Characteristic properties of bottom backscattering in the southern Baltic Sea at ultrasound frequencies

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Zygmunt Klusek, Jarosław Tęgowski,
Joanna Szczucka
Institute of Oceanology,
Polish Academy of Sciences,
Sopot

Antoni Śliwiński
Institute of Experimental Physics,
University of Gdańsk,
Gdańsk

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Abstract

The experimental results of an investigation into bottom reverberation in the Polish economic zone of the Baltic Sea were used to determine of the fundamental relationship between the parameters of backscattered signals, and the type of bottom and sediments. Numerous examples of the spatial distribution of these parameters are given.

1. Introduction

Sound scattering at the sea bottom plays an important role in propagation and offers the possibility of using remote sensing methods to determine the physical properties of sediments.

The acoustic properties of Baltic Sea sediments in the ultrasonic frequency range are practically unknown. One can only guess that they should correspond to those of sediments in other shallow seas. However, such an assumption should be valid only for sandy sediments. In large parts of the Baltic Sea there are sediment layers with specific properties related to the geological history of the sea, *e.g.* interbedded silts and clays, the intense, on-going sedimentation of organic substances, and biogeochemical processes. For example, in the Gulf of Gdańsk quite unique sediments appear to be like acoustically soft peats or semifluid silts and clays. In such cases, the acoustic recognition of an interface between the solid and liquid media becomes a problem, especially in the presence of aggregations of near-bottom organisms. Seismoacoustic methods of examining deeply buried sediments have been applied in the geological identification of the morphology and stratification of the Baltic bottom (*e.g.* Svirydov, 1977), but have yielded qualitative results only. On the other hand, quantitative measurements of the reflection and scattering of acoustic signals at the water-sediment boundary and of volume reverberation from the water-bottom boundary layer have been performed only at a few stations (Orłowski, 1984; Klusek, 1989). In his version of the multiple echoes method, Orłowski suggested applying the analogue echo integrator used in biomass estimation to measure the integrated reflection coefficient that he named the pressure sound reflection coefficient. Taking into account the limitations of this method, he determined the values of this parameter at a frequency of 38 kHz for the Baltic deeps (depths > 60 m) at 47 oceanographic stations and presented a geological interpretation of his results. Klusek (1989) performed measurements of bottom reverberation in the Baltic Sea using the same equipment (Simrad EK 38 and EK 120 echosounders, r/v 'Professor Siedlecki') but applying a digital technique. He determined (at the oceanographic stations only) the backscattering coefficient, duration of reverberation and attenuation coefficients in sediments at a frequency of 38 kHz (and sporadically at 120 kHz). Applying methods of cluster analysis, he also attempted, with varying success, to classify types of bottom reverberation, which with some limitations he treated as an acoustic classification of seafloor sediments.

In the history of measurements of the reflection and backscattering of acoustic waves from a sea bottom, various measures of reflected signals have been used: the average acoustic pressure amplitude, maximum amplitude, or the average backscattered energy. This has led to ambiguity in interpretation and difficulties in comparing results.

Various other kinds of acoustic signals have been used in bottom examination, like wide band pulse signals (explosions, electric discharges), complex signals (*e.g.* linear frequency modulated signals) and pulses with a tonal carrier – frequency.

The duration of the emitted signal varied over a wide range. In some cases, a short signal was applied to select reflection from the medium interfaces of layers. In others, the emitted signal duration was increased considerably so as to obtain a summation of the entire echo, including all reflections, *i.e.* from the water-bottom interface and the deepest layers, contributing to backscattering. Further extension of the transmitted signal does not cause the amplitude of the received echo to increase. A disadvantage of the first method was that phase relations are neglected; a drawback of the second one is the overlapping of the mainlobe and sidelobes of the transducer's directional characteristics. The existing experimental results are encumbered mainly with this systematic error.

The problem of bottom sediment type recognition using acoustic remote sensing methods has not been resolved yet (*e.g.* Alexandrou and Panzartatis, 1993; Orłowski, 1993; Pouliquen and Lurton, 1992; Stewart *et al.*, 1992). There has been a trend towards maximum experimental simplicity with a simultaneous increase in the complexity of signal processing.

This paper presents the results of bottom reverberation measurements performed within the Polish economic zone from r/v 'Oceania' during cruises in 1991–1993. The signal processing methods are described and some essential sea bottom acoustic parameters are discussed. The following bottom echo signal parameters were determined:

- the pressure reflection coefficient at the water-sediment interface,
- the integral backscattering strength,
- the duration of reverberation,
- the attenuation coefficient for selected sediment layers,
- the centre of gravity of the reflected pulse,
- the normalised moment of inertia of the echo,
- the skewness of the signal envelope shape,
- statistical moments of the signal envelope.

The most complete examinations were performed at a frequency of 30 kHz, hence it was chiefly the results at this frequency that attention was focused on.

2. Range and methods of measurements

Bottom reverberation measurements were performed with an ELAC LAZ–4700 echosounder working at 30 and 50 kHz. The echosounder was coupled through an A/D converter to the signal processing computer system. The sounding pulse durations were 0.3, 0.6 and 1 ms, and the interval between consecutive pulses was about 0.5 s. The bottom reverberation signals were recorded on disk in blocks of 64 or 128 pulses. Due to the coupling of the acoustic measuring system with the vessel satellite navigation system (GPS) the position and time were also registered for each pulse. The echo signal envelopes were read by 12-bit resolution A/D converters with a sampling frequency from 3 to 9 kHz. The echosounder was calibrated using standard spheres (99.99% Cu). The target strength of the sphere was determined from the formulas for the backscattering cross-section of an ideal elastic sphere (Morse and Ingard, 1968).

The measurements of the reflected acoustic wave parameters presented in this paper refer to the normal incidence of the beam on the bottom. They were performed during the sailing of the vessel using a towed V-fin body with the transducers mounted upon it, and at the oceanographic stations. The measurements covered practically the entire Polish economic zone of the Baltic Sea along transects more than 3000 km in length. Just the data set of echo profiles measured at 30 kHz contains about 4000 echo-integrated profiles, which corresponds to about 350 000 acoustic pulses put in for analysis. The vessel routes along which the echo signals were recorded at both 30 and 50 kHz are mapped in Fig. 1.

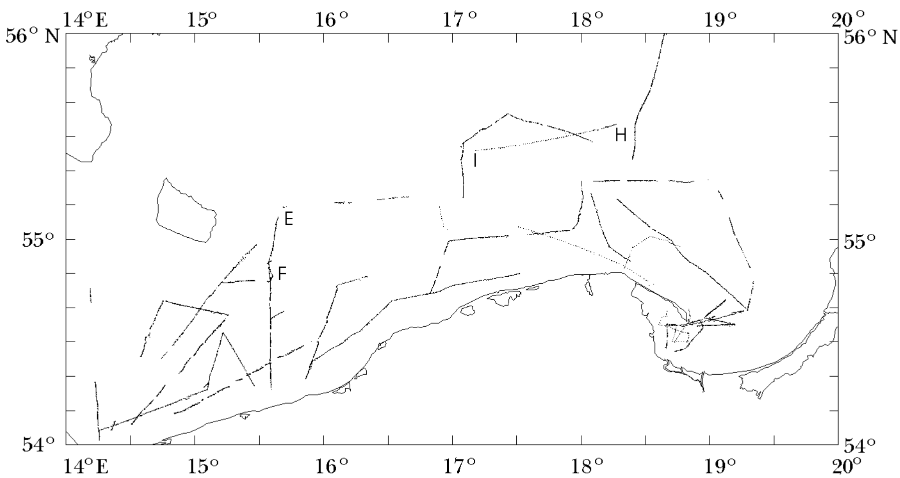

Fig. 1. Area of bottom measurements in the Baltic Sea during the cruises of r/v ‘Oceania’. The acoustic transects at the 30 and 50 kHz frequencies are indicated together

A central part of the measuring system is the PC computer connected with the following peripheral devices: A/D converters coupling the computer and the echosounder, an optical disc driver as a mass storage, and an interface to the satellite navigation system (GPS). A block scheme of the measuring system is presented in Fig. 2.

