REFRACTION OF SOUND IN THE SEA FLOOR

by

R. E. Christensen
W. H. Geddes

U.S. Naval Oceanographic Office
Washington, D.C.

Abstract

A major mode of propagation of acoustic energy at low frequencies is a shallow refracted path through unconsolidated sediments of the sea floor. Successful modelling of the bottom-refracted mode of propagation requires knowledge of the sediment thickness, sound velocity, and acoustic attenuation in the sediments. Unconsolidated sediments may be considered an extension of the water column with the acoustic floor of the ocean being the base of the unconsolidated sediments. Observed bottom loss results from two Pacific Ocean sites of differing sediment thickness are discussed. Lower losses noted at the low grazing angles from the thick sediment station are attributed to added acoustic energy that is received from shallow bottom-refracted arrivals. Lower losses noted at the high grazing angles from the thin sediment station, on the other hand, are attributed to added acoustic energy that is received from subbottom reflections occuring at the base of the unconsolidated sediments.

INTRODUCTION

Development of a low frequency acoustic propagation model requires a more complicated physical concept of the sea floor than is required for a high frequency acoustic propagation model. The attenuation of high frequency sound energy in bottom sediments precludes its propagation through the sediments for long distances. However, low frequency acoustic energy can be both reflected at the sea floor boundary (or subbottom boundaries) and refracted through the sediments. Experiments are being conducted by the U.S. Naval Oceanographic Office to study the effects of sediment layering on acoustic propagation results.

Refraction of sound energy through sea floor sediments was first described by Hill (1952). Geophysicists have since used the bottom-refracted arrival as a tool to estimate sound velocity characteristics of bottom sediments. Recently, as more emphasis was placed on long range propagation, acousticians have studied the effect of bottom-refracted arrival on low frequency propagation loss results (Morris, 1970; Hanna, 1973; Christensen, Geddes, and Frank, 1975).

Some of our recent work indicates that considerable low frequency acoustic energy is received by way of shallow bottom-refracted paths through the unconsolidated sediments of the sea floor. In an attempt to test this hypothesis, bottom loss surveys were conducted over areas of various sediment thickness in the eastern North Pacific Ocean. The results from these surveys and the relationship between low frequency bottom loss values and sediment thickness will be discussed in the paper.

DATA COLLECTION AND PROCESSING TECHNIQUES

Two ships were used to obtain quantitative measurements of bottom loss as a function of grazing angle and total propagation loss as a function of horizontal range. The USNS BENT was outfitted as the receiving ship and an AGOR class ship was outfitted as the shooting ship. The receiving ship remained stationary while the shooting ship proceeded along a designated shooting course, dropping about 50 MK 61 SUS sound sources at selected intervals, out to a horizontal range of approximately 30 miles (figure 1). The bottom-returned signal was received by a hydrophone (suspended from the receiving ship), amplified, and recorded broadband on a magnetic tape recorder. The hydrophone was calibrated by the Underwater Sound Reference Division (USRD), Orlando, Florida. An internal calibration, which consists of generating a known voltage through the system, was also incorporated in order to calibrate the remaining components of the acoustic system. During the conduct of the station a sound speed profile was obtained to accurately determine the amount of acoustic energy dispersed due to refraction of the ray paths in the water. Horizontal distances between ships were measured by a ship-to-ship electro-magnetic ranging system. Other pieces of vital information included bathymetry and sub-bottom profiles obtained along the shooting track by the shooting ship.

The magnetic tapes were played back in the laboratory and the data were processed utilizing the Fourier Acoustic Measurement and Analysis System (FAMAS) developed at NAVOCEANO (Hansen, 1975). The main component of this system is a Hewlett-Packard 5451 fourier analyzer. Bottom loss data were computed using total energy processing techniques by:

$$BL = SL - RL - PL - 6$$

where: BL = Bottom loss in dB,

SL = Source level in dB re 1 erg-sec/cm^2 @ 1 yd.,

RL = Received level in dB, re 1 erg-sec/cm^2 , and

PL = Propagation loss in the water in dB re 1 yd.

