10,20} = 2.2u_{10,40}$. From 40m to 10m water depth, the predicted amplification factor of 4 applies to depth-mean current speed i.e. $u_{3.7,10} = 4u_{14.8,40}$. Using logarithmic profiles with $z = 0.5$cm, this amplification would correspond to $u_{2,10} = 4.8u_{2,40}$ and $u_{1,10} = 4.8u_{1,40}$. However, observed factors were about 2.9 for 2m, and 2.5 and 2.1 (mean 2.3) 1m above the bed for off bank and on bank flow respectively. These results can be fitted by the transverse current component, u_1, at 1m above the bed proportional to $h^{-3/5}$ and this will be used for other depths in subsequent calculations. The above-discussed variation of depth-mean speed U as h^{-1} could still be satisfied by a greater speed increase near to the surface, above bank crest level. Mean water depths (chart depths plus half tidal range) have been used in considering the data, so that any effects of the actually different depths should cancel between ebb and flood tides.

For the site on Ower Bank, amplification factors may be a little further reduced through some diversion of current round bank ends, and by the presence of sand waves producing a larger bed roughness. The neglect of these factors will impose a slight over-estimate on the calculated bed level changes.

2.3.3 Longitudinal current component

Remarkably, the oscillatory longitudinal tidal current component seems to have been specifically discussed in the literature only by Venn and d'Olier (1983). Their approximate theory predicts no appreciable variation of the depth-mean component, V, over the narrow South Falls Bank. However, though their data gives nearly equal longitudinal speeds ($v_{10,20} = 0.93v_{10,40}$) at 10m above the local bed in 40m and 20m water depth, this corresponds to the depth mean at the shallower depth, V_{20}, equal to $0.84V_{40}$. For bed + 1m and bed + 2m, $v_{1,10} \equiv 0.77v_{1,40}$ and $v_{2,10} \equiv 0.78v_{2,40}$, corresponding to depth-mean V_{10} about 30-40% less than V_{40}.

Numerical evaluation of the relevant formulae (respectively, his equations 2.10 and 2.3) in the more adequate theoretical treatments of flow over a bank given by Huthnance (1973, 1982a), also predicts (smaller) decreases of longitudinal depth-mean tidal current speed on the upper parts of a bank from its value off the bank. Such decreases also occur in Sizewell-Dunwich Banks tidal current recordings (by about 30%, Heathershaw and Lees, 1980) and numerical modelling (by about 15%, Soulsby, pers. comm.). The above should also apply to longitudinal components of storm currents. A proportionality of $v_{1,h}$ to $h^{+1/5}$ agrees well with the above and will be assumed. Superimposed on the oscillatory tidal currents, there is predicted (Huthnance, 1973) and in some examples deduced by him from tidal current recordings, to be a residual longitudinal current, R say, to NW approximately on the SW side of most Norfolk banks and to SE approximately on the NE side. This current is taken as 0.1m/s (depth-mean) averaging the values for the two similarly placed SMSG current observing stations (Stations 14 and 15, Table 1 of Huthnance 1973). The observations were only for 24 hours each, but there is no other relevant data presently available. The equivalent 1-metre speed r_I is 0.07m/s.

2.3.4 Resultant current speed and direction

As positions successively further up a bank slope are considered, the increase of the near-bed transverse current component combined with the decrease of the longitudinal component gives a turning of near-bed current direction towards the crest of the bank. As a result sand-wave crests turn away from being nearly perpendicular to the contours. This behaviour of sand-wave crest orientation has been observed in a number of sidescan surveys on different banks, but usually true orientation values are not given. However, for the Leman Bank Caston (1972) gives an example with sand-wave crest orientation at the bank foot only 5° from perpendicular to the bank crest, but 39° at about 10m water depth. These angles imply a ratio of near-bed transverse to longitudinal component increasing from 0.088 at the bank foot to 0.81 near the bank crest. This increase, by a factor of 9, is about twice that inferred from Secs. 2.3.2, 2.3.3., and may be due to the upper bank small sand waves having been formed more recently by currents, associated with surface waves, than the larger sand waves near the bottom of the bank.

Estimation of the current direction at the site from the regional directions (Secs. 2.3, 1 to 3) is rather uncertain, because the orientation angles of the SE portion of Ower Bank and the nearest parts of Leman and Inner Banks are smaller, approximately 130°/310°, than those of central-southeast Well Bank and the NW end of Ower Bank, about 140°/320° to 145/325°. These latter angles may have had more influence on the regional depth-mean current directions (of 151° for extreme current and 329° to 335° for peak tidal current) because the latter portions of bank are longer. However, observations show tidal current directions in the site neighbourhood, which are much closer to the trend of the SE portion of Ower Bank (see Caston and Stride's (1970) fig. 1), e.g. a near bed direction of about 315° at a position a little SW of the site, beyond the bank foot ("Transocean 2" platform at 53°06'42"N, 2°03'22"E), and a near-surface tidal current station also SW of the SE portion of Ower Bank gave near-surface direction 321°. Sec. 2.6 uses contour, and regional peak current, directions 130°/310° and 151°/331°.

2.4 50-year extreme waves.

2.4.1 Regional values from Dept. of Energy "Guidance" notes

Regional values of 50-year extreme wave height and the corresponding most probable value of zero-up-crossing period of the highest waves in the site area are predicted to be 17m and 12 sec, by the diagrams included in the "Guidance" notes published by Dept. of Energy (1977). More recent data and shelf-sea wave forecasting techniques (Bretschneider, 1973; Carter, 1982) known to IOS do not indicate any need for significant changes for the Southern North Sea (L. Draper, pers. comm.). The method of derivation (Draper, 1972) uses firstly observations, largely from lightvessels (Smiths Knoll and Dowsing in regard to the site area) extrapolated to 50-year values, and secondly predictions from the Darbyshire (1963) wave forecasting techniques, both using 50-year extreme winds. "Regional" implies that no specific allowance was made for individual banks. The Norfolk banks collectively will have influenced the more extreme waves reaching Smiths Knoll lightvessel rather similarly to those reaching the site area.

2.4.2 Attenuation of the waves on crossing banks.

To reliably assess wave refraction and attenuation caused by crossing individual banks, wave refraction computations would be needed for each wind direction required (particularly between NW and NE). Where the resulting wave heights exceed about 0.8 times local water depth the waves would be assumed to break and be reduced to that height. The computations would be complex through having to cover a large area, and of doubtful accuracy because of the length and narrowness of the banks, and uncertainty about boundary conditions. So far as attenuation is concerned, an approximate substitute is derivable from figs. 3, 4 of Tucker, Carr and Pitt (1983). They found that waves, after crossing the crest of the Sizewell-Dunwich bank system, had been attenuated to significant height of about three-fifths mean bank crest water depth, with no systematic change of wave period (their fig. 6). Assuming this result to be applicable to offshore banks in deeper water, (3/5) times water depths over bank crests can be compared with the significant height, about (17/2.3) = 7.4m, corresponding to the 50-year extreme wave height, 17m. The factor 2.3 assumes (Ewing 1973) a 12-hour duration of unchanged wave conditions.

2.4.3 Tidal and storm surge water level variations

Observed M2 and S2 tidal ranges for the site position are about 1.4m and 0.6m (Prandle, 1980) so that mean springs range is about 2m and extreme springs range about 2.6m. 50-year extreme storm surge values in the area are predicted as +2.2m and -2m (R.A. Flather, pers. comm.). The 50-year minimum water level is predictable approximately as mean springs low water level lowered by the 50-year extreme negative surge of 2m (R.A. Flather, pers. comm.). This comes out to 1.7m below chart datum (extreme springs low water, about 0.3m below mean springs low water). Similarly the 50-year maximum water level is predicted as 0.3m plus 2m (mean springs range) plus 2.2m (50-year maximum positive surge) = 4.5m above chart datum.

2.4.4 Wave attenuation by Ower and neighbouring banks

The most favourable conditions for maximum wave height in the site area would be expected to occur at tidal high-water times during the part of a severe storm sequence with northerly gales and an extreme positive water level surge. The waves would be travelling to approximately S with a 50-year maximum of water depth over the banks crossed of chart depth plus 2.3m (tide) + 2.2m (surge) plus say 1m for an extreme reduction of level at the bank crest (not at the site) by the wave action (Sec. 2.6.4), i.e. chart depth + 5.5m. Taking minimum crest chart depth as 5m, wave attenuation to significant height $^3/5$ of (5m + 5.5m), i.e. 6.3m, is predicted. Maximum attenuation would be predicted near low tide times together with an extreme negative surge (2m). However, the corresponding 3m water depth with extreme waves would cause maximum crest erosion, say 2m. This implies significant wave height $^3/5$ of about crest chart depth, i.e. $^3/5$ of 5.0m, i.e. 3.0m. In fact some of the wave energy is likely to only cross lower portions of bank crest, or to reach the area by wave refraction so that it travels SE between banks rather than over them. Thus the above significant height estimates are increased tentatively to 7m and 4m (mean wave heights $^1/\sqrt{2}$ of these = 5m, 2.8m).

Attenuation of the waves from some directions over the shallow Dogger Bank further north has in principle been taken into account in the 50-year extreme height of about 18m given by Dept. of Energy (1977) just north of all the Norfolk Banks.

2.4.5 Waves from Southeast

In contrast, waves from SE at the site have a fetch almost free from banks and might produce equally high waves. For example, an extreme SE gale might have speed 20m/s lasting at least 11 hours, so that the waves were determined by the 150km fetch. Predicted significant heights are 4m, 4.4m, 4.7m, averaging 4.37m, mean wave height 3.1m, by the methods of respectively Carter (1982), Bretschneider (1973) and Darbyshire (1963).