Many numerical programs have been worked out for measurements, collecting observation materials *on line*, creating a data base on the optical disc and signal processing.

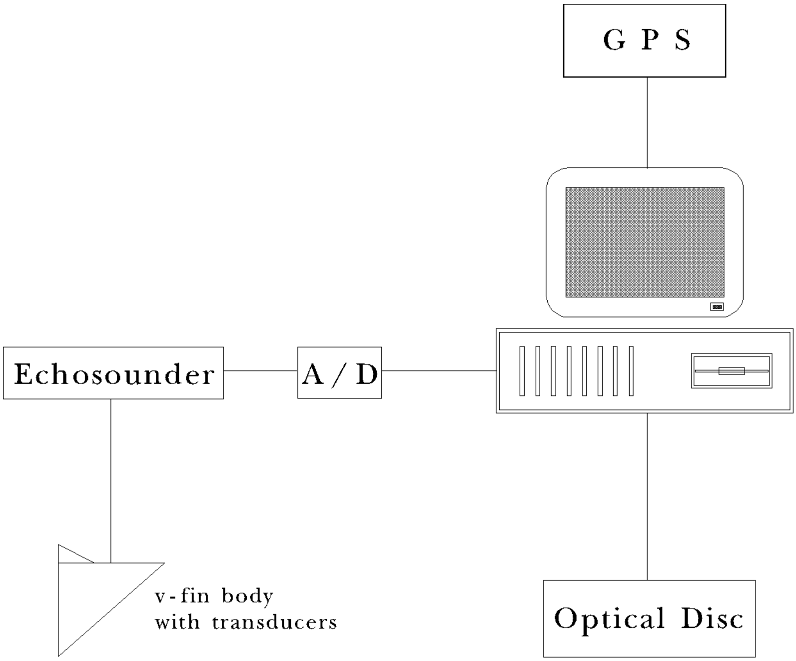

Fig. 2. Block diagram of the measurement setup

The system of data collection and processing was designed to take into account the following criteria:

- the possibility of application to various frequencies and echosounder types,
- the flexibility and simplicity of the data base service,
- the possibility of using various types of A/D converters,
- the possibility of calibrating the measuring system.

3. Pre-processing of signals

The majority of measurements were performed while the vessel was sailing. To obtain maximum separation from the influence of the ship's rolling, the acoustic transducers were mounted on the towed V-fin body, which was more stable than the vessel itself. However, during extremely harsh weather conditions, the acoustic transducer often appeared to rock through even a few degrees, which influenced the form and the level of the echo signal envelopes. To eliminate unwanted altered echo pulses three procedures were proposed and applied during *off line* signal processing of selected pings. In one, only echo signals in the block whose flight time was shorter than some threshold value were selected (this corresponded to the vertical incidence of the acoustic beam). The method failed in the case of a corrugated or sloping bottom. Two other versions could be applied as an alternative: the selection of echoes with local maxima of the envelope's echo gravity centre (its highest position), or the selection of locally strongest echo signals. Each of the two last methods qualified about 25% of signals for further processing.

Sometimes, uniformly dispersed swarms of organisms located close to the soft bottom effectively interfere with the automatic data processing. Only because it was possible to compare the character of signals along longer transects was the program operator able to decide from which depth the signal received from the bottom boundary had originated.

Even within the 64-echo sequence changes in the bottom depth can appear, which corresponds to a variation in the echo return times. Therefore, a bottom level alignment procedure was needed. The distance to the bottom in the selected pulses was aligned to the shortest one in a given block. The appearance of a sharp, non-diffuse echo maximum corresponding to the water-sediment interface, compared with the length of the transmitted pulse, testifies to the efficiency of the applied algorithm. However, it must be said that because various pulse – selection criteria were taken for averaging, differences appeared in the values obtained for the backscattering strength S_{bs}. These differences did not usually exceed 2 dB and they depended both on the character of the bottom and on the weather conditions (sea state). Greater differences, exceeding even 3 dB, occur in the evaluation of the reflection coefficient at the water-bottom boundary. The values of S_{bs} are highest for the logical product of the second and third methods and lowest for the first one.

The square voltage values corresponding to the selected echo signal were summed and averaged. The in-block averaged echo profiles were used as the basis for further calculations of the reverberation parameters.

Fig. 3 illustrates the efficiency of the selection algorithm in data collection when the ship is strongly pitching and rolling. Here, the pulse selection procedure based on the centre of gravity of the echo acoustic energy was used. The averaged echo profile obtained with the aligning algorithm is situated on the right-hand side of the figure.

4. Parameters of bottom reverberation signals

To evaluate the reflection coefficient of an acoustic wave from the bottom, a direct method based on measurements of reflected signals and the calibration parameters of the acoustical system was used. To calculate the backscattering strength from the bottom materials, the formalism of volume reverberation was applied. This emerged from the fact that besides the zone of sands, the layer of sediments taking part in backscattering had a thickness equal to tens of spatial lengths of the sounding pulse and had to be

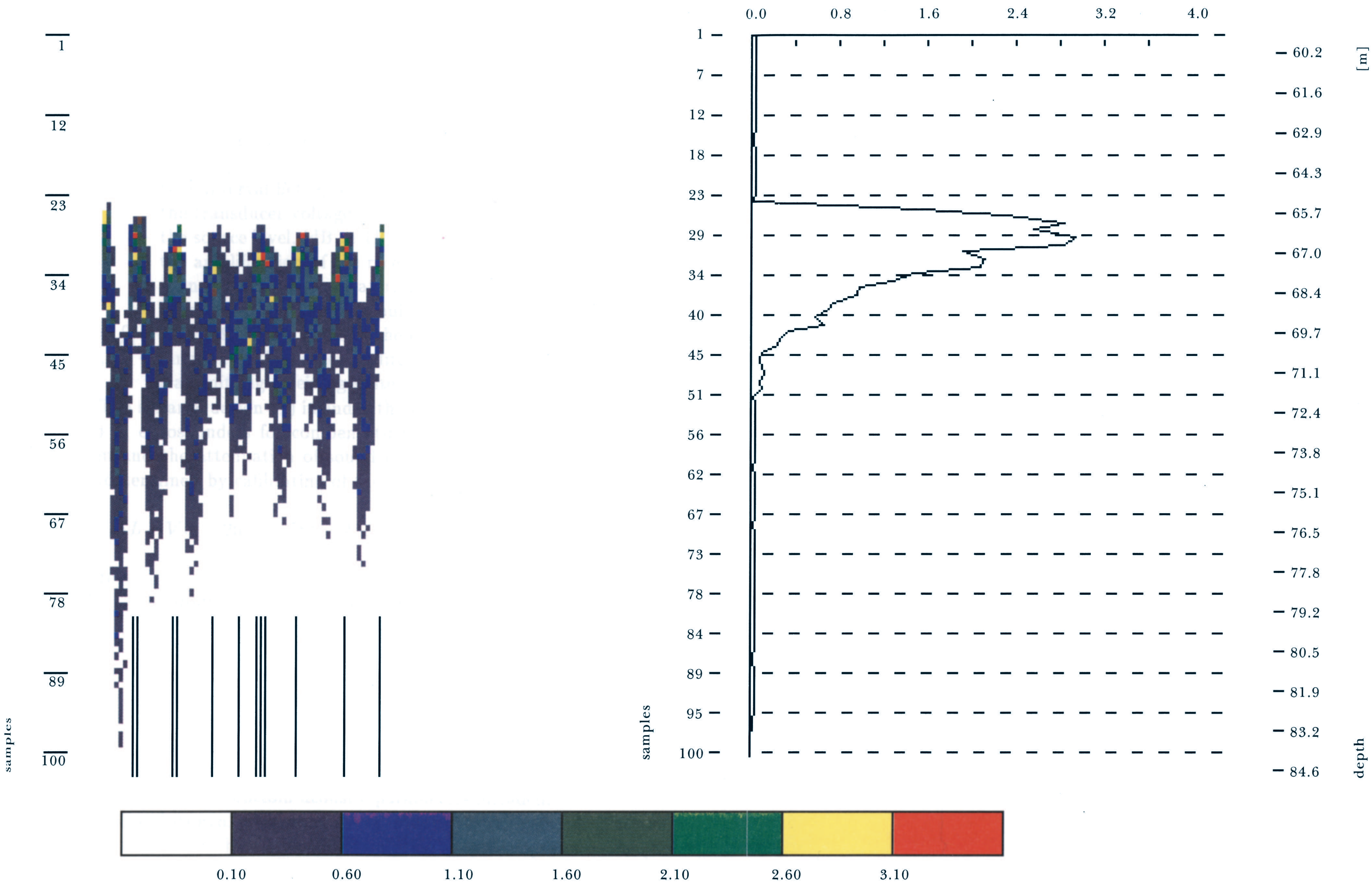

Fig. 3. Sequence of echoes and averaged profile as an example of the signal processing method