In addition to the bottom path, acoustic energy is also received via the surface paths. Since the signal from all four paths were integrated a 6 dB correction was required in the above equation. As a check on the receiving system, values of source levels (SL) were measured independently and compared to historical values (Christian, 1967; Gaspin and Schuler, 1971). Received levels (RL) for a given frequency were calculated by algebraically summing the hydrophone sensitivity level, gain level, and recorded level of the bottom return. The propagation loss term (PL) was obtained from a computer program. Inputs to the bottom loss computer program included values of source level, component values of received level, source depth, receiver depth, water depth, horizontal range, and values of sound velocity as a function of water depth. Outputs from the program included tabulated values of bottom loss versus grazing angle and total propagation loss as function of horizontal range for standard 1/3 octave frequencies from 63 Hz to 3150 Hz. The program also provided plots of the above information. Values of bottom loss and propagation loss for each station are stored on a master digital magnetic tape.

ANALYSIS PROCEDURES

In some of our earlier work (Christensen, Frank, and Geddes, 1975) an arrival was identified at the lower frequencies (20 to 200 Hz) that was not present at the higher frequencies (2000 to 20,000 Hz). We concluded that by treating the unconsolidated sediments of the sea floor as a fluid and considering the sediment sound velcoity as an extension of the water column sound velocity, two basic bottom paths should exist as shown in figure 2. Energy at all frequencies would be expected to be received at point, R, from a source, S, via (A) the bottom-reflected path. In addition, low frequency acoustic energy could be expected to be received via (B) the bottom-refracted path. High frequency acoustic energy could reasonably be expected not to be received via (B) the bottom-refracted path due to high attenuation within the sediments (Hamilton, 1972).

Furthermore, the bottom-refracted path was found to decrease very rapidly with an increase in horizontal range (decrease in grazing angle) between source and receiver. This resulted in rapid decrease in propagation loss (bottom loss) at a range of about 16 kiloyards or 25° bottom grazing angle.

In an effort to further study the effects of the bottom-refracted arrival, two stations were selected on the basis of the thickness of the unconsolidated sediment layers. Selection of initial sites were based on a sediment thickness study preformed by the Lamont-Doherty Geolological Observatory (Ewing, 1968). Refined estimates of thickness were obtained from seismic profiles taken either along the shot run or in the nearby vicinity of the station. To minimize the effects of bathymetry, stations with similar bottom roughness characteristics were chosen. The stations were also conducted over ares of similar sediments to discount any differences in bottom loss due to differences in sediment type. Piston cores nearby each site were obtained and analyzed. These, along with seismic profiles, were used to tie in long cores obtained by the JOIDES project (McManus, et.al., 1970). Distances between the selected station and JOIDES holes ranged between 100 miles for station A and 170 miles for station B. Sediments at all sites were found to consist of clays and oozes with virtually little or no silt-size or sand-size material.

RESULTS AND DISCUSSION

The results from two stations, stations A and B, are shown in figures 3 through 7. Bathymetric and subbottom profiles along each shot run are shown in figures 3 and 5. Only the subbottom termed "basement" was plotted. Basement as defined here is interpreted to be the base of the unconsolidated sediment layer. All depths are based on water and sediment sound velocities of 4,800 feet per second.

A graph showing bottom loss as a function of grazing angle is shown beneath the bathymetric and subbottom profiles for each station. Bottom loss data at 80 Hz (1/3 octave bandwidth) was selected because it is representative of other low frequency data from 63 Hz to 315 Hz. Selected low frequency (20-300 Hz) traces from Stations A and B are shown in figures 4 and 6, respectively. A summary of bottom loss results for all frequencies is presented in figure 7 where mean values for grazing angle bands of 90°-20° and 20° to 0° are shown. Discussion of figures 3 through 7 follows.

Station A

Station A is located near the seaward edge of a deep-sea fan. Sediments are 1,000 feet thick near the start of the shot run to about 650 feet thick at 45,000 yards horizontal range (figure 3a). The average sediment thickness under the reflecting points of each shot (half the horizontal range) is equal to approximately 900 feet. Sediments from an eight-foot core, obtained 45 miles from the shot run, consist of clays and silty clays (mean grain size from .0009 to .0015 mm. with 78% porosity. The sediments from a 1000-foot JOIDES core, about a 100 miles from station A, were identified as siliceous-fossil ooze and mud.