(The differences between the methods' predictions are by smaller percentages for the extreme waves from northerly points). However, the wave periods forecast for this SE gale are only about 6.6 sec and the wave oscillatory speeds at the bed and the wave enhancement of sand transport rates much less than for waves of similar height from the north, even though the attenuation discussed earlier of waves from north affects longer-period waves more strongly, and the mean period of extreme-height waves is assumed reduced from 12 sec to 11 sec, as derived for Smith's Knoll L.V. from observations there. No account has been taken of modification of the waves by the currents, but its effects should largely cancel between the currents to the NW and SE quadrants.

2.4.6. 50-year wave parameters at the site

To estimate 50-year wave significant height and period at the site reliably from the above-discussed regional values would require use of wave refraction computations. Of course wave recordings at the site, by a waverider buoy, Sec. 4, would have been preferable, and would still be valuable in autumn 1984 - spring 1985 to include any gales from long-fetch directions. Lacking refraction computations or wave observations, 50-year wave period and mean height at the site are taken to approximately equal the above regional values, i.e. 11 sec, and 5m or 2.8m for maximum or minimum water depth.

2.5 Sediment size distribution

While IOS have no bed sediment sample analyses from Ower Bank itself four are available from Well, Leman and Inner Banks, together with Houbolt's (1968) 26 samples from Well Bank. The similar tidal current speeds and wave conditions on these four banks and their isolation from sand sources make big differences in sand size distribution unlikely. Houbolt (1968) notes a test boring near the NW end of Ower Bank with "fine to medium sand" (125-500μm) and presents size analyses of the sand in the 26 samples (from 5 traverses) of Well Bank. The median diameters were mostly between 210 and 280 microns (μm). Two IOS samples, one on top of Leman Bank, one on the sand wave "apron" adjoining the head of Inner Bank gave smaller median diameters, 207 and 209μm, with respectively 6 and 16% smaller than 125μm, and 41 and 34% in the range 125-177μm, and 5 and 2% mud (<62μm), and zero and 11.8% gravel (>2000μm) respectively. Another two IOS samples, from Well Bank, respectively from the foot of the gentle slope and the top of the steep slope, had median diameters 304μm and 274μm, with 3% and zero mud and 0.3% and 9.5% gravel. This gravel in the two bank foot samples may be from the interbank floor. However, Houbolt reports a few per cent of gravel or very coarse sand grade in most of his Well Bank samples (though some will be rather fragmental shelly material). For calculation of (mainly bedload) sand transport rates a median diameter d_{50} of the mobile material of 250μm is assumed. Mud content over about 15% (Terwindt, 1971) and median diameter over 0.5mm (Terwindt, 1971) could hinder sand wave formation.

2.6 Predictions of extreme short-term sand transport rates and consequent bed level changes.

2.6.1. Sand transport

The site is sufficiently far from the end of the bank that there can be assumed to be no change in the longitudinal current component along a contour, although its magnitude decreases slowly between successive contours towards the crest (Sec. 2.3.3). However, as a result of the faster increase in the transverse current component towards the crest (Sec. 2.3.2), the transverse component of the sand transport vector has positive gradient towards the crest on the (northgoing) tide. On the southgoing tide, though the gradient is now in the opposite sense, the currents are likely to be less, except that extreme storm contributions are greater in the southgoing sense.

The local time rate of erosion is equal to

$$C^{-1}\delta q_x/\delta x \qquad (3)$$

in terms of transverse gradient of the volume transport rate transverse component, q_x, while **C** = 0.6 is the volume packing coefficient of the sand.

The rate of erosion (deposition if negative) at the site is therefore estimated by

$$[(q_x)15c - (q_x)25c]/\mathbf{C}(x_{15c} - x_{25c}) \qquad (4)$$

where 15c, 25c refer to the 15m and 25m chart contours, $(x_{15c}-x_{25c})$ being their separation distance, 716m, according to the section (Fig. 12). The sand transport vector, $\underline{q}$, at and near the site is of course oblique to the contours and the transverse component, q_x, upslope or downslope is required. The vector, $\underline{q}$, is taken parallel to the current vector, $\underline{U}_1$, at 1m above the bed. The transverse component q_x of the vector $\underline{q}$ is then calculated, assuming $\underline{q}$ acts in the same direction as resultant velocity, $\underline{u}_1$.

Since the tidal currents are strong it is assumed that the wave induced velocities near the bed stir up the sediment thereby enhancing the sediment load, and that is then transported approximately in the direction of the tidal currents.

2.6.2 Formulae for sand transport rate under currents alone

The sand transport rate required is that directly relevant to bed level changes, i.e. excluding fine material - very fine sand grade and smaller, i.e. <125µm, which can travel long distances once put into suspension: e.g. 40km in a single storm in the German Bight, Gadow and Reineck, 1968. For sizes over about 125 microns, many grains will sometimes move as bed load and sometimes in suspension. "Bedload" transport rate prediction formulae usually include such grains in suspension. The distinction from "total load" sand transport rate prediction formulae is that the latter include suspension load at all levels in the water, especially rivers and flumes where it is more readily measured. Such "total load" prediction formulae e.g. Ackers and White (1973), Engelund and Hansen (1967), have been developed or calibrated mainly from measured bed-load plus all suspension load, for which large numbers of data sets are available for rivers and flumes, and are therefore expected to over-estimate rates for the present purpose. In principle we require "bedload" in the above sense, including grains >125µm travelling short distances in suspension. It is approximately the transport rate involved in tracer dispersion, and in sand ripple and sand wave displacement or shape changes. The first two prediction methods to be used are of this type and the second two of "total load" type.

(a) Hardisty formula

Many studies have shown that the bedload transport rate under a steady uniform current is related to the cube of the near-bed velocity, which is an expression of the power of the current. A predictive formula for bed load, calibrated using flume data, has been presented by Hardisty (1983). This states that

$$\underline{q} = k_1 \left(|\underline{u}_1|^2 - |\underline{u}_{1,crit}|^2 \right) \underline{u}_1/\rho_s \qquad (5)$$

where $|\underline{u}_{1,crit}|$ is the movement threshold value of $|\underline{u}_1|$ for the particular grain size and k_1 is a coefficient given by 0.68×10^{-5} and 0.47×10^{-5} gm cm^{-4}s^2 for median diameter 0.18 and 0.27mm respectively, so that for a grain size of 250µm, k_1 is given the value 0.51×10^{-5} gm cm^{-4}s^2 by interpolation. Its use may imply a 15% over-estimate of transport rate, since the individual flume data sets for very high transport rates can be shown to give k_1 values averaging $0.44.10^{-5}$ gm cm^{-4}s^2.

(b) Sternberg bedload formula

Another version of the cubic velocity dependence is due to Sternberg (e.g. 1972)

$$\underline{q} = K\, |\underline{u}_*|^3 / g(\rho_{s/\rho} - 1)\,\mathrm{cm}^2\mathrm{s}^{-1} \qquad (6)$$

For the present study we require values of k for $|\underline{u}$ about or above 1m/s. One value given both by approximate theory and very high transport rate flume data (Engelund, 1981) is K = 5. Siegenthaler (1982) deduced K = 6.6 or 9.4 (the greater, 9.4, will be used) from mean spring and mean neap tide deposit layer thicknesses and independently known tidal range ratio in tidal estuary cross-strata. Langhorne (1981) gives

$$K \simeq 0.18[(|\underline{u}_*|^2/2.86) - 1] \qquad (7)$$

from detailed measurements of shape changes of a large sand wave over tidal cycles with u_1 up to 90 cm/s.

...e total load prediction method

73) method is expressed in terms of the transition between
...e for bedload alone and suspension load alone using
...asoning. The necessary coefficients were derived empirically
00 data sets. The formulation is fairly complex, but
...ved by Heathershaw (1981). Its predictions were later
e well with a variety of other deep river and flume data
d Crabbe, 1973). Its predictions also agree with tracer
r (the shallower site T1 in) Swansea Bay (Heathershaw, 1981),
that they overestimate bedload transport rates under currents
...tion will have enhanced the tracer dispersion.

...nd Hansen prediction method

...tal load formula was developed largely from flume data
... those authors' successful method for predicting flow
...nd gives about as good agreement as any method with independent
...er data sets (White, Milli and Crabbe, 1973). The formulation

$$q = \frac{0.05\, \rho_s |\underline{U}^2| |\underline{u}_*|^3}{\rho g d_{50} (\rho_{s/\rho} - 1)^2} \qquad (8)$$

...icted sediment transport rates, using the above methods,
... Table 2. Calculations were made for the chart depths of
...tres for the highest and lowest water level conditions (+4.5m
tide and extreme positive surge (and maximum SE going tidal current,
of Sager and Sammler, 1975), and - 1.7m for lowest tide
surge, and approximately maximum NW going tidal current.
...ies (Table 1) are derived from the considerations outlined in
..., 2.3. (with regional mean depth 32m). Despite the differences in
...ions, the calculated sediment transport rates are encouragingly close.

...ransport rates are the resultant rates which have different
the bank orientation at the two depths spanning the depth of
... platform site. The along-bank transport-rate component is

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of wave propagation. The value 0.0162 for the constant was derived from laboratory measurements but seems to give reasonable field predictions. The orbital velocity of the waves near the bed is estimated from linear theory which is surprisingly accurate even for large-amplitude waves (Grace 1973).

(b) Owen-Thorn enhancement factor for "total load" sand transport

This factor is an entirely empirical relationship found from measurements in the Thames Estuary, of profiles of suspension concentration and of velocity fluctuations near the bed. Owen and Thorn (1978) give a graph of sand transport rate enhancement factor F_{OT} for various rms oscillation velocities, u'_{rms}. The value of F_{OT} ranges between values of 3 for u'_{rms} of 8 cms^{-1} to 30 for u'_{rms} of about 25 cms^{-1} (the maximum obtained) taken to indicate proportionality to ${u'_{rms}}^2$.