treated as a volume scattering medium. The equation used for calculations of the backscattering strength was as follows (Urick, 1967):

$$S_V(z) = 20\,log U_i - (SL + VR) - Gain - 10\,log(\Psi) - 10\,log\left(\frac{c\tau}{2}\right), \quad (1)$$

where

U_i – the voltage of the ith sample corresponding to the depth,
$z_i = C\,\Delta t\; i/2$, [V]
Δt – time interval between two consecutive samples,
VR – the transducer voltage response, [dB re 1V/Pa]
SL – the source level, [dB re 1Pa]
$Gain$ – the amplification of the received signal (in dB),
c – sound velocity in sea water, [m s^{-1}]
τ – duration of the sounding pulse, [s]
$\Psi = \int_\Omega b^2(\Theta, \varphi) d\Omega$ – solid angle of the directivity characteristics,
$b(\Theta, \varphi)$ – function of the energetic directivity characteristics of the transmitting-receiving system.

The sonar equation (1) includes the time varied gain (TVG) commonly used in echosounders for compensating the geometrical divergence of the beam and the attenuation of sound in sea water. The quantity $SL + VR$ was determined by calibrating of the echosounder with a standard sphere:

$$SL + VR = 20\,log(p_o\gamma) = 20\,log\left(\frac{U_{\max,\,sph}\, r_{sph}}{k_{sph}}\right) - 10\,log\,\sigma_{bs,\,sph}, \quad (2)$$

where

$p_o\gamma$ – product of the pressure on the acoustic axis at a distance of 1 m from the transmitter and the sensitivity of the receiver,
$SL + VR = 20\,log(p_o\gamma)$,
$\sigma_{bs,\,sph}$ – backscattering cross-section of the calibration sphere,
r_{sph} – distance between transducer and calibration sphere,
$U_{\max,\,sph}$ – maximum voltage of the echo signal from the sphere,
k_{sph} – gain factor at the calibration measurement,
$Gain = 10\,log\;\; k_{sph}$.

Calculations of the bottom acoustic parameters included:

• **The integral backscattering strength** at the bottom as the basic parameter which in a formal description may be represented as (Urick, 1967):

$$S_{bs} = 10\,log\,(\int_{z_1}^{z_2} S_V(z)dz), \quad (3)$$

where the depth interval $[z_1, z_2]$ is established automatically by adjusting the voltage thresholds or by the operator, and $S_V = 10\,log(S_V)$.

After including the calibration procedure, the calculation algorithm (1) is expressed as follows:

$$\begin{aligned} S_{bs} &= -(SL+VR) - Gain - 10\,log\Psi - 10\,log\left(\frac{c\tau}{2}\right) + \\ &+ \ 10\,log\left(\frac{\Delta t}{\tau}\sum_{i=1}^{N} U_i^2\right), \end{aligned} \tag{4}$$

where

N – number of samples in the echo signal.

• **The reflection coefficient** at the water-sediment interface, calculated according to the formula (Clay and Medwin, 1977):

$$V = \frac{2H\,p_r}{p_o}, \tag{5}$$

where

H – distance from the transducer to the bottom,

p_r – reflected wave pressure measured at the echosounder transducer.

Assuming an ideal form of TVG and neglecting attenuation in the medium, the formula (5) can be expressed in measured quantities as

$$V = 2\,\frac{U_r}{k\,p_o\gamma}, \tag{6}$$

where

U_r – sample voltage of the echo signal envelope corresponding to the reflection at the water-sediment interface,

k – amplification factor of the echosounder during measurement.

The value of the reflection coefficient at the water-sediment interface was calculated from the first local maximum of the voltage in the bottom echo signal.

• **The reverberation time**, determined as the time T_{50} or T_{90}, in which 50 or 90% of the acoustic energy of bottom reverberation returned, and the ratio T_{50}/T_{90}, which also provides information about **the skewness of the echo envelope**.

An example of T_{50} is:

$$\int_0^{T_{50}} p^2(t)dt = \frac{\int_0^{\infty} p^2(t)dt}{2}. \tag{7}$$

• **The attenuation coefficient** β describing the attenuation of acoustic waves in bottom materials. This was evaluated as follows (Klusek, 1990): in the first step, the limits of the quasi-linearity interval of the dependence $< S_V(z) >= f(z)$ were found. For that section the coefficients of a linear regression were determined. The slope coefficient of $< S_V(z_i) >$ represents the searching value of β. The critical value of the linear correlation coefficient between the series $< S_V(z_i) >$ and z_i plays an auxiliary role in accepting or rejecting the hypothesis.

The acoustic wave attenuation coefficients were determined with a high degree of uncertainty resulting from the assumed homogeneity of the bottom materials in the layer contributing to the scattering (Klusek, 1990), and also from the impossibility of discriminating between the signal scattered by interface corrugation and the one scattered by volume inhomogeneities. It should be stated here that in cases when the layers are distinctly separated (see Fig. 6), attenuation coefficients are determined for each layer separately. An additional source of error during the evaluation of the β coefficient was the fact that the local sound velocity in bottom materials was not known exactly (here it was always assumed to be $c = 1460$ m s^{-1} as in sea water).

• The statistical properties of bottom reverberation signals and the shapes of envelopes represented by such parameters as the **statistical moments of the signal envelope, fluctuation and similarity measures of the signals and envelope skewness**.

The measure of signal fluctuations δ in a ping is defined as

$$\delta = \frac{1}{N-k} \sum_{i=1}^{N-k} \left(\frac{p_i^2 - p_{i+k}^2}{p_i^2} \right), \tag{8}$$

where k is the number of samples corresponding to half the length of the transmitted signal. The linear correlation coefficient between two values of adjacent averaged blocks of echo profiles and the similarity coefficient of adjacent averaged echoes cs_j introduced by the authors and defined as

$$cs_j = \frac{1}{N-1} \sum_{i=2}^{N} \frac{1}{0.5 + (U_{i,j}/U_{\max,j} - U_{i,j-1}/U_{\max,j-1})^2} - 1, \tag{9}$$

where N is the number of samples in the longer of the two echoes, were applied as measures of signal similarity. One of the properties of the echo signal is **envelope skewness**. This is a rather rarely used description of the third statistical moment of instantaneous signal values. In calculating the envelope skewness coefficient, the voltage U_i for consecutive samples acts as the probability density function $W(x)$. This parameter can serve as a measure of the sequence of sediment deposition in the bottom. Using the skewness value one can distinguish regions where reflections come from the layers closer to the water-sediment interface from those where reflections come from layers deeply submerged below the soft sediments.

5. General characteristic of bottom reverberation in the southern Baltic Sea

The spatial distribution of integral bottom backscattering strengths S_{bs} determined at 30 kHz within the Polish economic zone is presented on the map in Fig. 4. According to the authors, this parameter is an important one (but not the only one), which can be used to characterise acoustic reverberation in the southern Baltic Sea, and represents the integral reverberation characteristic for the measurement station. The integrated depth ranges from around 1 m in sands to 40 m in semi-fluid sediments. The map of S_{bs} values reflects trends in the sediment profile. Shallow flat areas covered with a layer of sand or gravel are characterised by values of $S_{bs} > -10$ dB. In areas of sand deposited in a thin layer on silt or mixed with silt, the reverberation level decreases to around –15 dB. By contrast, S_{bs} values in deep areas decrease below –20 dB and may approach –30 dB in some cases. There is a relatively good correlation between the integral backscattering strength and the bottom hardness.

