DISTRIBUTION OF GAS-CHARGED SEDIMENT IN NORTON SOUND AND CHIRIKOV BASIN, NORTHEASTERN BERING SEA[1]

M.L. HOLMES[2] & D.R. THOR[3]

ABSTRACT

Holmes, M.L. & D.R. Thor 1982 Distribution of gas-charged sediment in Norton Sound and Chirikov Basin, northeastern Bering Sea. In: C.H. Nelson & S.D. Nio (eds): The northeastern Bering shelf: new perspectives on epicontinental shelf processes and depositional products – Geol. Mijnbouw 61: 079-089.

Numerous zones of anomalous acoustic responses caused by gas in the subsurface sediment layers have been detected on seismic reflection records from Norton Sound and Chirikov Basin. Sound sources used range in size and power from 3.5 kHz transducers to 1326 in^3 (21.7 l) air gun arrays. The frequency and distribution of these zones suggest that as much as 7000 km^2 of the northeastern Bering Sea may be underlain by gas-charged sediment. Much of the gas is of shallow biogenic origin, having been generated in buried peat deposits. Compressional velocity is about 1.5 km/s in these layers, 7 percent below the velocity in gas free areas as determined from seismic refraction studies. Seismic velocity beneath a large gas seep south of Nome decreases to about 1.2 km/s in the interval from 250 to 440 m below the seafloor, where thermogenic gases of deeper origin are migrating upward along a system of basin margin faults.

INTRODUCTION

Discovery of the submarine seepage of natural gas south of Nome, Alaska, in 1976 (CLINE & HOLMES, 1977) prompted a comprehensive review of seismic reflection data from the Norton basin area (Fig. 1). The same types of anomalous acoustic responses associated with the seep zone (CLINE & HOLMES, 1977; HOLMES & CLINE, 1978; NELSON ET AL., 1978) were first recorded by GRIM & MCMANUS (1970) in the course of a high resolution seismic study of the northern Bering Sea in 1967. They interpreted the zones of acoustically impenetrable seafloor on their sparker records as representing a Yukon River deposit very near the surface of the present-day seafloor. The highly reflective nature of this proposed surficial deposit was thought to cause the sudden termination of deeper reflectors observed along parts of the seismic track

(GRIM & MCMANUS, 1970). Air gun reflection records collected in Chirikov Basin during a cruise by NOAA (then ESSA) in 1968 (WALTON ET AL., 1969) also crossed a few of these reflector termination anomalies.

CLINE & HOLMES (1977) were the first to suggest that these acoustic responses in the northern Bering Sea were caused by the presence of bubble phase gas in the nearsurface sediment; HOLMES & CLINE (1978), NELSON ET AL., (1978), and KVENVOLDEN ET AL. (1979) presented detailed analyses of the deep penetration and high resolution seismic reflection records collected over the seep zone and the geochemistry of sediment samples collected from Norton Sound and Chirikov Basin on USGS cruises in 1977 and 1978.

The main objective of this study was to determine the geographic extent and distribution of zones showing anomalous acoustic responses on seismic reflection records from Norton Sound and Chirikov Basin. Certain characteristics of these acoustic anomalies could then be analyzed to determine the most probable cause of the anomaly (gas, change in sediment type, and other factors). During the past 12 years, seismic records used for this study have been collected aboard U.S. Geological Survey and University of Washington research vessels along some 27,000 km of trackline (Fig. 2).