Results

The calculated sediment transport rates and erosion/deposition rates are shown in Table 2. Only the Bijker technique is included. The Owen-Thorn enhancement factor is of the order of 200, and it is thought that, since it refers to suspension and a smaller grain size, and was derived from data for much smaller and shorter-period waves, with unknown turbulent fluctuations included, the extrapolation would be inappropriate.

The wave action enhances the sediment transport rates and causes potential erosion/deposition over a period of 3 hrs of several centimetres. Again this would be reduced by the requirement to average over the tidal cycle.

2.6.4. Relevance of Huthnance's (1982a,b) papers

It was originally thought, and implied in the study schedule, that numerical application of two papers (1982a,b) by J.M. Huthnance would form a major part of the study. The two papers form easily the most comprehensive theoretical treatment yet of offshore tidal sand banks, firstly long straight banks and secondly some "humps" of mathematically simple form and of finite length.

Use of the formulae in the first paper and in Huthnance (1973) for current distribution over a long straight bank was mentioned in Sec. 2.3.3. In the 1982 papers the theoretical assumptions made are suitable for the

Norfolk banks but the theory developed in the first paper concerns only (1) bank initial formation (2) "final steady states", the latter being under regular tidal currents with a relevant subsection on the modifications of the final steady states by constant wave conditions. Some examples in the second paper of bank evolution are not relevant to the present problem. The waves have the effect of flattening and broadening the final equilibrium bank profile (see Huthnance's fig. 7), very markedly so that his fig. 7's curves would correspond to level changes of $^1/3$ of bank height over parts of the bank slopes. However, the time taken to attain the profiles is several times the basic time scale, of 135 years for his numerical values. It does not seem possible to argue that this timescale can be greatly reduced by taking extreme waves and by reconsidering Huthnance's assumed numerical values and coefficients. These were chosen to apply to moderate continuous waves produced by a constant long-fetch wind of 10 metres/sec. Huthnance's sand transport rate formula is within 10% of Hardisty's (equation (5) above). However, even if stormy conditions with a wind speed of 25 m/s say, persisted all the time the time scale would still be of the order of 50 years. A single storm has gales affecting the southern North Sea for a week or less and that is under 0.1% of 50 years. However, if the bank crest rather than the evolution of the whole bank is considered, the sand transport rates in extreme conditions are predictable as the order of 10 times the maximum in Table 2 and the assumed temporary crest level reductions of 1 and 2m assumed in obtaining extreme conditions in Sec. 2.4 seem of the right order, and consistent with the evidence presented in Section 1.

2.7 Conclusions

1. Total bed erosion at site depth caused by a single 50-year storm would be less than 10cm. Early in the storm other bed level changes would be caused by smoothing out of any sand waves present.

2. Bedload sand transport rates are approximately proportional to the cube of local 1-metre current speed under strong currents, but to the cube of local significant wave height under extreme waves at times of less strong current. Bed level change rates are, further, proportional to the sine of the local angle between current direction and contours. Thus the values in Table 3 may be 2 or 3 times overestimated through the use, in the absence of adequate local information, of large-scale regional current direction off the bank.

Table 1. Depth, current and wave numerical values for sand transport rate estimates

Case	Chart depth m	Water depth m	1-metre current speed $\lvert \underline{u}_1 \rvert$ m/s	1-metre current direction	Angle of current to contours α
AHW	25	29.5	1.065	332.9°	22.9°
BHW	15	19.5	1.035	340.3°	30.3°
ALW	25	23.3	1.177	335.7°	25.7°
BLW	15	13.3	1.191	348.6°	38.6°

Case	Mean wave height m	Wave period s	Wave orbital speed at bed m/s	Corresponding factors of increase	
				Bed shear stress (9)	Transport rate
AHW	5	11	0.964	3.33	6.07
BHW	5	11	1.386	6.10	15.07
AHW	2.8	11	0.670	1.92	2.67
BHW	2.8	11	1.024	3.10	5.46

Table 2. Predicted sand transport rates and bed level change rates.

(a) Currents only

Case	Upslope (+) or downslope (-) component of sand transport rate (cm^2s^{-1})				
	Bed load			Total load	
	Hardisty	Sternberg		Ackers and White	Engelund and Hansen
		K=9.4	K from (7)		
AHW	0.658	1.17	0.46	3.5	3.4
BHW	0.824	1.47	0.57	4.2	3.8
ALW	1.05	1.85	0.94	10.4	6.5
BLW	1.57	2.76	1.45	11.9	6.9
(b) Above values modified for wave action by multiplication by the factors given in Table 1.					
AHW	4.1	7.4	2.9	22	21
BHW	12.4	22.2	8.6	63	57
ALW	2.8	4.9	2.5	28	17.4
BLW	8.6	14.0	7.9	65	38

Table 3. Predicted effects on bed level

(a) Currents only

Case	Average erosion (+) or deposition (-) rate, using equation (4) on values in Table 2(a).		Corresponding erosion (+) or deposition (-) at these rates in 3 hours	
	$cm\ s^{-1}$		cm	
	Hardisty	Sternberg max.	Hardisty	Sternberg max.
HW	$.386.10^{-5}$	$0.7.10^{-5}$	0.042	0.076
LW	$1.21.10^{-5}$	$2.1.10^{-5}$	0.13	0.23
	(b) As above but using the values in Table 2(b).			
HW	19.10^{-5}	34.10^{-5}	2.1	3.7
LW	$13.5.10^{-5}$	21.10^{-5}	1.5	2.3

2.8 Notation

15c, 25c (as subscripts) refer to chart depths 15m, 25m.

C	volume packing coefficent of sand on the bed.
d_{50}	median diameter of sand on the bed
F_B, F_{OT}	enhancement factors of bed shear stress by wave action in Bijker's (B) and Owen and Thorn's (OT) methods.
g	gravitational acceleration.
h	local water depth, averaged over surface waves but taking account of tidal water level and any wind-driven (surge) effect on water level
K	multiplying coefficent in Sternberg's formula, equation (6).
k_1	multiplying coefficient in Hardisty's formula, equation (5).
$\underline{q}, \lvert\underline{q}\rvert$	vector volume sand transport rate, its magnitude and
q_x, q_y	x and y components.
R	excess of peak NW-going over peak SE-going depth-mean longitudinal component of tidal current (estimate for site).
r_1	1-metre current speed derived from R.
$\underline{u}_z, \lvert\underline{u}_z\rvert,$	vector water velocity, its magnitude and z and y components
u_z, v_z	at level z above the bed.
$u_{z,r}; v_{z,h}$	u_z, v_z where local water depth h needs to be specified.
u_1 crit	value of u_1 for which sand movement begins.
$\underline{u}_*, \lvert\underline{u}_*\rvert,$	vector friction velocity, its magnitude and
u_*, v_*	x and y components.
$\underline{u}_{wb}, \lvert\underline{u}_{wb}\rvert$	wave orbital velocity and its magnitude
$\underline{U}, \lvert\underline{U}\rvert$	depth mean velocity, its magnitude and x and y
U, V	components. Can be given subscript h.
x, y, z	Cartesian coordinates, z vertically upwards, x perpendicular and y parallel to contours. (x,y taken in directions 040°, 310° at the site).
z_o	bed roughness length.
α	angle between local 1-metre current direction and contours
ρ, ρ_s	water and sand densities (about 1.03 and 2.65 gm cm^{-3}).

SAND WAVES

3.1 OBSERVED HEIGHTS OF SAND WAVES - NORFOLK BANKS

Houbolt's intensive study of the Norfolk banks from Smiths Knoll to the Indefatigable first described sand waves over the banks (Houbolt, 1968). Asymmetric sand waves were found on the gentle flanks, many as high as 6m. The steep sides of the sand waves faced slightly towards the sand bank crest in a NW direction, implying sand transport towards the crest. Sparker records illustrate large sand waves up to 5m over some but not all, sections over the Well Bank. These records were obtained on Houbolt's survey of 12 July 1963.

Caston (1971) found the largest sand waves to be present on the lower part of the gentle flanks of Smiths Knoll, Hewett Ridges, Leman Bank and the Ower Bank. The sand waves diminished in height upwards towards the crest. Smaller sand waves were present on the steep slopes, <1m on Leman). The sand wave crests changed orientation upslope so that they became subparallel to the bank crest at the top of the slope. The steep sides of the sand waves faced the bank crest, implying sand transport up both sides of the sand bank.

Detailed studies of sand waves over sand banks off the Thames approaches (Caston, G.F., 1981) confirmed as a general pattern that the largest sand waves are found low on the gentle flank of a sand bank, diminishing in height and wavelength up the slope as they face towards the crest. Smaller sand waves are found on the steep slopes.

Sonographs taken in May 1968 by Huntings Ltd were examined for the tracks on Fig. 13. The expected pattern of sand waves was observed on all the bank crossings. On both flanks of the Ower Bank the sand waves have sinuous crests. On the gentle flank the sand wave height diminishes from approximately 1.5m on the lower flank to 1m mid-slope. No sand waves are present on the flattish bank top. The wavelength of the sand waves reduced up slope from about 18m to about 12m although this varies along the sinuous crests. On the steep slope the sand wave crest lengths are much shorter. Their heights diminish up slope from 1.5 to 1m, and wavelengths from 12 to 8m. Larger sand waves (3-6m) occur in patches between the sand banks.

IOS* sidescan sonar data for Well and Leman banks obtained in July 1981 (tracks on Fig. 13) observed sand waves of 1-2m, wavelength 25-30m at the base of the slope and 1m sand waves, 10m wavelength on the slopes, decreasing upwards. The presence of aprons of large sand waves (2-4m) SE

* Institute of Oceanographic Sciences

of the heads of Well and Leman was confirmed. It is to be expected that an apron of sand waves is present at the Ower head also.