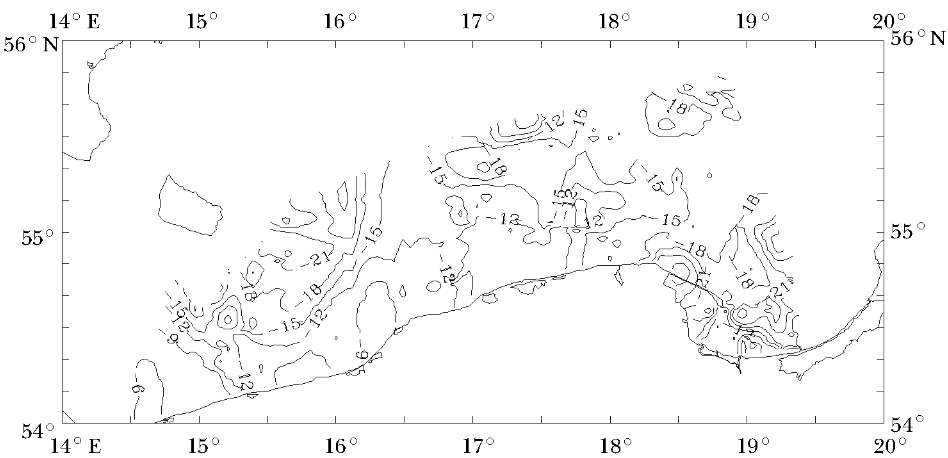

Fig. 4. Spatial diagram of the integral bottom backscattering strength in the Polish economic zone of the Baltic Sea at the 30 kHz frequency

The spatial distribution of T_{90} at 30 kHz in the Polish economic zone of the Baltic Sea is illustrated in Fig. 5. Clearly distinguished are two deeps – the Gdańsk Deep and the Bornholm Deep – where acoustic signals have penetrated deeply into the soft silty and clayey bottom. The duration of the echo signal from the bottom of the deep is 40 or even 50 times longer in comparison with that of the transmitted signal, while for a sandy bottom these times are comparable.

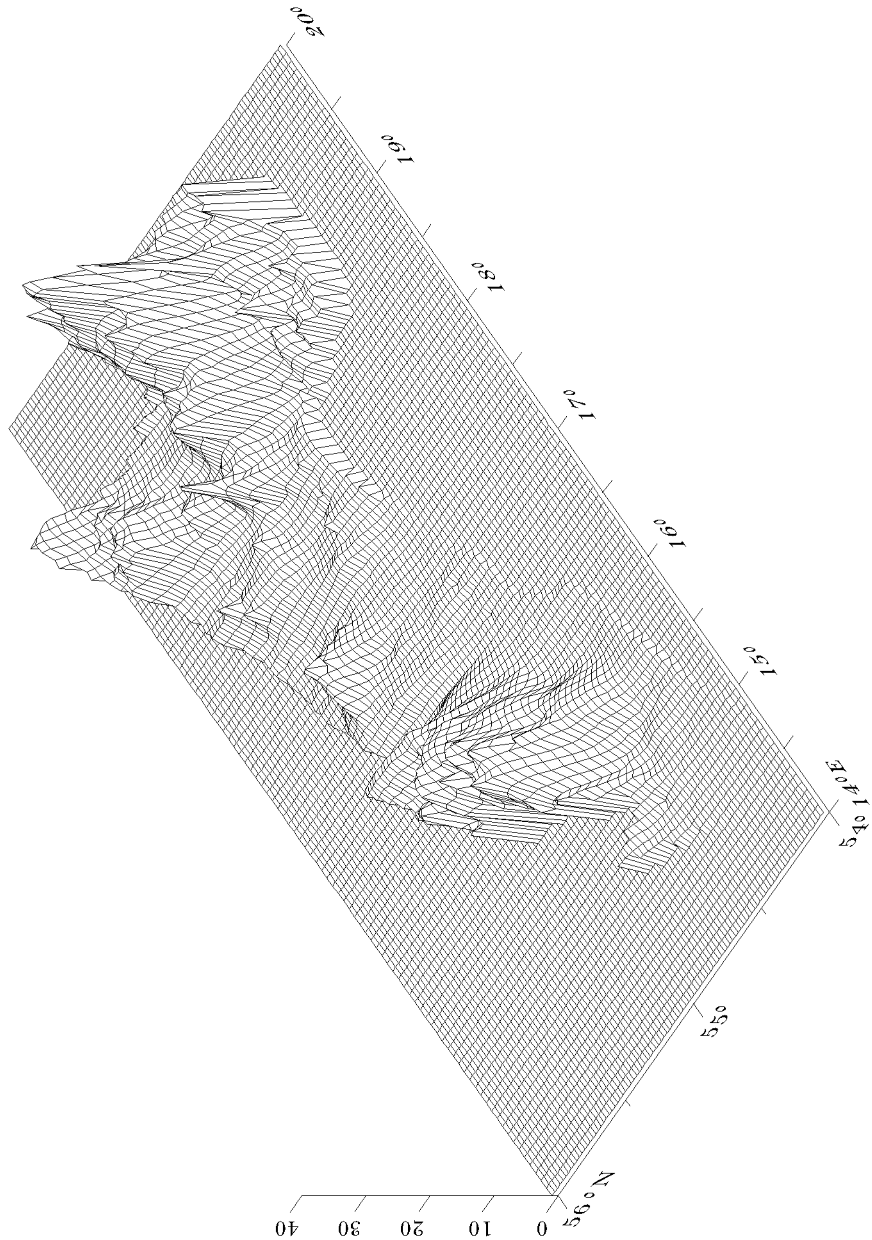

Fig. 5. Spatial diagram of the time T_{90} in the Polish economic zone of the Baltic Sea at the 30 kHz frequency

Examples of echo profiles in the voltage scale and the curves approximating them, applied in evaluations of the coefficient β [dB m^{-1}] for the two types of sediment are presented in Fig. 6. The right-hand diagram shows a typical profile of a sandy bottom with shallow penetration of acoustic waves ($\beta = 16$ dB m^{-1}, the determination coefficient $r^2 = 0.997$); the left-hand diagram is a profile of a composite bottom with unconsolidated sediments deposited on a harder stratum. The attenuation coefficient for the first layer is $\beta = 1.7$ dB m^{-1} ($r^2 = 0.96$) and in the deeper layer $\beta = 1.9$ dB m^{-1} ($r^2 = 0.93$). The best fit curves are also drawn in the diagrams. The vertical line determines the limits of the approximation. By comparing the attenuation coefficients for the two frequencies 30 and 50 kHz we get the following results:

in silts (for transects in the vicinity of the station at lat. 54° 37′ N, long. 15° 02′ E)

$\beta_{30} = 2.15 - 2.3$ dB m^{-1} (0.07 – 0.08 dB m^{-1} kHz^{-1})
$\beta_{50} = 4.5 - 5.1$ dB m^{-1} (0.08 – 0.1 dB m^{-1} kHz^{-1})

and in the fine-grained sands (near the station at lat. 54° 22′ N, long. 15° 35′ E)

$\beta_{30} = 5.2 - 7.8$ dB m^{-1} (0.17 – 0.025 dB m^{-1} kHz^{-1})
$\beta_{50} = 12.5 - 13.5$ dB m^{-1} (0.25 – 0.27 dB m^{-1} kHz^{-1}).

The calculated values of β at 30 kHz over the whole area investigated lie within a range from about 1 dB m^{-1} in waterlogged silts to over 25 dB m^{-1} in sands.