[2]U.S. Geological Survey, 7600 Sand Point Way NE., Seattle, Washington 98115, U.S.A.
[3]U.S. Geological Survey, 345 Middlefield Road, Menlo Park, Calif. 94025, U.S.A. Present address: Exxon Production Research, P.O. Box 2189, Houston, TX 77001, U.S.A.
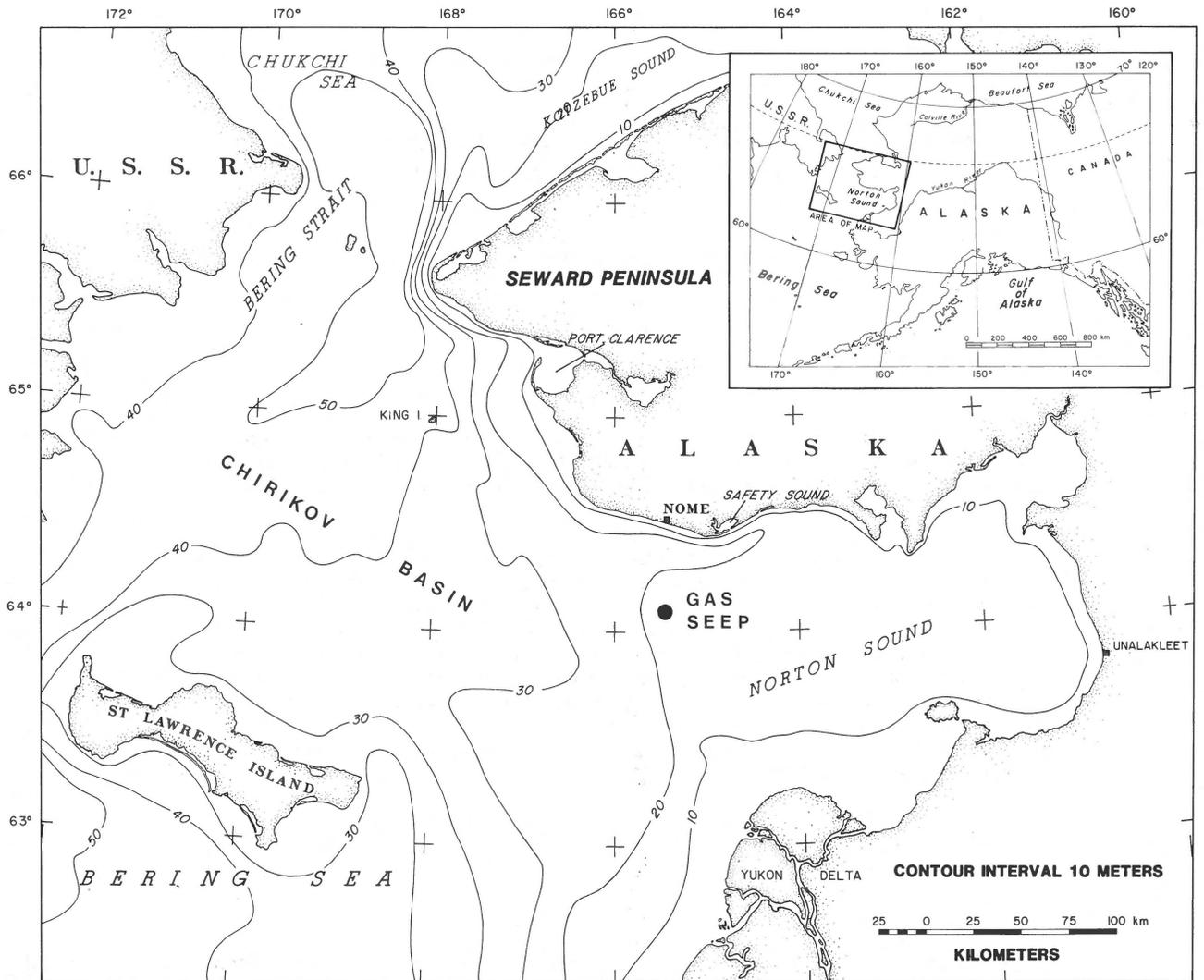
Fig. 1
Location map of study area showing Norton Sound, Chirikov Basin, and the Norton Sound gas seep (Cline & Holmes, 1977; Holmes & Cline, 1979).

Sound sources used in these geophysical studies included medium- and high-resolution sparker, 40 to 1326 in³ (0.66 to 21.7 l) air gun, boomer, and subbottom profilers.

PHYSIOGRAPHIC SETTING

The floor of the northern Bering Sea is a broad shallow epicontinental shelf (Fig. 1). Water depths in Chirikov Basin, in the western part of the survey area, range from 20 to 50 m. Norton Sound is bounded on the north by Seward Peninsula, on the east by the Alaska mainland, and on the south by the Yukon River delta. Water depths in Norton Sound range from 10 to 25 m. The surficial sediment of Norton Sound is primarily derived from the Yukon River and consists of coarse silt and very fine sand underlain by nonmarine peaty mud rich in organic matter (NELSON & CREAGER, 1977). Surficial

sediment in Chirikov Basin consists mostly of glacial gravel and transgressive fine sand (NELSON ET AL., 1974; MCMANUS ET AL., 1974).