A preliminary examination of B.G.S.* sonographs obtained in May 1981 (tracks Fig. 13) found large sand waves (8m) on the Hewett ridges but elsewhere large sand waves were only found in patches between the banks. A crossing of the Ower bank showed the same sizes and orientation of sand waves as in 1968. No sand waves were apparent on the bank top.

IOS sonographs obtained in April 1982 again showed large sand waves (5m) only between the banks. The tracks (Fig. 13) did not cross the Ower bank but any change in sand wave size or pattern should apply to the Ower. Sand waves less than 1m were present on the slopes of Leman and Well bank heads. On Broken bank sand waves on the gentle flank were 1-2m high but rounded in shape. No sand waves were present on the tops of the bank heads, or on the central bank sonographs. The paucity and small size of sand waves at this time suggests a degradation of the sand waves during recent storms.

* British Geological Survey, formerly Institute of Geological Sciences.

3.2 EXPECTED HEIGHTS OF SAND WAVES - SE END OF OWER BANK

The time available forthe present study only allowed a preliminary examination of the sonographs but no large sand waves were observed to occur on any of the linear banks, on any of the survey dates. From the consistent pattern observed in 1968 and 1981 the expected height of sand waves at 20m on the SW flank of the Ower Bank head would be 1-1.5m. These sand waves would probably be sinuous crested, with a wavelength of 10-12m and at this depth their steep sides would probably face in a northerly direction. At times these sand waves may be degraded or even smoothed out by storm waves, although removal may occur more readily over the higher central parts of the bank than on the slopes of the sand bank head. However the sand waves on Well Bank observed by Houbolt were considerably larger than those on any sonographs examined in the present study (up to 5m). If exceptional conditions can build larger sand waves on Well Bank then it is probable that larger sand waves will form on the Ower Bank at the same time (see below).

3.3 PREDICTED OCCURRANCE OF LARGE SAND WAVES

It is predicted that large sand waves could form most readily at times of above-mean 'spring' tidal currents and for summer temperatures (which only fall slowly until October) i.e. for the autumn equinoctal spring tides. They could also build more gradually at other spring tides in summer with assistance from moderate waves. The latter conditions are known to have occurred before Houbolt's 12.7.63 survey. Large sand waves are predicted to be much less likely in winter because the lower temperatures require higher current speeds to build sand waves and also because of the more frequent stormy periods. During storms, if near bed wave oscillatory speeds exceed current speeds, sand waves are largely smoothed out. The formation or decay of a large sand wave does not alter bed levels by as much as its maximum crest-trough height. For instance, a reduction of bed level of up to 2m might be associated with the trough of a 4-5m sand wave. Its wavelength could vary from 60 to 300m.

3.4 PREDICTED MOVEMENT OF SAND WAVES

SMSG observations for 4-5m sand waves west of Leman Bank, where tidal current speeds are rather stronger, about 15%, measured an average movement of 4m per day for 32 days. Predicted values for the same group of sand waves are a maximum movement of 11m for a single tide and a net movement of 150m per year. This rate of movement will be greater for smaller sand waves such as those expected to be present at the proposed platform site on the Ower sand bank (Discussion, Sec. 2).

MONITORING PROCEDURES

More observations have been made over the Norfolk banks than for most other groups of sand banks but even so data is sparse. Estimates of long-term changes are based on charts of unknown accuracy. More recent charts demonstrate the variability in the growth and movement of sand banks over one or two decades. The site surveys conducted on behalf of Shell used in Section 1 of this report illustrate the importance of actual measurements in the area of interest. There is no substitute for direct observation and without these surveys the figures for bed level changes on the Ower Bank would have been very rough estimates. The pattern of growth of the Ower Bank head over the last 18 years may not be consistent in the future, especially if there were many gales from unusual directions so Shell is recommended to continue to monitor the actual bank evolution and real bed level changes by repeat surveys. Additional environmental monitoring would help to explain the observed changes between surveys and would facilitate more accurate predictions of future changes.

4.1 SURVEYS

Regular echo-sounder and side-scan sonar surveys are of prime importance. These would determine the sand wave height, wavelength and crest orientation. The latter would demonstrate the sand transport direction. If a survey was conducted on or after a NW or N gale the sand wave crest orientation would give the sand transport direction as modified by the storm wave oscillatory movements. Repeat surveys on the same grid pattern would also measure short term bed level changes. It is suggested that the accurate survey of 25-281.84 (Figure 9) is repeated next winter. If necessary the tracks could be reduced to the main NE-SW lines at over 400m spacing and single intervening lines at approximately 200m spacingwhich would still give adequate coverage with dual channel side scan sonar. Estimates of the size and migration rate of sand waves near the platform site could be assisted by bottom photographs and the use of a TV camera.

4.2 ENVIRONMENTAL MONITORING

Current recordings. The predictions contained in Section 2.3 "currents" of this report are very uncertain due to the paucity of relevant data and theory. Near bed current recordings at or near the platform site are particularly important. Continuous measurements for periods exceeding a month could be tidally analysed to determine spring tidal current speeds and direction. The analysis, just received from Shell of their successful current recordings at 25m chart depth near the site has helped to check the present predictions.

Wave recordings. It is suggested that a waverider buoy should be deployed at the platform site, starting September 1984 to monitor the winter gales.. Those from N and NW are of particular interest.

Wind recordings. An anemometer on the platform would monitor extreme conditions at the site, to correlate with the current and wave reocrds.

Sediment sampling. A few samples should be taken at or near the site and their grain size distribution analysed. The median diameter is particularly useful for sand transport rate prediction methods. The percentage of mud, (and non shelly gravel) and coarse sand grade and larger, should be determined since greater than about 15% and 50% respectively (Sec. 2.5) would discourage sand wave formation.

These measurements will enable more precise predictions to be made about future waves, current speeds and sand transport rates especially under extreme conditions. The advantage of a fixed platform and remote sensing instruments is that extreme conditions may be monitored, in a way impossible from small ships. It is at such times that major sand movements occur, yet we know least about extreme conditions. Environmental monitoring was strongly recommended in the SMSG report 1968 and an appendix gave practical advice on deploying instruments from offshore structures. These SMSG recommendations are still valid, and if followed would ensure that predictions such as those made in Section 2 would have a much sounder basis of fact. Shell-Esso is urged to start a programme of environmental monitoring as soon as is practicable, to increase our knowledge and understanding of the processes active in the North Sea.

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LIST OF FIGURES

Figure 1. Location of proposed platform site.