For comparison, the sound attenuation coefficients in sediments obtained by other authors with different methods are given below:

for soft sediments in the Baltic Sea (Ulonska, 1968)

$\beta_{50} = 3$ dB m^{-1} (0.06 dB m^{-1} kHz^{-1})	silts, silty clays
$\beta_{200} = 30$ dB m^{-1} (0.15 dB m^{-1} kHz^{-1})	clayey silts
$\beta_{50} = 20$ dB m^{-1} (0.40 dB m^{-1} kHz^{-1})	sandy silts
$\beta_{200} = 45$ dB m^{-1} (0.225 dB m−1 kHz^{-1})	sandy silts

for soft sediments in the Baltic Sea (Schirmer, 1971)

$\beta_{1.2} = 0.29$ dB m^{-1} (0.24 dB m^{-1} kHz^{-1})	clayey silts
$\beta_{1000} = 383$ dB m^{-1} (0.38 dB m^{-1} kHz^{-1})	clayey silts

for sands in other sea areas

$\beta_{30} = 20$ dB m^{-1} (0.67 dB m^{-1} kHz^{-1})
$\beta_{50} = 25$ dB m^{-1} (0.5 dB m^{-1} kHz^{-1})
$\beta_{200} = 80$ dB m^{-1} (0.4 dB m^{-1} kHz^{-1}).

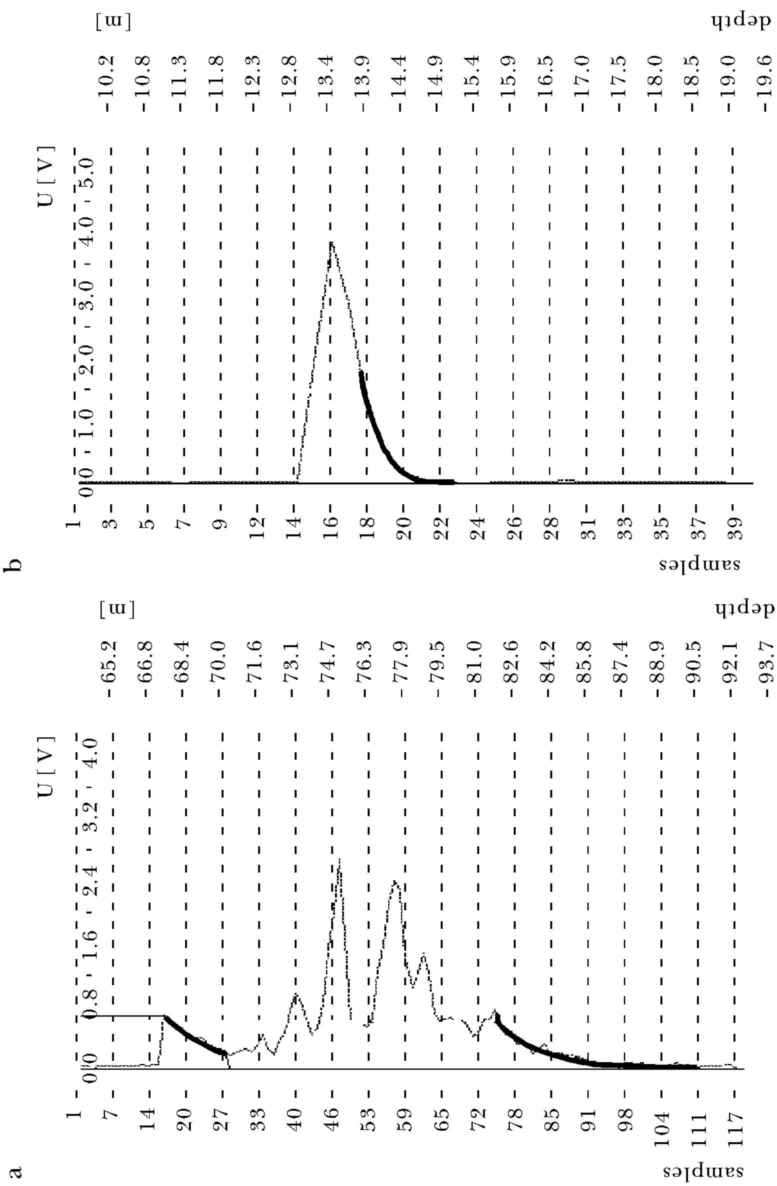

Fig. 6. Examples of echo profiles on a voltage scale and the curves approximating them applied in the evaluation of the attenuation coefficient β [dB m^{-1}] for two types of bottom: stratified bottom (a), sandy sediments (b)

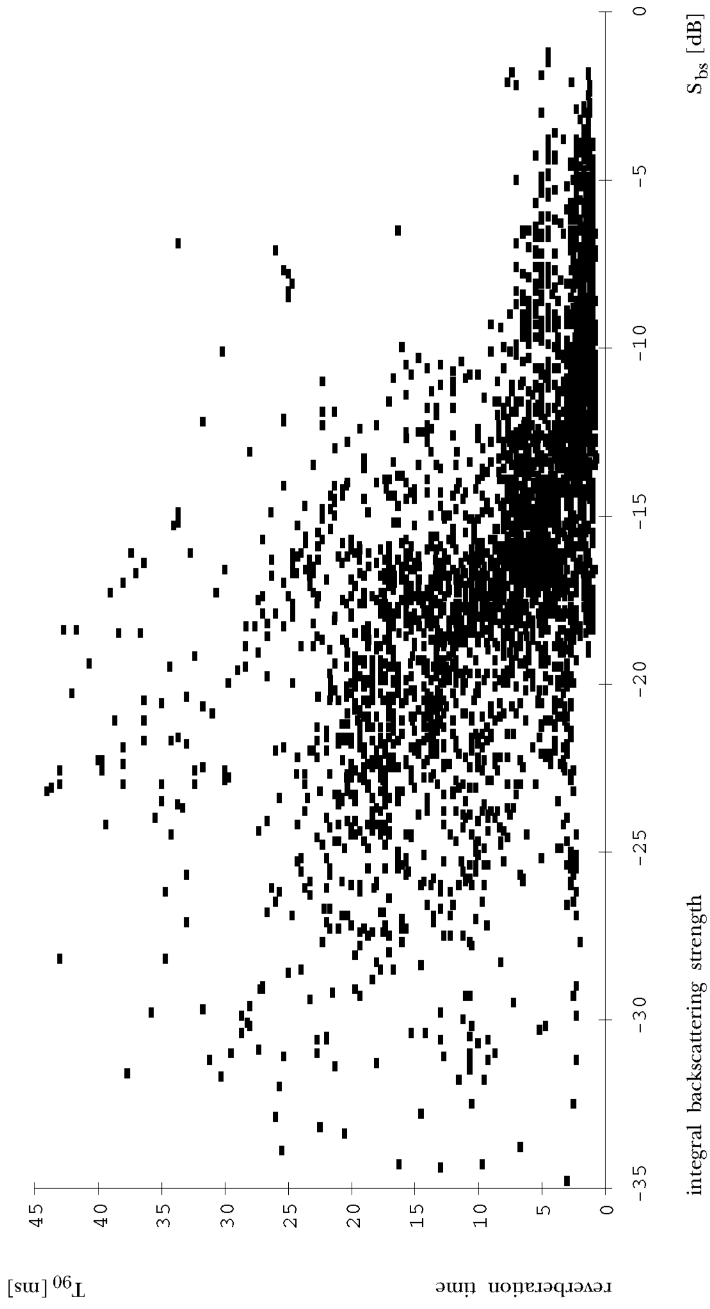

Fig. 7. Relationship between the integral backscattering strength and the time T_{90} at the 30 kHz frequency in the Polish economic zone of the Baltic Sea