DESCRIPTION AND CAUSE OF ACOUSTIC ANOMALIES

The distribution of the many crossings of acoustically anomalous zones along more than 20,000 km of seismic-reflection lines (Fig. 3 and 4) suggests that they occur in large patches beneath much of the seafloor of Norton Sound; the total area may be as much as 7000 km². Two distinct types of acoustic anomalies were observed on the seismic-reflection records: Reflector pull-downs and reflector terminations (HOLMES & CLINE, 1978). Reflector pull-downs similar to those shown in figure 5 have been observed and described by several other
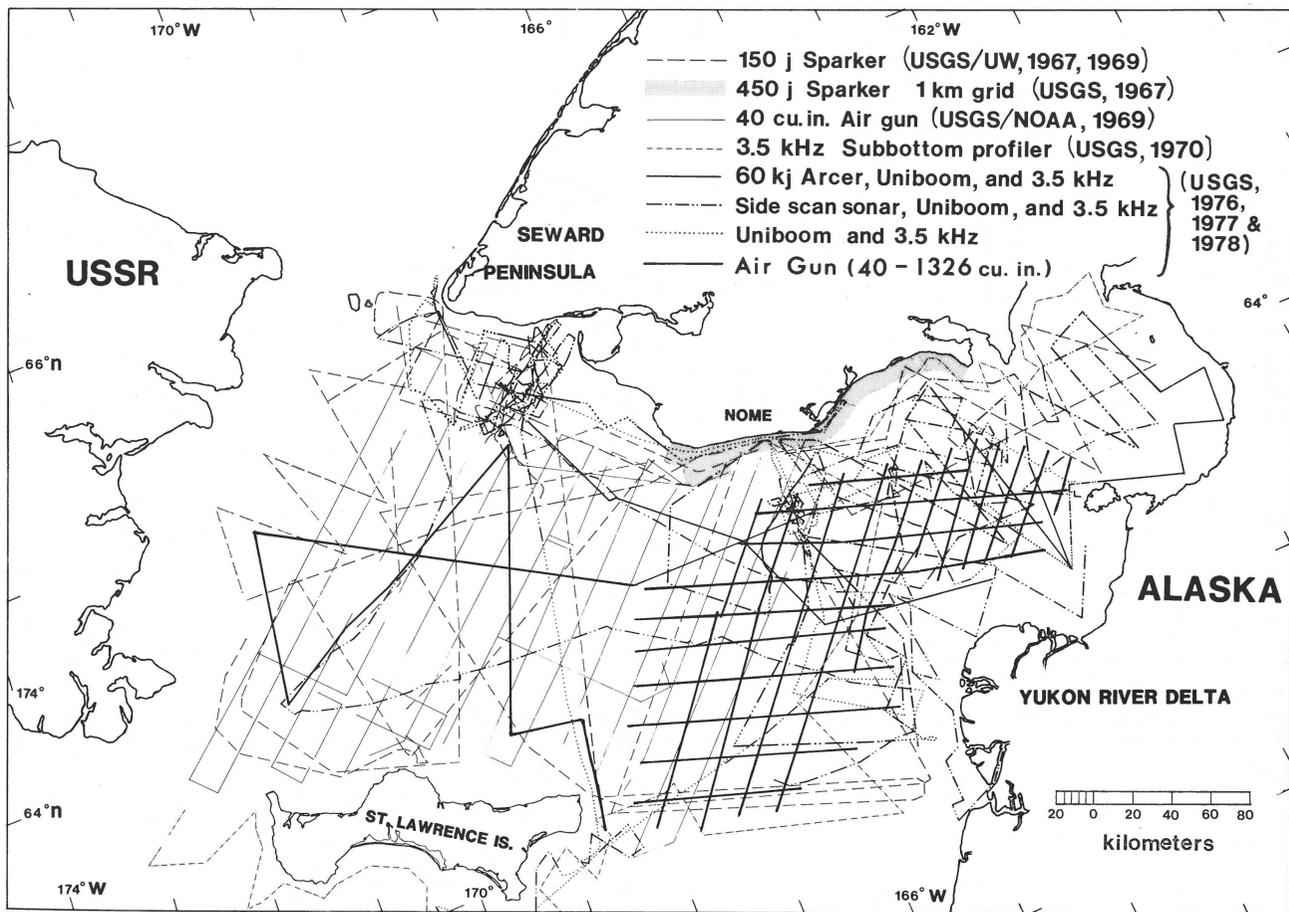
Fig. 2
Seismic-reflection tracklines in the northern Bering Sea. Cruise dates and sound sources used are also shown.