Bottom loss values at 80 Hz are 8 dB at near-normal incidence (figure 3b) and increase to 11.5 dB at 21° grazing. A marked decrease in bottom loss is noted at 20° grazing angle and values drop to 2.8 dB; from 20° to 5°, bottom values continue to decrease to about 0 dB. The observed rapid decrease of about 9 dB in bottom loss corresponds to the onset of the shallow bottom-refracted arrival noted previously (Christensen, Frank, and Geddes, 1975). The bottom returns from station A were reprocessed using a low frequency wide-band filter (20 Hz to 300 Hz) for purposes of locating the bottom-refracted arrival. Refracted arrivals were identified at grazing angles less than 20° (figure 4). The reflected arrival from the water-sediment interface is designated by the letter "A" and was determined from high frequency oscillographic trace (not shown). As can be seen in the low frequency traces (figure 4), 4), negligible energy is received at the water-sediment interface whereas considerable energy is received from the bottom-refracted arrival (designated by the letter "B"). Subsequent high amplitude traces are from surface paths of the bottom-refracted arrival (e.g., about 200 and 300 milliseconds at 17.2°).

Station B

Station B is located in the vast abyssal hills province of the eastern North Pacific Ocean. Sediment thicknessess were relatively constant and averaged about 250 feet along the reflecting point portion (0.5 to 2.5 kiloyards) of the shot run (figure 5a). Unfortunately, the nearest piston core is about 450 nautical miles from station B. However, the core is from the abyssal hills region and probably typifies sediment characteristics on the acoustic station. Sediments consist of silty clays with a porosity of 72%. Average sediment sound velocity values, measured along the eight-foot core, average 4938 ft/sec, or 148 ft/sec less than the bottom water sound velocity. The sediment from a JOIDES core located about 170 miles from the station, consists of brown clays with basalt (basement) encountered at 110 feet.

Bottom loss values at 80 Hz (figure 5b) average about 7 dB in the 90° to 40° grazing angle band, and about 5 dB in the 40° to 10° grazing angle band. An increase in bottom loss values is observed at grazing angles less than 10°. Upon comparison with station A (figure 3b), the sharp decrease in bottom loss values noted at grazing angles less than

20° in the station A results does not appear in the station B results. This suggests the absence of the shallow bottom-refracted arrival noted in the bottom returns from Station A. Indeed, the low frequency record traces from the wide-band filter (20 to 300 Hz) showed no indication of refracted arrivals for any of the bottom returns.

However, it should also be noted that the overall bottom loss values from 90° to 20° (figure 5b) for station B are significantly less than bottom loss values over the same grazing angle band for station A. The largest difference is noted from about 50° to 20°, where bottom losses from station B average 5.5 dB less than values obtained from station A. Where the unconsolidated sediments are relatively thin, such as station B, considerable energy at the higher grazing angle is apparently reflected from basement rock. Inspection of the low-frequency (20-300 Hz) records indiates this to be the case. As shown in Figure 6, the dominant arrival from a record trace obtained at 87.2° is not from the water-sediment interface, but occurs from a subbottom reflection occuring 80 milliseconds later. This travel time difference corresponds to time differences between the sediment surface and basement as identified on our seismic records (figure 5b). On the other hand, over areas of relatively thick sediments, such as station A, the basement is too deep to contribute much energy as a subbottom reflector. Consequently, reflections occur predominantly from, or near, the water-sediment interface. Since the sediments have very low sound velocities, high losses near the angle of intromission would be expected (Kinsler and Frey, 1962). This is the probable explanation for slightly higher losses observed in the 50° to 20° range (figure 5b). Before losses become too high, however, low frequency is received from the bottom-refracted arrival at grazing angles less than 20° as noted earlier.

Bottom Loss Vs. Frequency

Bottom loss values were averaged over two grazing angle bands for comparison of results ranging from 63 Hz to 3150 Hz from the two stations. Mean values for the 90° to 20° grazing angle band are shown in figure 7a; whereas, mean values for the 20° to 0° grazing angle band are shown in figure 7b.