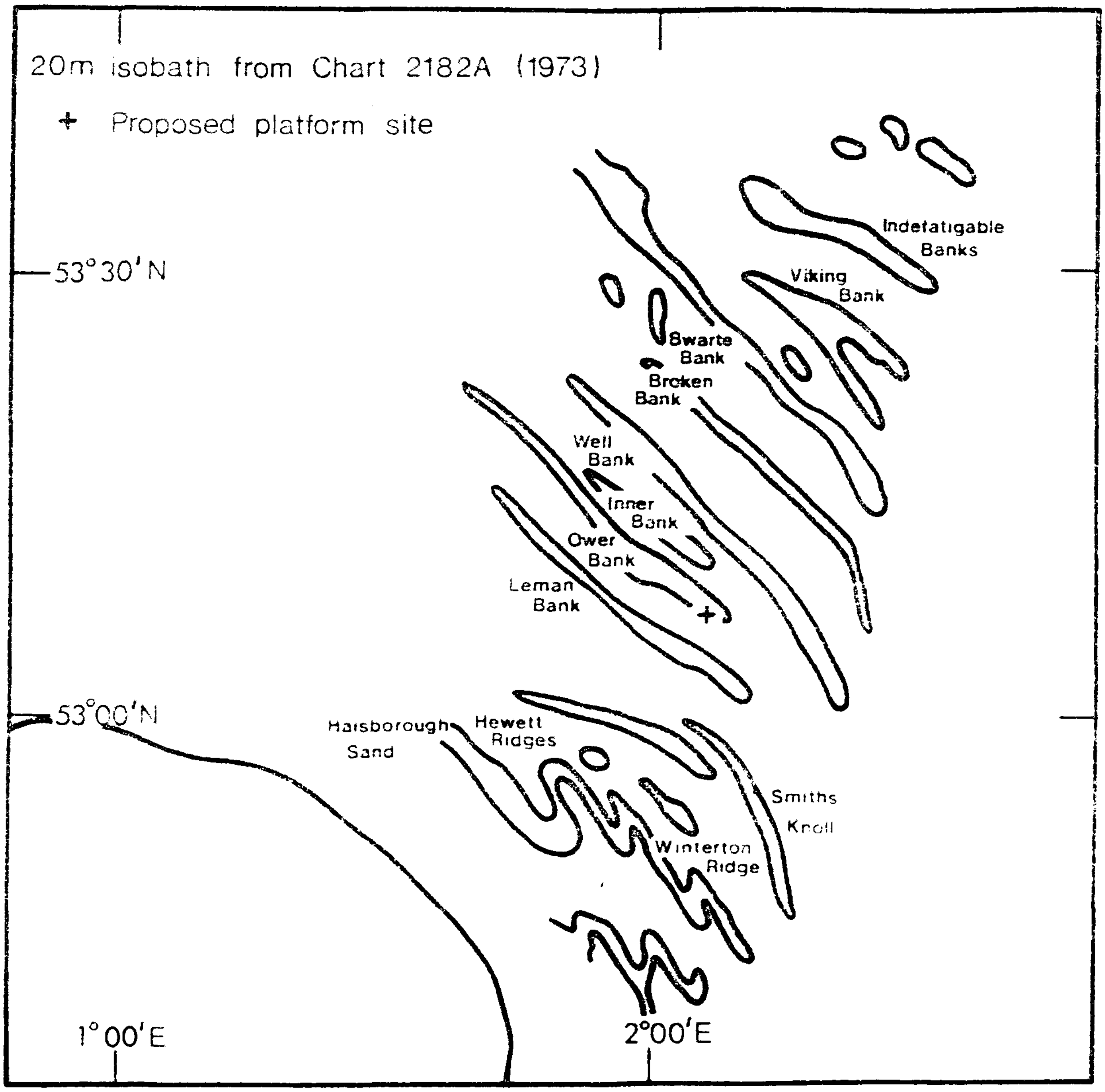
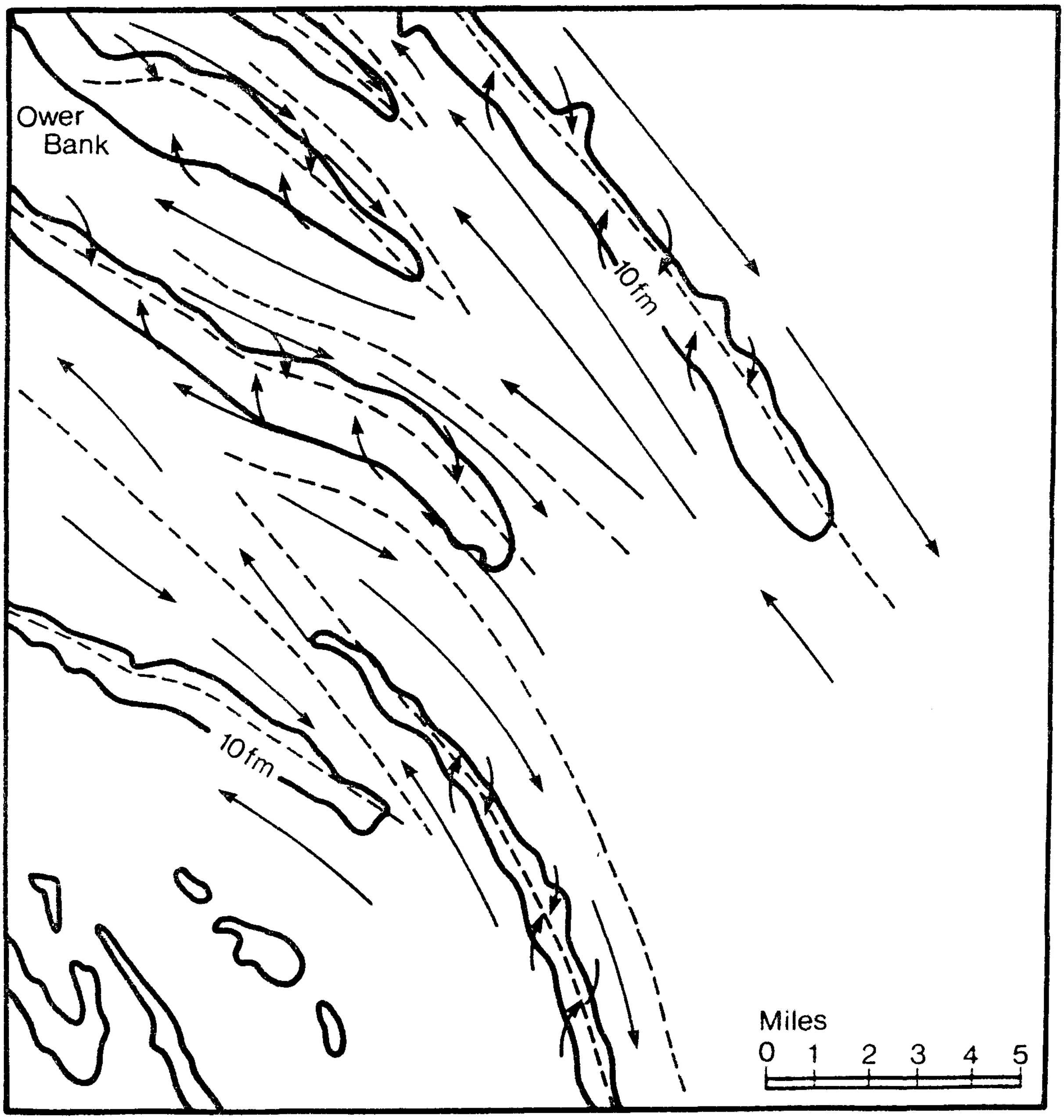


Figure 2. Sand transport directions (after Caston, 1968)
10 fathom isobath shown.



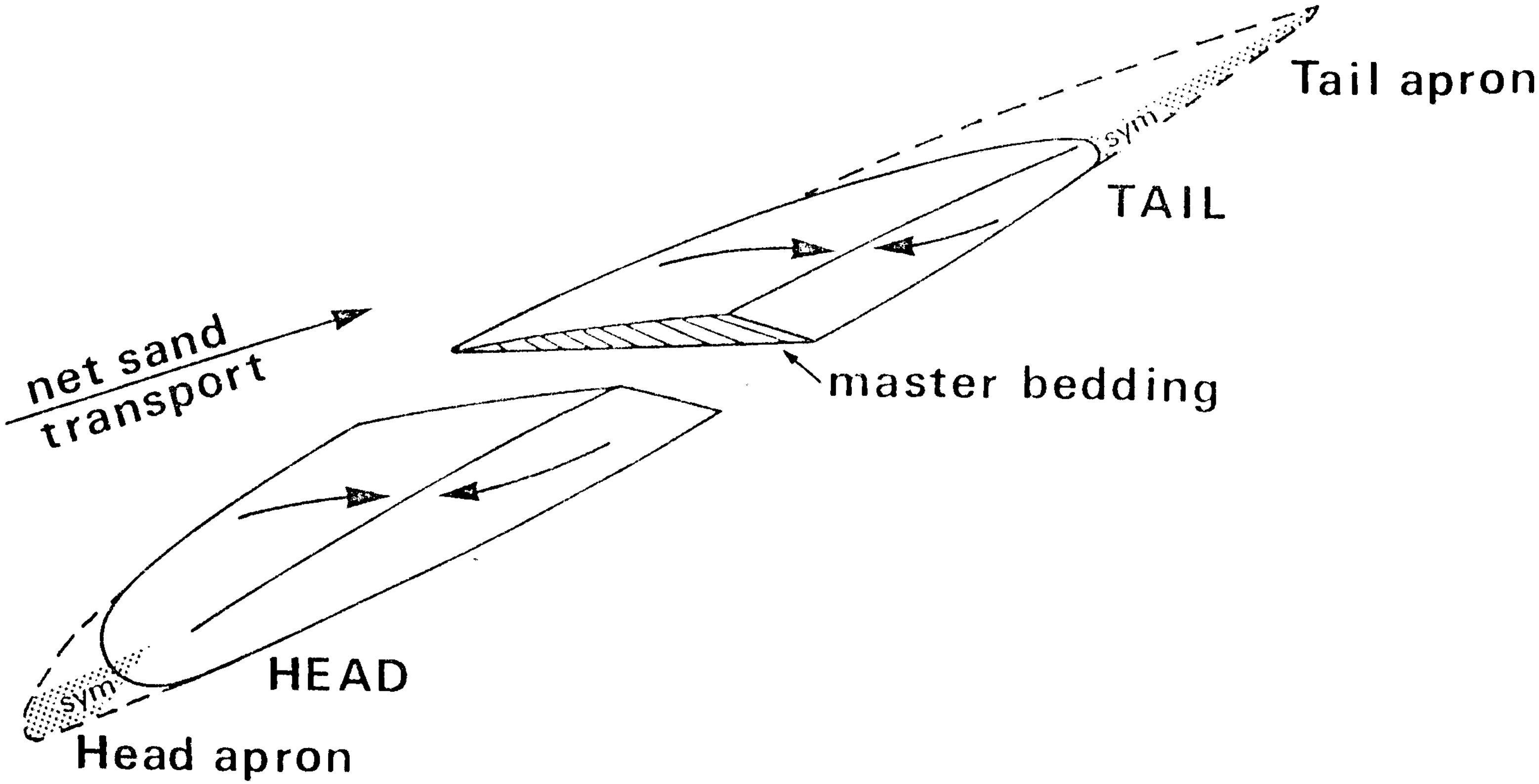


Figure 3. Model of an active sand bank (after Stride, 1982).

Figure 4. 10m and 20m isobaths from charts of 1956-58 (after Provotorov, 1983).