investigators from both deep shallow water areas where gas has accumulated in the subsurface strata (LINDSEY & CRAFT, 1973; COOPER, 1978). The low compressional velocity in gas-charged horizons causes the recorded time section (seismic record) to be distorted relative to the true depth section. The greater travel time through the gassy sediment produces a zone of pulled down reflectors beneath it on the seismic record. The gas need not to be in the free state (bubble phase) to produce this phenomenon; although the decrease is much greater if free gas is present in the sediment interstices, gas-water or oil-water solutions have compressional velocities less than the velocity of water alone (CRAFT, 1973). The strong horizontal reflectors exhibiting a 180° phase shift which is associated with the observed pull-downs (Fig. 5) could be the result of reflections from interfaces between gas-charged zones and strata where water alone fills the pore spaces. The decrease in both compressional velocity and density due to the presence of gas in the sediment results in a large negative reflection coefficient at the top of the gas-charged layer (CRAFT, 1973; SAVIT, 1974). Such a condition would produce acoustic responses similar to the strong horizontal reflectors

above the reflector pull-downs (Fig. 5).

Crossings of the acoustic anomaly associated with the gas seep south of Nome are shown in figures 5 and 6. The anomaly covers an area of about 50 km²; it is characterized by a sudden termination of subbottom reflectors and a marked pull-down of the reflectors at its margins (Fig. 6). The subbottom depth to the top of the feature causing the anomalous acoustic signature appears to be quite shallow, generally varying between 25 to 100 m across the anomaly. Places on seismic records where the surface of the acoustically opaque zone rises abruptly to within a few meters of the sea floor (NELSON ET AL., 1978) may indicate the locations of the active seeps (KVENVOLDEN ET AL., 1979).

Calculations by CLINE & HOLMES (1977, 1978) indicated that the concentrations of the low molecular weight hydrocarbons that accumulated in the sediment beneath the seep zone were far below theoretical saturation values. This finding was in conflict with the seismic reflection data, which strongly suggested the presence of bubble phase gas in the sediment. The paradox was resolved by the recent discovery that the seeps consist primarily of CO_2 rather than hydrocarbons, and
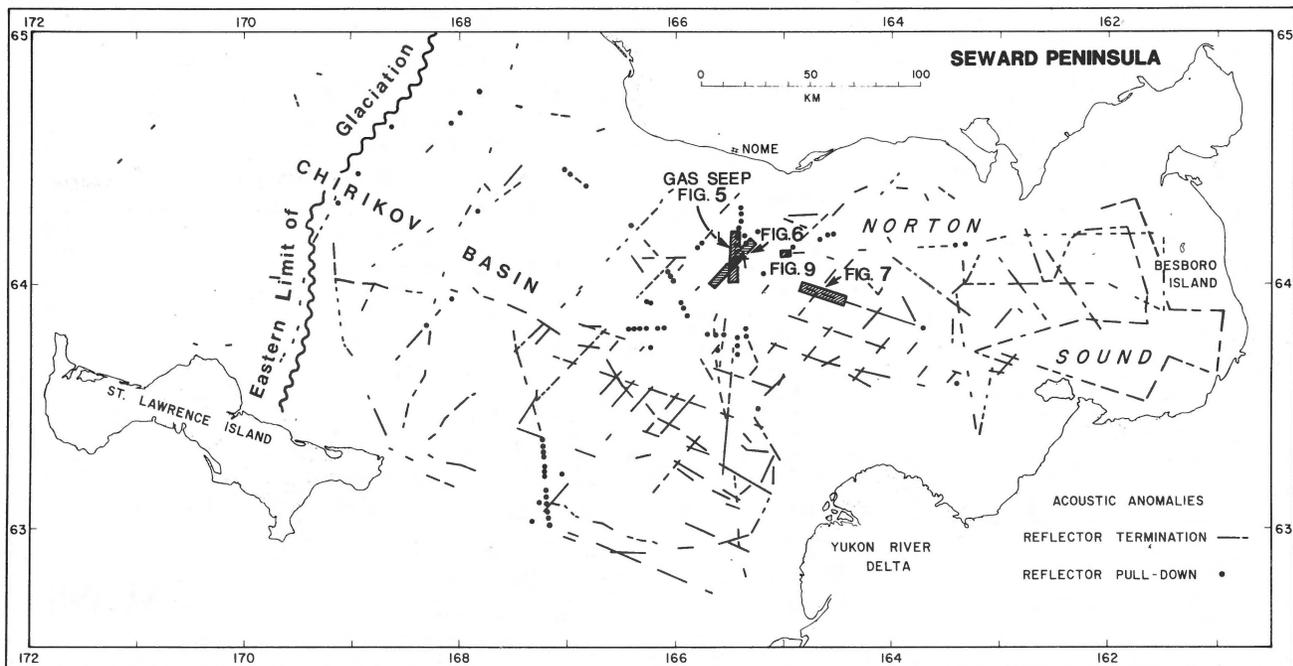
Fig. 3
Location of anomalous near-surface acoustic responses observed on single-channel (air gun) seismic reflection records from Norton Sound and Chirikov Basin. Also shown are the locations of the Norton Sound gas seep (Cline & Holmes, 1977), and the seismic record sections shown in figures 5, 6, 7, 9.