Very little freqeuncy dependency is noted in figure 7a for station A (thick sediment layer). However, for station B (thin sediment layer), an increase of about 2 dB per octave is observed from 3150 Hz to 315 Hz while no frequency dependency is noted between 315 Hz and 63 Hz. Higher standard deviations are noted for station A than station B suggesting a greater grazing angle dependency. This is consistent with our findings at 80 Hz (compare figure 3b with 5b). Even more variability is noted at the higher frequencies (500 Hz to 3150 Hz) which can be attributable to a greater effect of the angle of intromission noted on station A bottom loss results.

In the high and mid-grazing angle bands (figure 7a), slightly higher average losses are observed at the higher frequencies for station B than for station A but significantly lower losses are noted at the lower frequencies. Greatest differences in mean values occur between 63 Hz and 500 Hz with station B results averaging about 4 dB less than station A. As noted in the discussion at 80 Hz, this decrease in low frequency bottom loss in the 90° to 20° grazing angle band can be attributed to subbottom-refracted energy received from the basement rock.

A decrease in mean bottom loss values in the 0° to 20° grazing angle band (figure 7b) with decreasing frequency is observed on station B with about a 1.5 dB per octave slope. On the other hand, station A shows little frequency dependency between 1,000 and 3150 Hz, but shows a sharp decrease in bottom loss (almost 4 dB per octave) between 1000 Hz and 250 Hz. Below 250 Hz, the slope on station A decreases to about 1.5 dB per octave.

In the 20° to 0° grazing angle band (figure 7b), the opposite results are observed from that shown in the 90° to 20° grazing angle band (figure 7a) for frequencies less than 1250 Hz; that is, station A bottom loss values are lower than station B bottom loss values, throughout the frequency spectrum. Furthermore, the biggest differences occur at the lower frequencies with values ranging from 5 dB at 63 Hz to 3 dB at 315 Hz. This decrease in low frequency bottom loss at the lower grazing angles is attributed to added energy being received via shallow refracted paths through the relatively thick sediment layer of station A.

CONCLUSIONS AND SUMMARY

Over the area of relatively thick unconsolidated sediments (≅ 900 feet thick), the dominant mechanism for returning acoustic energy at the lower grazing angles and lower frequencies is from refractions through the sediment layer. For example, at 80 Hz, bottom loss values in the 20° to 0° grazing angle band averaged 10 dB less than bottom loss values in 50° to 20° grazing angle band. The most dominant effects of the bottom-refracted arrival are observed in the 63 Hz to 315 Hz frequency range.

Over an area of relatively thin layer of unconsolidated sediments (≅ 250 feet thick), the dominant mechanism for returning acoustic energy at all frequencies and grazing angle are reflections from the bottom and subbottoms. Furthermore, considerable energy does seem to be returned via subbottom reflections from basement rock. This is most pronounced at lower frequencies and higher grazing angles. Also, the effects of the bottom-refracted arrival were not observed over the area of thin sediments and virtually no grazing angle dependency was noted throughout the frequency spectrum of 63 Hz to 3150 Hz.

A comparison of low frequency acoustic results from the thin sediment station to results from the thick sediment station shows: (1) lower bottom loss results in the high and mid-grazing angle bands and, (2) higher bottom loss results in the low grazing angle band. For example, in the 90° to 20° grazing angle band, bottom losses averaged 4 dB less for the thin sediment station than for the thick sediment station at frequencies from 63 Hz to 500 Hz. In the 20° to 0° grazing angle band, however, bottom losses averaged 5 to 3 dB more for the thin sediment station than for the thick sediment station at frequencies from 63 Hz to 315 Hz. The lower losses observed at the higher grazing angles are due to added low frequency energy that is received via subbottom reflections from basement rock. The higher losses observed at the lower grazing angles (when compared to a thick sediment area) occur because no energy is received from shallow bottom-refracted arrivals through the sediment layer. It is concluded that the sediment layer is not thick enough to provide the sound velcoity excess (from the sound velocity gradient within the sediment) to support a bottom-refracted path. The sediment thickness cut-off for the area studied appears to lie between 250 feet and 900 feet, or more accurately, between 0.1 and 0.37 seconds of two-way travel time from the water-sediment interface to the base of the unconsolidated sediments.

More work is required to develop a comprehensive relationship between low frequency bottom loss results and sediment thickness. More sophisticated statistical analyses requiring additional acoustic data may provide greater insight into the problem. Certainly more information on sediment thickness, sediment sound velocities, and attenuation of sound energy through the sediments are needed.