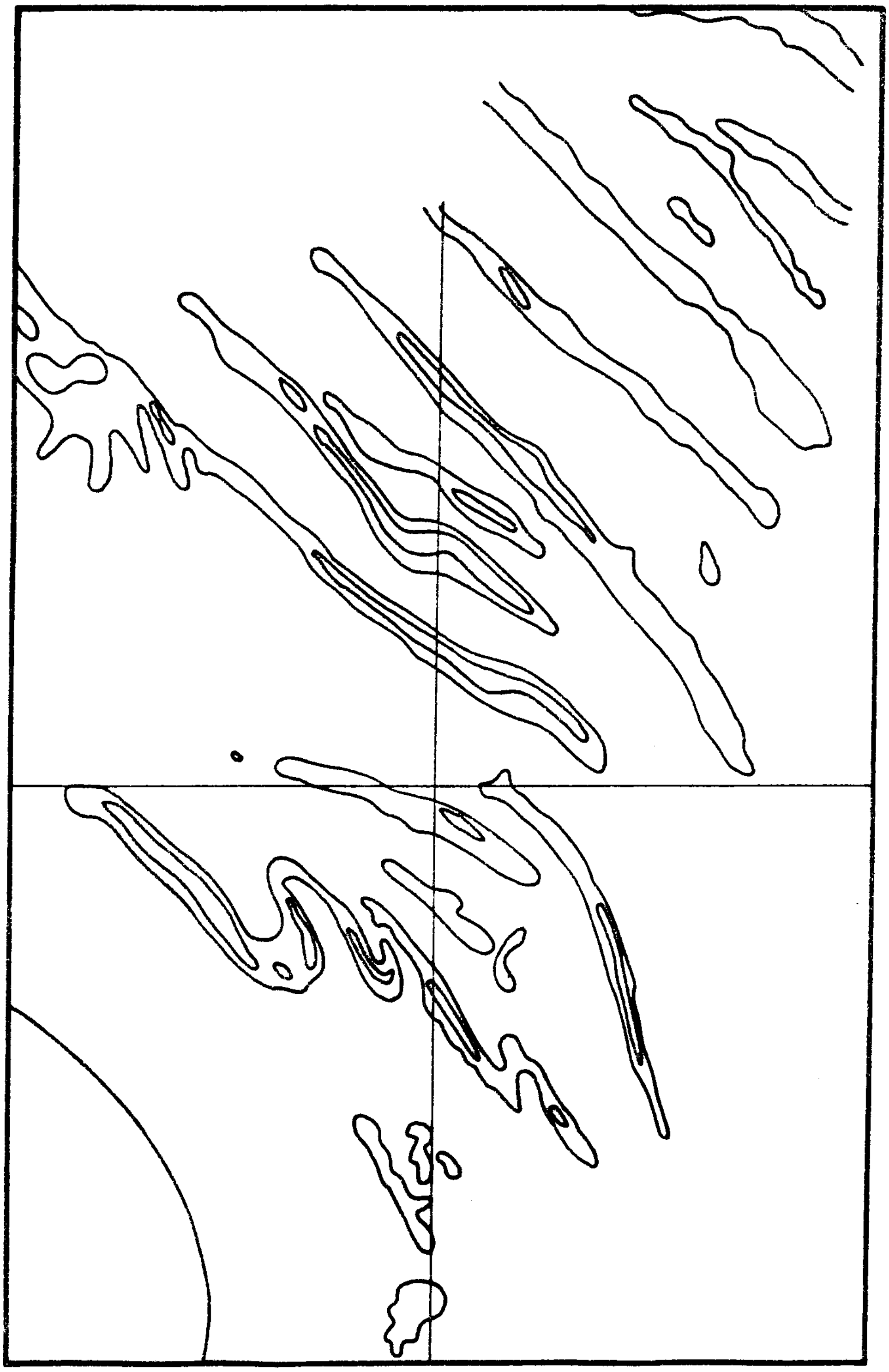


Figure 5. 10m and 20m isobaths from charts of 1968-70 (after Provotorov, 1983).

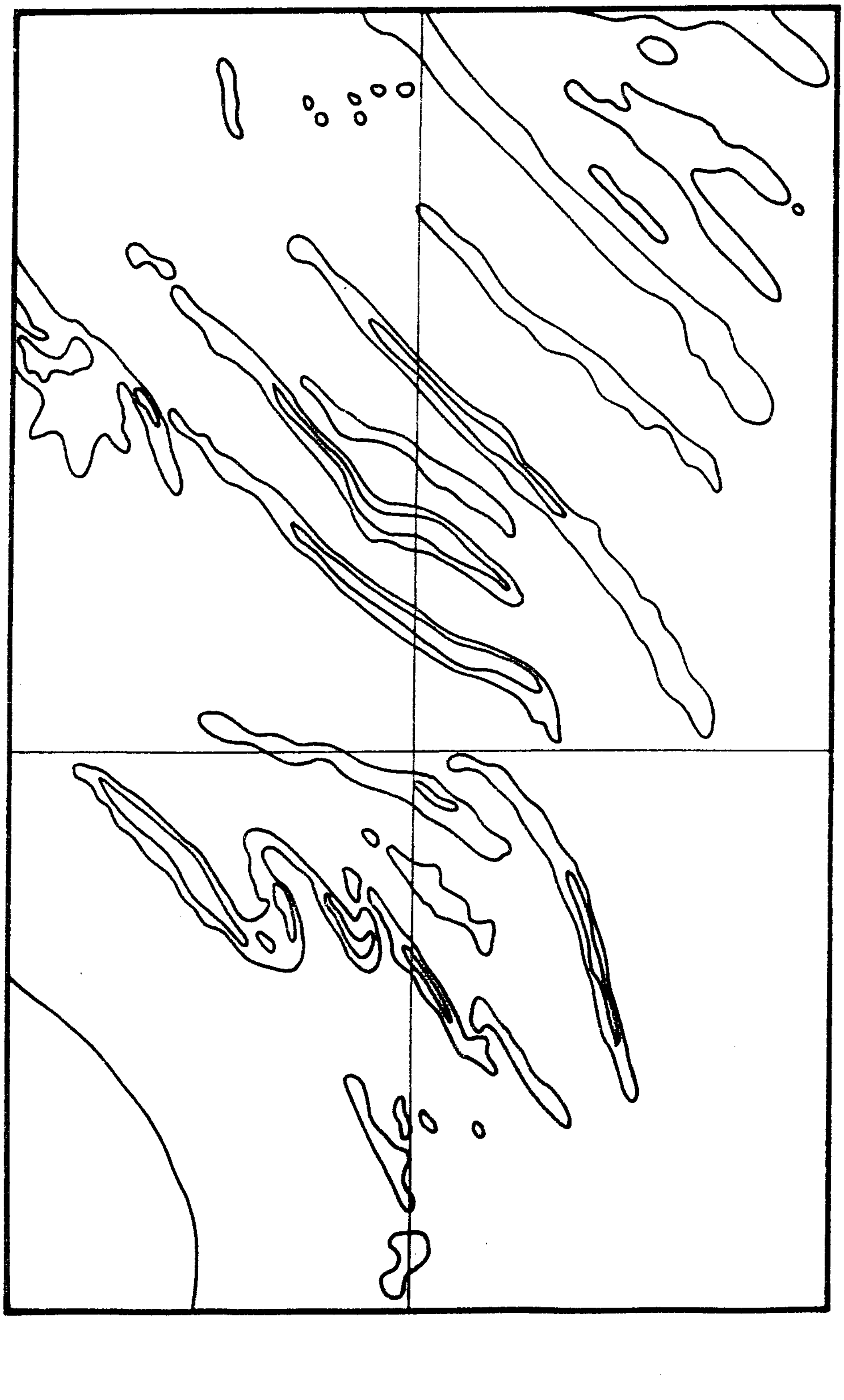


Figure 6. 10m and 20m isobaths from charts of 1976-80 (after Provotorov, 1983).