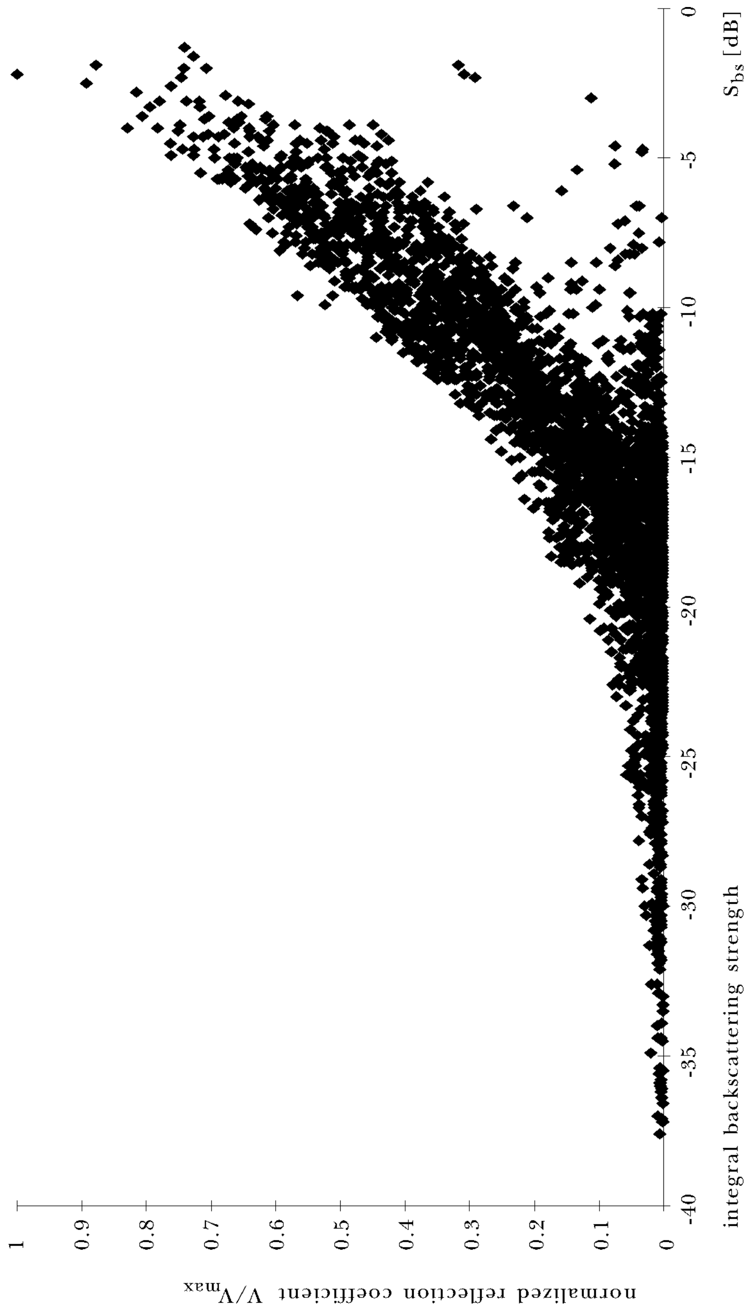

Fig. 8. Relationship between the integral backscattering strength and the normalised reflection coefficient at the water-sediment interface at the 30 kHz frequency for the entire investigated sea area

Fig. 7 presents the relationship between the integral backscattering strength and the time T_{90}. It confirms the general trend that bottom reverberation time is inversely proportional to backscattering strength (deeper signal penetration and attenuation over a longer distance). By comparing the integral backscattering strength measurements and the reflection coefficient at the water-sediment interface (Fig. 8) one finds points to be aligned in two branches. An expected, most of the data are located on the exponential curve; they represent a homogeneous bottom. A striking contrast in the impedance is equivalent to strong reflection at the water-sediment interface and is accompanied by an increase in the integral backscattering strength. On the other branch the cases corresponding to sediment incompatibility – that of the bottom surface and that of the layer yielding the maximum backscattered energy – appear in a narrow band of $V/V_{\max}$ values close to zero. This is the area where soft sediments usually overlie a harder bottom. Small values of V can be accompanied by various values of S_{bs}.

6. Examples of spatial variations in the acoustic properties of sediments along selected transects

The transect E–F from Fig. 1, presented in Fig. 9, is an interesting example of these measurements, and refers to a geologically documented sea area, *i.e.* the Bornholm Deep (The geological map of the Baltic Sea bottom – Ronne-Nexe sheet, 1992). It should be stated that a full geological interpretation of the acoustic data is not possible because the length of the cores taken in this area for bottom identification by geologists never exceeds 6.5 m, whereas acoustic signals penetrate much deeper. This transect begins at lat. 55° 06′ N, long. 15° 39′ E, and ends at lat. 54° 48′ N, long. 15° 34′ E. The transect begins at the Christianso Saddle Bank (the area of sediment displacement from the South-East Bank). At the bottom surface a thin layer of clayey sands is deposited on silts and clayey silts (2–4 m) resting on a substratum of till clays (the left-hand side of Fig. 9). This is followed by an accumulative moraine plain. The profile of the first 15 m of sediments consists of silty clays, clayey silts of glacial-drift origin, varved silts, varved clays and till clays. Below these are Cretaceous sediments, probably sands and sandstones. Along this transect the uplift of the water-glacial moraine bar with interbedded fine-grained sand is clearly distinguished. The acoustic characteristics of the transect can be described as follows:

• At the Christianso Saddle, echo signals from depths down up to 10 m are registered. Here, an acoustically soft layer of sea sediments 1 m in thickness is separated. Next, there are two-layer interfaces about 2 m distant from each other (silt-sea clay and sea clays-till clay interfaces). The thickness