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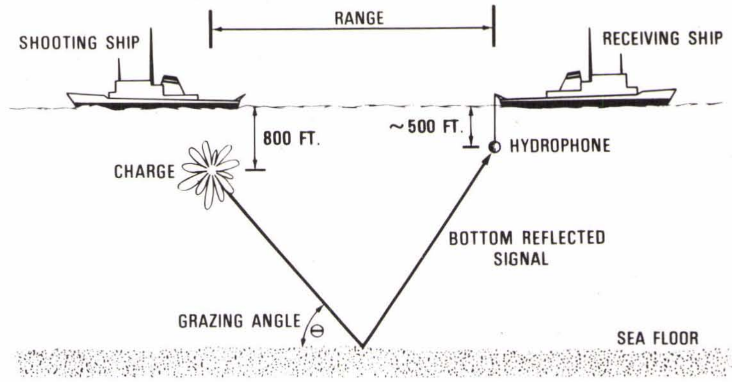


FIG. 1

GEOMETRY OF AT-SEA EXPERIMENT

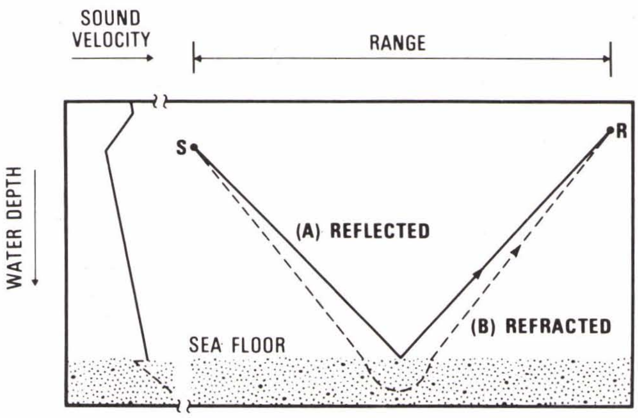


FIG. 2

SCHEMATIC SHOWING (A) THE BOTTOM-REFLECTED ARRIVAL AND (B) THE BOTTOM-REFRACTED ARRIVAL BASED ON A COMBINED WATER-SEDIMENT SOUND VELOCITY PROFILE

FIG. 3

ACOUSTIC RESULTS ON STATION A. NOTE THE RELATIVELY THICK LAYER OF UNCONSOLIDATED SEDIMENT ALONG SHOT RUN (a).