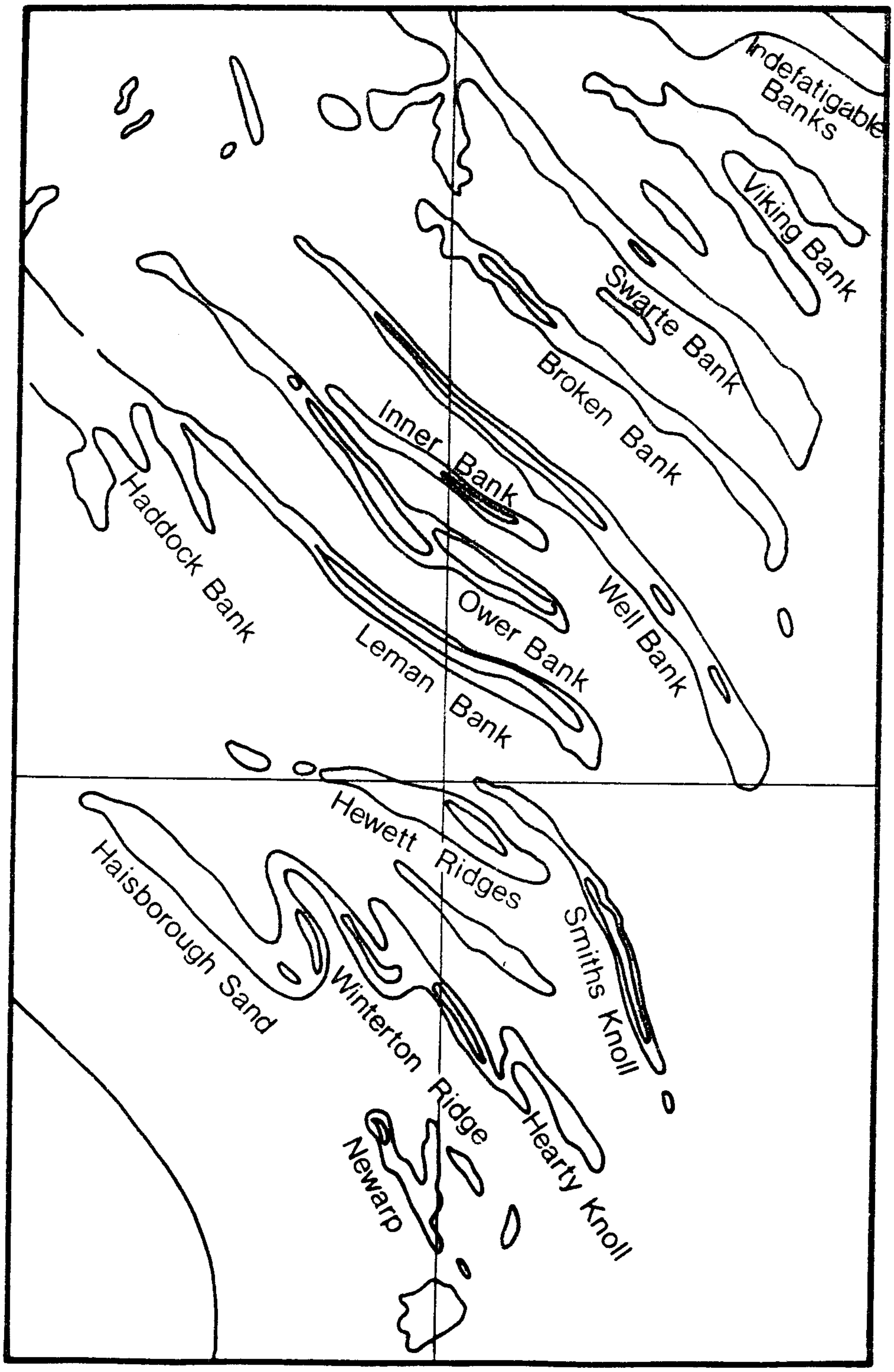


Fig.7

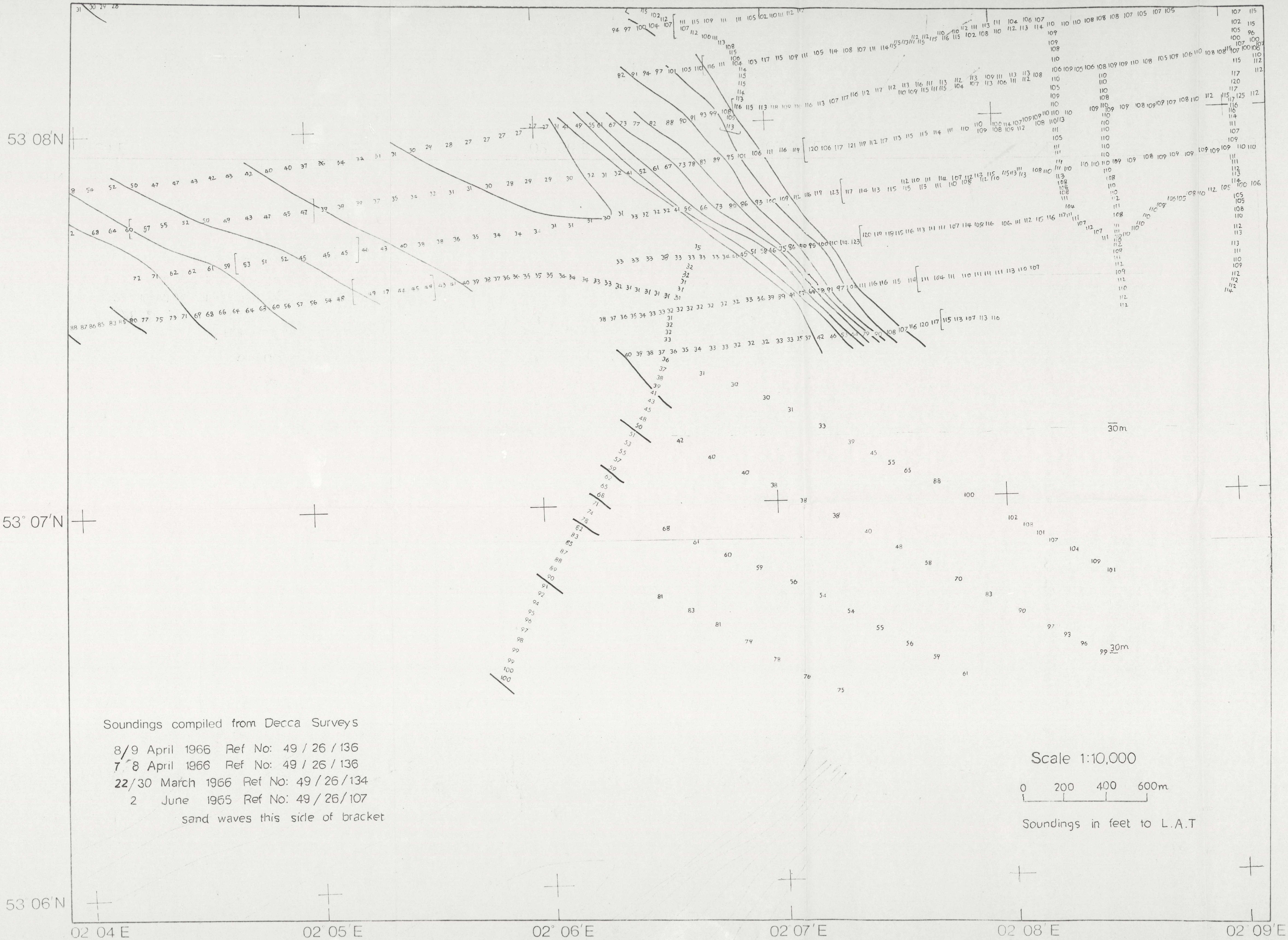

53 08'N
53° 07'N
53 06'N
02 04'E
02 05'E
02° 06'E
02 07'E
02 08'E
02 09'E
30m
30m
Soundings compiled from Decca Surveys
8/9 April 1966 Ref No: 49 / 26 / 136
7/8 April 1966 Ref No: 49 / 26 / 136
22/30 March 1966 Ref No: 49 / 26 / 134
2 June 1965 Ref No: 49 / 26 / 107
sand waves this side of bracket
Scale 1:10,000
0 200 400 600m
Soundings in feet to L.A.T

Fig. 10

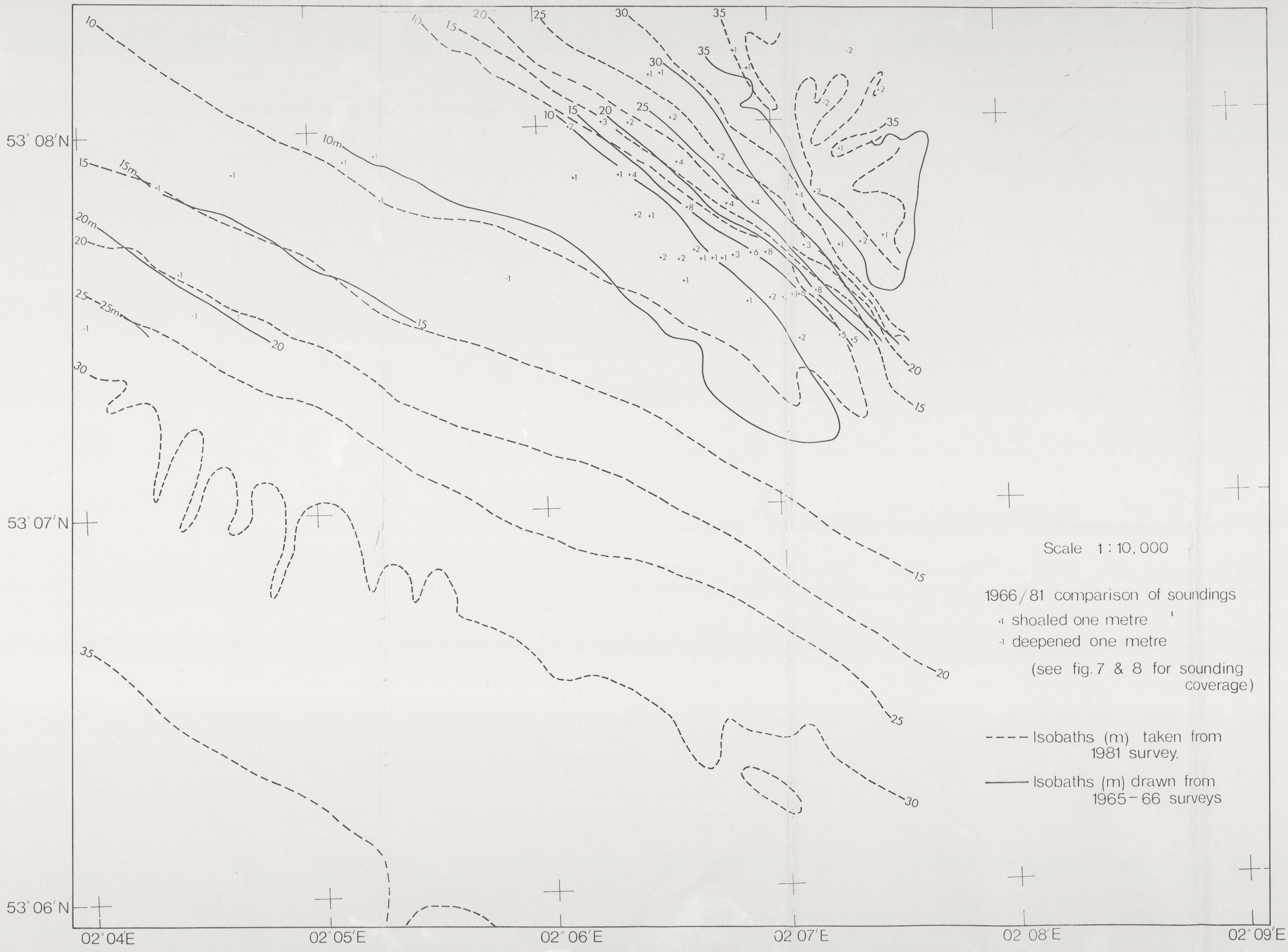

53° 08′N
53° 07′N
53° 06′N
02° 04′E
02° 05′E
02° 06′E
02° 07′E
02° 08′E
02° 09′E
Scale 1 : 10,000
1966/81 comparison of soundings
+1 shoaled one metre
-1 deepened one metre
(see fig. 7 & 8 for sounding coverage)
Isobaths (m) taken from 1981 survey.
Isobaths (m) drawn from 1965-66 surveys