that CO_2 is present in the free state in the sediment interstices (KVENVOLDEN ET AL., 1979).

Some other reflector termination anomalies observed on air gun records in Norton Sound (Fig. 7) differ greatly from the one associated with the gas seep by exhibiting only slight reflector pull-downs at their margins and lacking the spectacular 'wipe-out' appearance of the seep anomaly. Low frequency reflections at 0.6, 0.9, and 1.2 seconds can be traced across the acoustic anomaly zone (Fig. 7); these reflectors show a distinct pull-down relative to the corresponding reflectors in the normal section. Attenuation of all but the low frequency energy is a distinctive characteristic of the reflector termination zones.

Anomalous acoustic responses were also observed on minisparker (800 joule) and boomer reflection records (GRIM & MCMANUS, 1970; NELSON ET AL., 1978; KVENVOLDEN ET AL., 1979). Small reflector pull-downs observed on the airgun records usually appear as abrupt reflector terminations on the high resolution profiles. Anomalies seen on boomer records (Fig. 8) characteristically are near the surface (10 meters or less) and at some places the top of anomalies is in the bottom return pulse on the record and its depth cannot be easily resolved. Core-sample gas analysis confirms that the top of the gas-charged sediment zone can be within a few tens of centimeters of the surface (KVENVOLDEN ET AL., 1979). The thicknesses of these near-surface gas zones are unknown, because only the top of the zone acts as a reflector and no

energy is returned from lower reflectors.

An anomaly approximately 20 km east of the Norton Sound gas seep, shown on part of a minisparker record (Fig. 9), was at first thought to be related to a near surface zone of diffractions (point source reflectors); this diffraction layer is commonly observed on high-resolution records over the reflector wipe-outs. Careful examination of the seismic data (Fig. 9), however, shows that the diffractions are also present outside the acoustic anomaly zones. Gas in the near-surface sediment apparently attenuates energy reflected from deeper horizons in the gas-charged zones, thereby making the zone of diffractions more apparent on records over the gas-charged zones. The patches of diffracted arrivals observed on the high resolution records in Norton Sound and Chirikov Basin may be caused by coarse sediment (cobbles and pebbles) buried in or a few meters beneath the Holocene section.