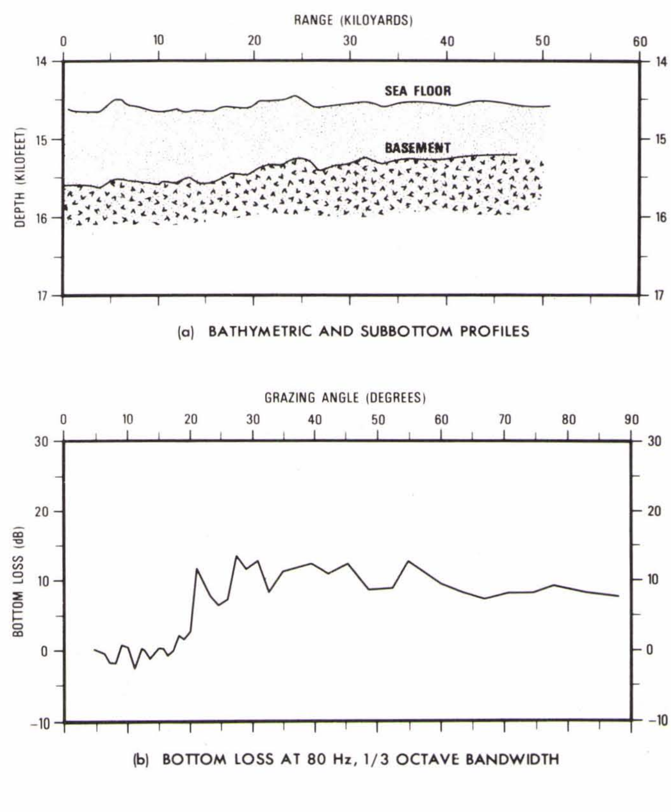
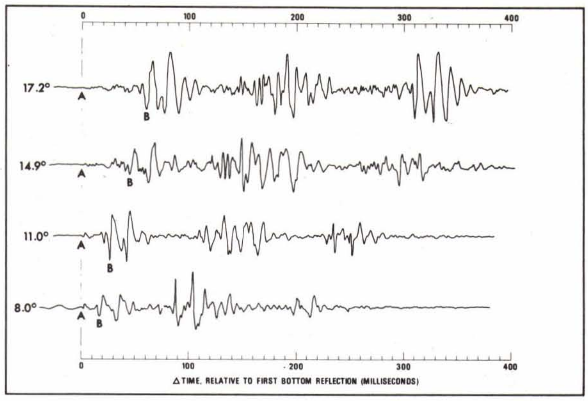
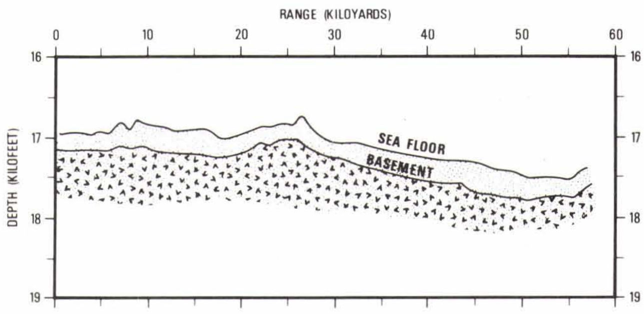
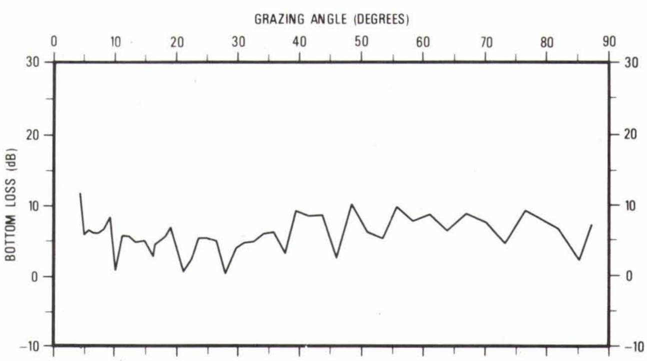


FIG. 4
REPRODUCTION OF LOW FREQUENCY (20–200 Hz) OSCILLOGRAPHIC TRACES FROM FOUR SHOTS AT VARIOUS GRAZING ANGLES (θ) ON STATION A. FIRST BOTTOM-REFLECTED ARRIVAL IS NOTED BY THE LETTER "A" AND THE BOTTOM-REFRACTED ARRIVAL IS NOTED BT THE LETTER "B"





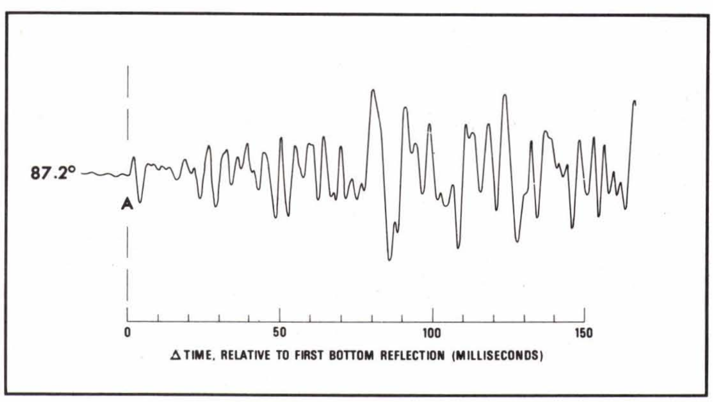
(a) BATHYMETRIC AND SUBBOTTOM PROFILES



(b) BOTTOM LOSS AT 80 Hz, 1/3 OCTAVE BANDWIDTH

FIG 5
ACOUSTIC RESULTS ON STATION B. NOTE THE RELATIVELY THIN LAYER OF UNCONSOLIDATED SEDIMENT ALONG SHOT RUN (a)