Fig. 11

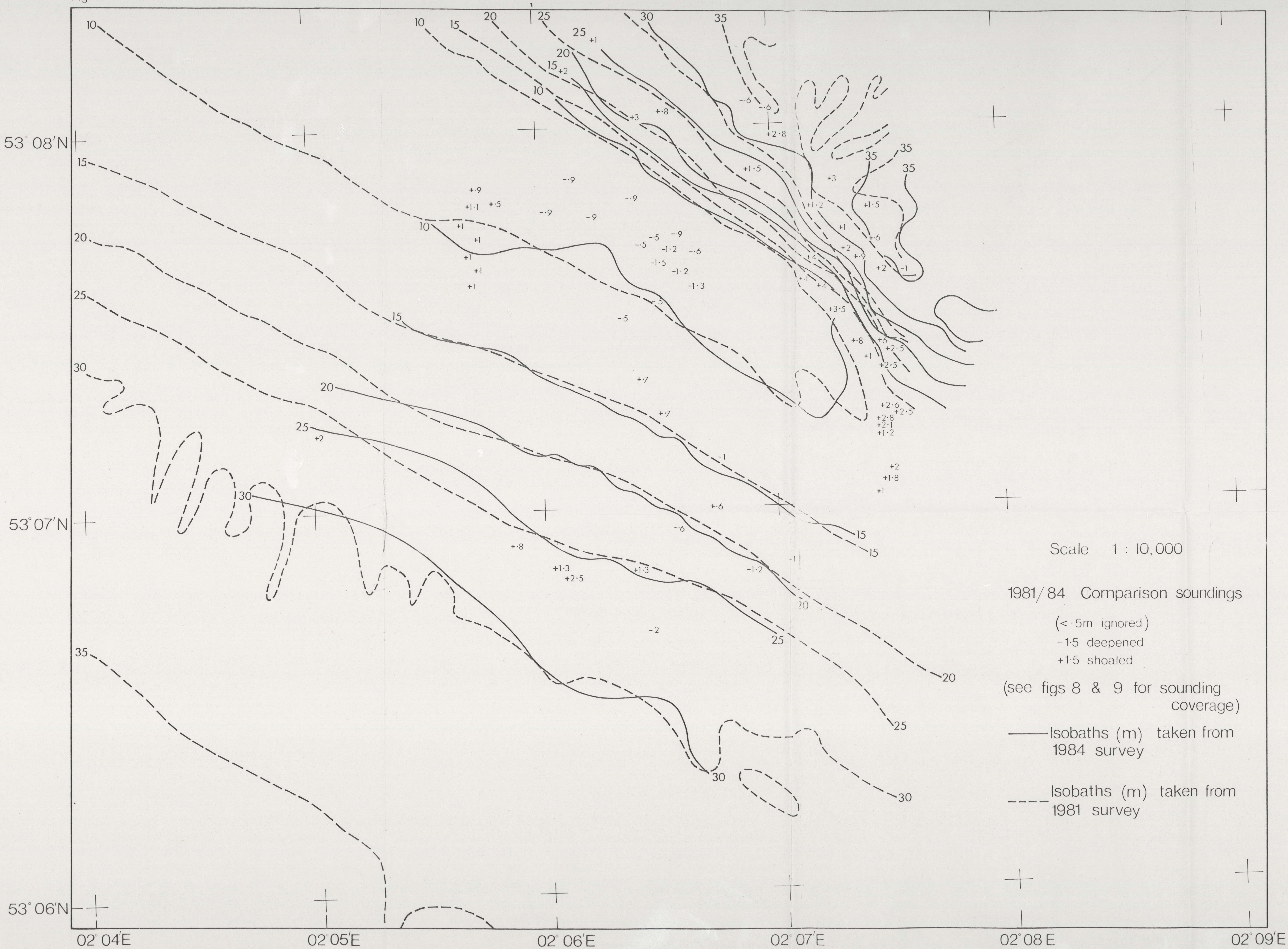

53° 08'N
53° 07'N
53° 06'N
02° 04'E
02° 05'E
02° 06'E
02° 07'E
02° 08'E
02° 09'E
Scale 1 : 10,000
1981/84 Comparison soundings
(< ·5m ignored)
-1·5 deepened
+1·5 shoaled
(see figs 8 & 9 for sounding coverage)
Isobaths (m) taken from 1984 survey
Isobaths (m) taken from 1981 survey

Fig. 12 Cross section of Ower bank Soundings taken from 1981 survey (Fig. 8)

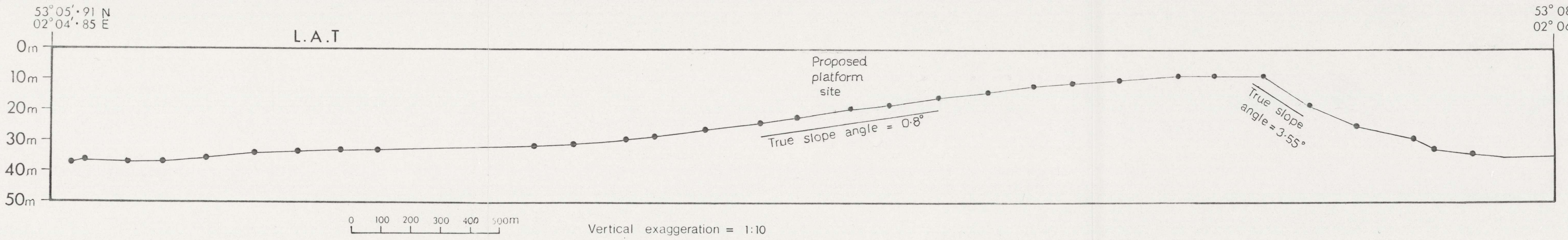
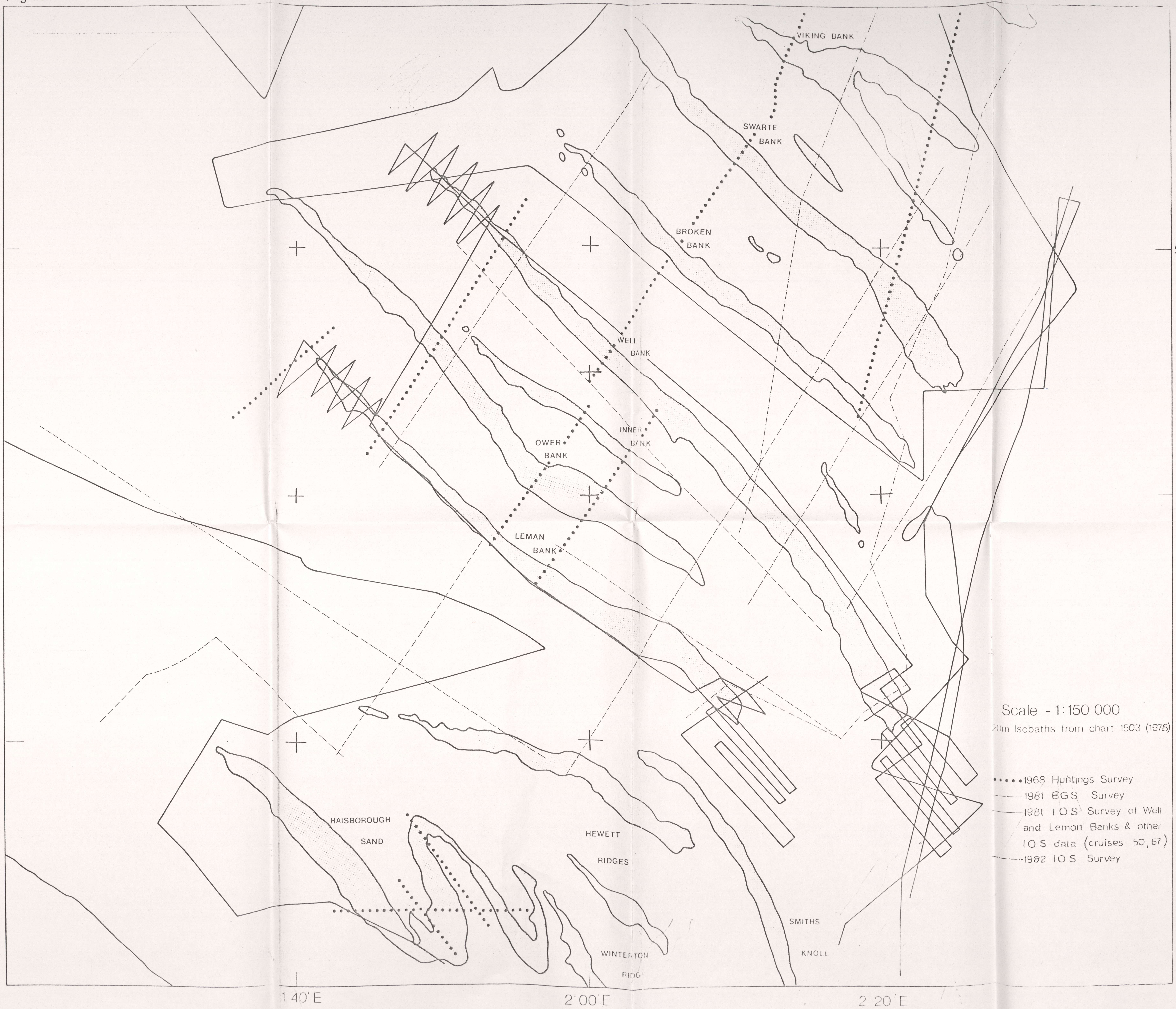


Fig. 13



VIKING BANK
SWARTE BANK
BROKEN BANK
WELL BANK
INNER BANK
OWER BANK
LEMAN BANK
HAISBOROUGH SAND
HEWETT RIDGES
WINTERTON RIDGE
SMITHS KNOLL
53° 20'N
53° 10'N
53° 00'N
1 40'E
2 00'E
2 20'E
Scale - 1:150 000
20m Isobaths from chart 1503 (1978)
1968 Huntings Survey
1981 BGS Survey
1981 IOS Survey of Well and Lemon Banks & other IOS data (cruises 50, 67)
1982 IOS Survey