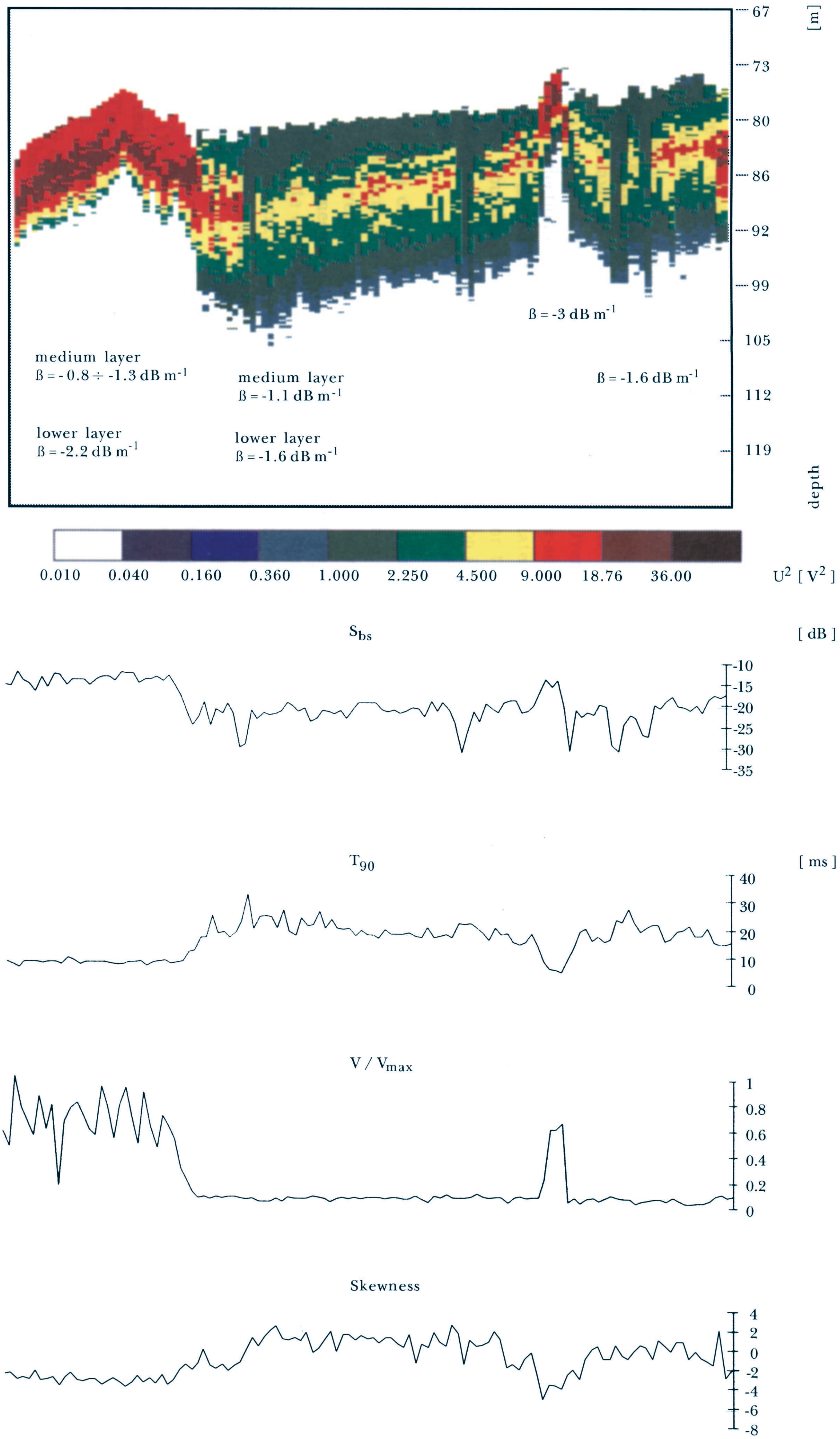

Fig. 9. Echogram and selected echo parameters for the acoustic transect in the Bornholm Deep area

of the acoustically registered layer of sea clays is about 2 m, which is in agreement with the geological corer data of 24 R14 (The geological map of the Baltic Sea bottom – Ronne-Nexe sheet, 1992). The ' reverberation tail ' (Fig. 9) in boulder clays is 2.5 m in length and the attenuation coefficient $\beta = 0.8 - 1.3$ dB m^{-1}. Below this, there is a local weak maximum and then an exponential drop corresponding to $\beta = 2.2$ dB m^{-1}. The weak increase in the echo from a depth of 5.5 m over the greater part of the area of that formation is explained by the existing separation between different types of clays. However, there is no geological confirmation that two sediment types have been identified at this depth.

In that region the characteristic integral backscattering strengths range from –12 to –15 dB and T_{90} values from 5 to 9 ms. When the sea becomes shallower, the layer of soft sediments disappears, but the configuration of all three layers mentioned above remains unchanged. Over this part of the transect, the reflection coefficient is greatest at the water-sediment interface. Another feature is that the reflection coefficient fluctuates in value at the water-bottom boundary. The most probable reason for this is the varied thickness of the soft sediments, or small-scale corrugation (the equivalent of ripple marks).

• In the area of the accumulation plain, a 6 m layer of marine silty clays with acoustical properties close to those of sea water is detected. The increase in the reverberation level at the lower boundary of that layer is most probably connected with an increase in sediment density. It was not possible to evaluate the attenuation in that layer with the method applied here. Below this, there are two layers within 2 m of each other (clayey silts, probably more consolidated than the silty clays above them). Deeper still, over a distance of 5 m there is an exponential slope of the echo envelope with a value of $\beta = 1.45 - 1.6$ dB m^{-1}. That layer is deposited on other sediments (varved silts with a higher attenuation $\beta = 1.6 - 1.9$ dB m^{-1}). Unexpectedly, acoustic waves penetrate the bottom to a great depth (up to 25 m). The frequencies applied did not allow the deeper mudstones to be penetrated. However, by working with the total power of the echosounder at maximum gain, echo signals were obtained from layers deposited deeper than 5–6 m (but with simultaneous loss of the information about shallower layers because of the signal overloading). The attenuation coefficient in these sediments in the 81–94 m depth range was equal to $\beta = 1.57 - 1.68$ dB m^{-1}, only slightly larger than for the 78–88 m depth range, where $\beta = 1.48 - 1.58$ dB m^{-1}.

In that region the integral backscattering is smaller than in the adjacent region – from –20 to –25 dB (–20 dB being the most probable value). The duration of reverberation is much longer here and reaches maximum values of $T_{90} = 17 - 29$ ms, as yet registered only in the Gdańsk Deep.

• At the water-glacial accumulation uplift the integral backscattering strength again increases up to $S_{bs} = –13.5$ dB, with the attenuation coefficient exceeding 3 dB m^{-1} (0.1 dB m^{-1} kHz^{-1}) and the time $T_{90} = 4 - 6$ ms.

• After crossing the moraine bar in a southerly direction there are strong fluctuations of the acoustic echo level most probably connected with the strong corrugation of sediment layers down to the Cretaceous bed as in the northern part of the map. The echograms show stronger scattering patches of a shape similar to fish shoals. The slope of the echo envelope for the deepest layers increases and for the last data it attains a value of $\beta = 1.6$ dB m^{-1} (0.05 dB m^{-1} kHz^{-1}). The backscattering strength varies from –18 to –22 dB. Only in two blocks does it attain $S_{bs} = –31$ dB; T_{90} is $15 - 20$ ms.

Fig. 9 shows: above, the echogram on the transect described earlier and below, the spatial distribution of the averaged echo signal parameters assigned to it. They are in turn:

a) the integral backscattering strength S_{bs},

b) the echo duration T_{90},

c) the reflection coefficient at the water-sediment interface normalised with respect to the maximum value on the entire acoustic transect $V/V_{\max}$,

d) the skewness coefficient of the averaged echo signal envelope.

Fig. 10 presents both measures of the degree of similarity of the averaged echo profiles along the same transect. They are the coefficient of linear correlation between the acoustic pressure values of the consecutive profiles (the profiles synchronised with respect to the first sample at the bottom interface) and the square of the pressure difference normalised with respect to the number of samples.

Through their changes in local maxima both measures reflect variations in the profile shape at the interface of different types of bottom or sediments. The fact that local variations in the values of these parameters from the 1st to the 30th term are small is evidence of bottom homogeneity in the Christianso Saddle. The first strong minimum (for the 30th term) relates to the boundary between clays and a clayey silt bottom. Stronger fluctuations in these parameters in further parts of the transect are connected with variations in bottom layer arrangement and provide evidence of the increasing influence of random factors shaping the average echo signal envelope.

An example of the other types of sediments and their spatial distribution is the transect enclosing the Słupsk Furrow and the South-Central Bank

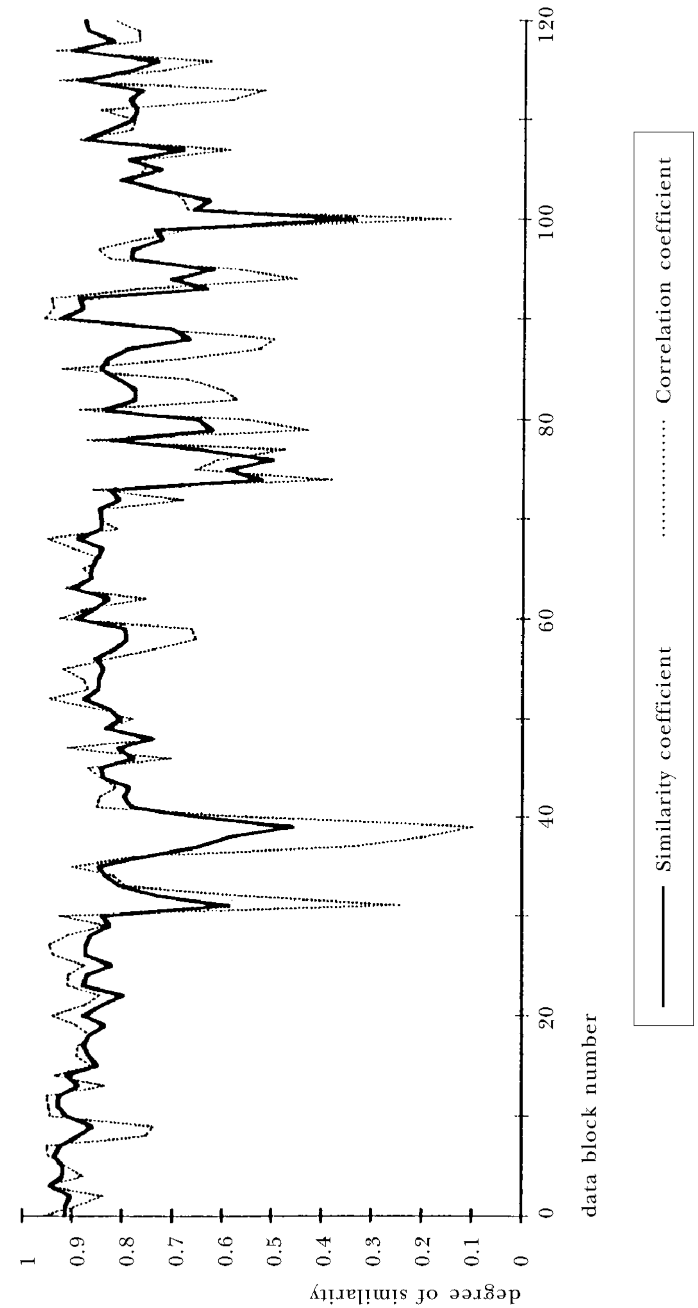

Fig. 10. Similarity measures of consecutive block-averaged echoes for the acoustic transect in the Bornholm Deep area