FIG. 6
REPRODUCTION OF LOW FREQUENCY (20–300 Hz) OSCILLOGRAPHIC TRACE FROM A NEAR-NORMAL INCIDENCE SHOT ON STATION B. NOTE THAT THE MAXIMUM ARRIVAL APPEARS 80 MILLISECONDS AFTER THE FIRST BOTTOM-REFLECTED ARRIVAL (DESIGNATED BY THE LETTER "A")



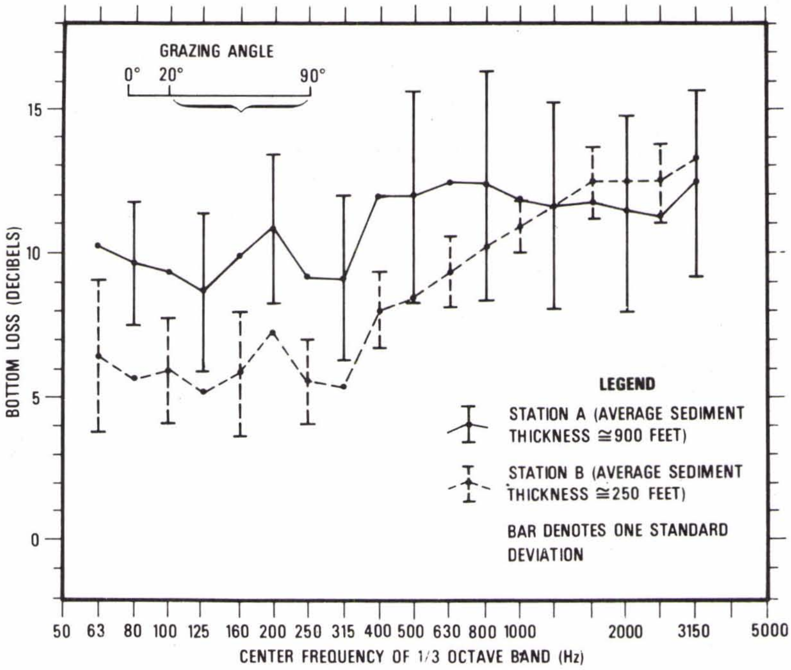


FIG. 7 (a) COMPARISON OF STATIONS A AND B SHOWING FREQUENCY VERSUS MEAN BOTTOM LOSS IN A 20 TO 90 GRAZING ANGLE BAND

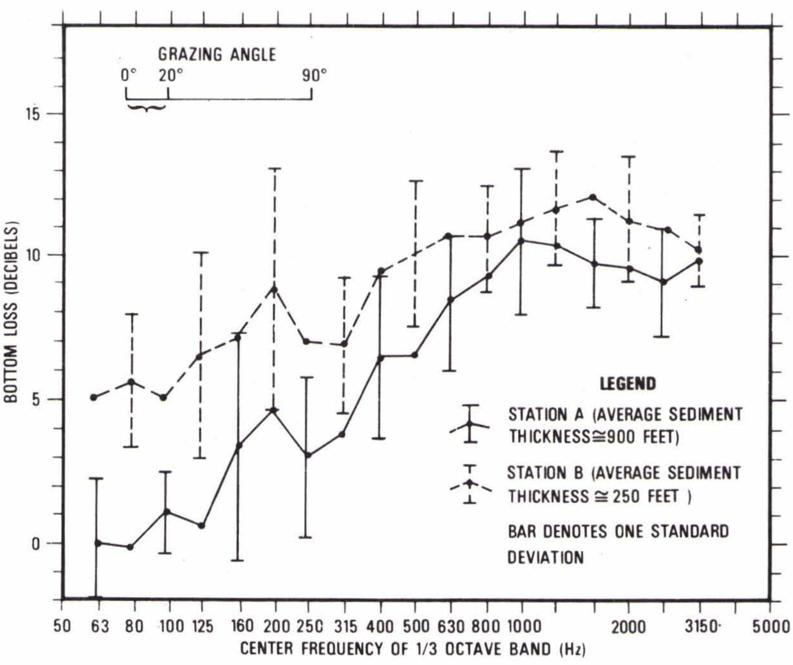


FIG. 7 (b) COMPARISON OF STATIONS A AND B SHOWING FREQUENCY VERSUS MEAN BOTTOM LOSS IN A 0 TO 20 GRAZING ANGLE BAND