(Fig. 11). On the acoustic transect map (Fig. 1) it is marked H–I. The most easterly point of the transect (lat. 55°33′ N, long. 18°17′ E) is situated at the edge of the Słupsk Furrow (left-hand side of Fig. 11). The 7 m-thick upper sediment layer consists of silts and clayey silts deposited on subaqual clays. In the following part of the acoustic transect the depths decrease to 63 m. In that part the upper sediment layer represents mixed sandy silts, silty sands and fine- or medium-grained sands deposited on subaqual clays, which fact is reflected in the stronger acoustic echo signal. Further on, one can see the passage through the Słupsk Furrow where in the upper layer mixed sediments like sand-clay-gravel or sand-clay-silt occur. The total echo from the upper layer increases ($S_{bs} = -12$ dB), attaining a local maximum of reflection from the bottom surface. After crossing the Słupsk Furrow the echo level decreases. This is due to the appearance in the upper sediment layer of marine clayey silts and marine silty clays deposited on clayey silts. But at a sea depth of 62 m, there appears a strong echo coming from marine clayey sands deposited on clayey silts and marine silty clays. Starting from a depth of 55 m, the whole signal is reflected from a 2 m-thick sediment layer consisting of fine-grained sands. Unexpectedly, this kind of sands gives atypically low values of S_{bs} of the order of –14 dB. This kind of record occurs right up to the end of the acoustical transect (55°26′ N, 17°01′ E).

7. Conclusions

The paper presents the measurements of backscattering acoustic signals in the southern Baltic Sea and attempts to correlate them with the geological properties of the sediments occurring there. The acoustic properties of the bottom were characterised by the following parameters:

- integral backscattering strength,
- reflection coefficient at the water-bottom interface,
- echo duration,
- attenuation coefficient in separate layers,
- normalised moments and other statistical parameters of the signal envelopes.

On the basis of marine investigations done over several years, acoustic maps of backscattering strength and reverberation time have been drawn for the southern Baltic Sea area. Using selected marine transects, the relationships between several acoustic parameters and the geological structure of the bottom has been presented. Each one of the selected parameters carries information about the nature of the bottom, but only the integral values related to the entire acoustically penetrated layer of sediments can be used for

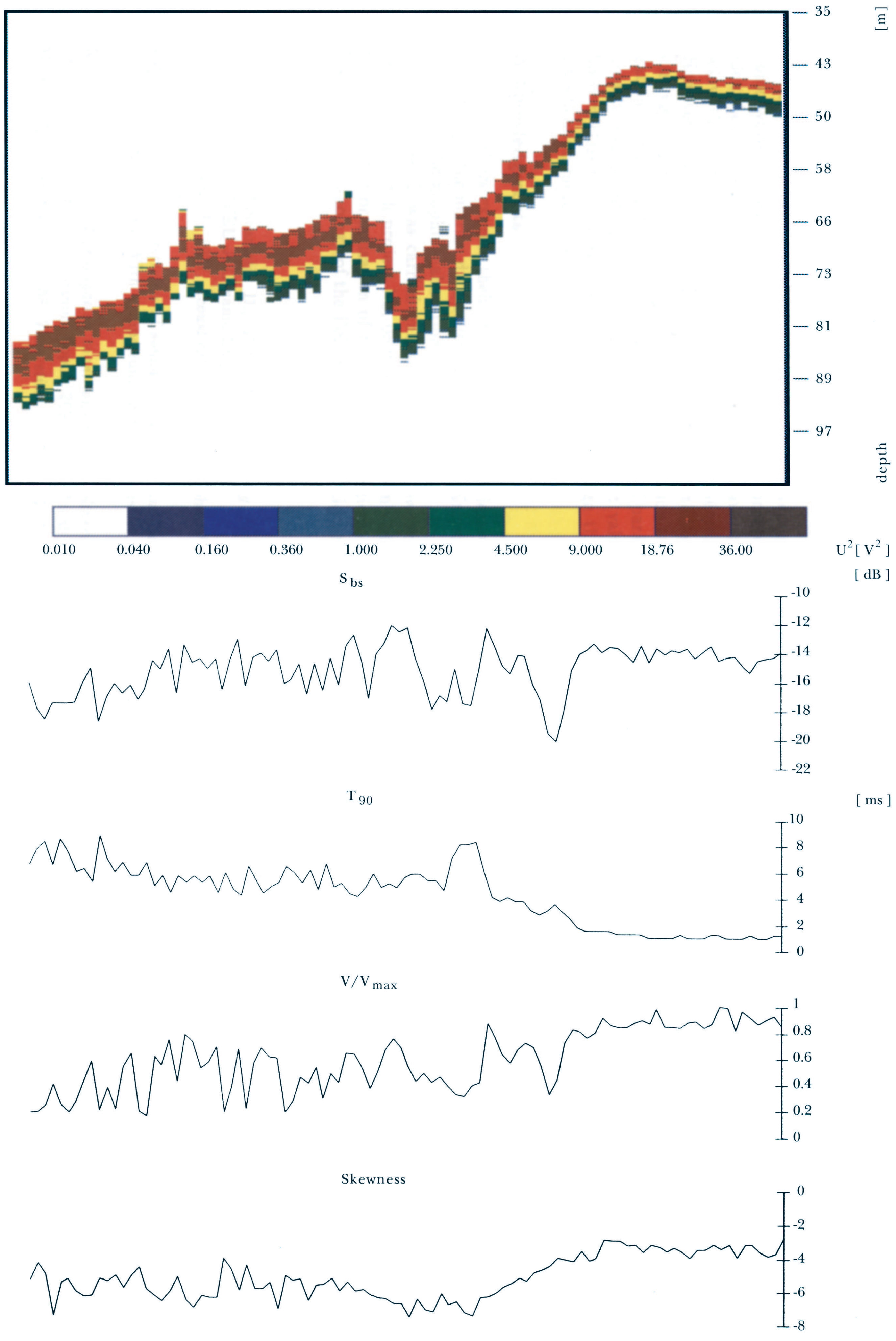

Fig. 11. Echogram and selected echo parameters for the acoustic transect in the Słupsk Furrow area

classification purposes. The stratified bottom classification cannot be based on the reflection coefficients determined at the water-bottom interface or on attenuation coefficients in sediments because they are local values and are related to only one of the interface layers. Only for large attenuations are these values representative of a homogeneous thin layer close to the interface. However, they may be successfully applied in the classification of homogeneous bottom materials.

A comprehensive knowledge of elementary phenomena related to ultrasonic wave backscattering is essential for further progress in the acoustic identification of sea bottom types. The acoustic parameters introduced here allow the bottom type and the nature of the sediments to be determined. However, so far we have only been able to measure these parameters. Forecasting them in different combinations of stratification and interface corrugation is still a task for the future. The selection of parameters considered here is insufficient upon which to base independent values to be used for bottom classification, so it seems too early to assign the acoustic bottom classification more closely to the geological one.

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