The extensive reflector termination anomalies observed in Norton Sound and Chirikov Basin (Figs. 3 and 4) are probably caused by a subsurface accumulation of gas in quantity sufficient that scattering and attenuation of the seismic signal, even from large sources, is almost complete. The sharp reduction in apparent amplitude of reflected arrivals was observed over virtually all reflector termination anomalies crossed in the course of the geophysical surveys. It is indicative of an unusually low impedance contrast at the sea floor; the most likely explanation is the presence of free (bubble-phase) gas in the sediment.
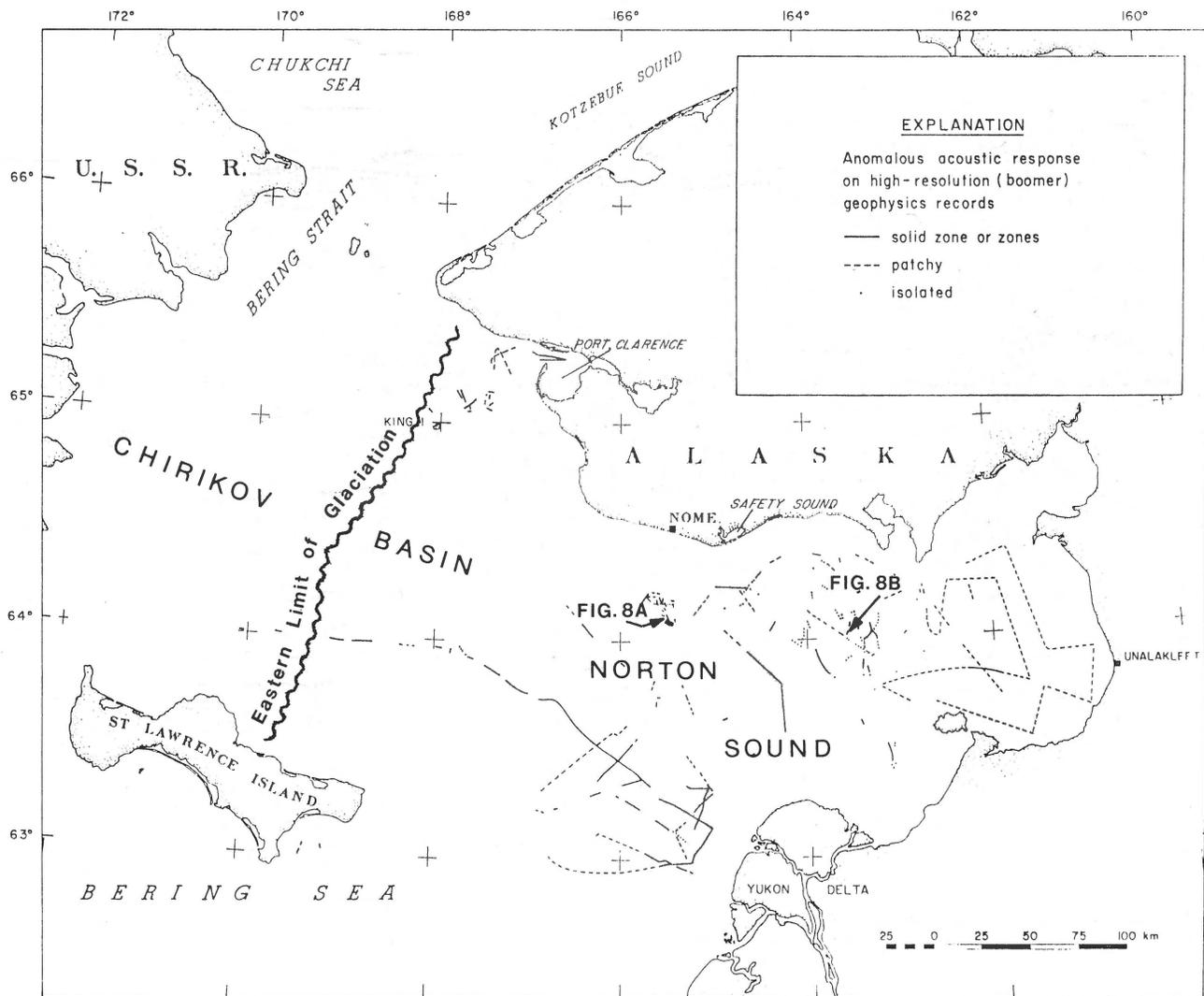
Fig. 4
Locations of anomalous near-surface acoustic responses observed on boomer reflection records from Norton Sound and Chirikov Basin. Also shown is location of seismic record section in figure 8.

Geochemical analyses by NELSON ET AL. (1979) have shown that biogenic methane is present at saturation volumes in near-surface peaty muds at several station sites in Norton Sound. At many of the sites sampled, but not all, acoustic anomalies are associated with the known saturated gas conditions.

REFLECTOR PULL-DOWN ANALYSIS

In an effort to gain more quantitative estimates of the velocity changes caused by the presence of gas, a method was developed for computing the compressional velocity in gas-charged zones over which single channel seismic-reflections records show a distinct pull-down of reflectors. Compressional velocity data obtained from sonobuoy refraction profiles (HOLMES & FISHER, 1979) were first used to construct an average thickness versus reflection time curve for the 'normal' gas-free section in Norton basin.

The next step was to carefully measure reflection times to several marker horizons that can be traced across a pull-down zone. The reflection times measured from the single channel seismic sections were first corrected for source to receiver offset using the formula

$$T_v^2 = T_r^2 - \frac{x^2}{V_w^2}$$

where T_r = apparent reflection time from the record, x = source to receiver offset, V_w = compressional velocity of seawater, and T_v = corrected (normal incidence) reflection time.
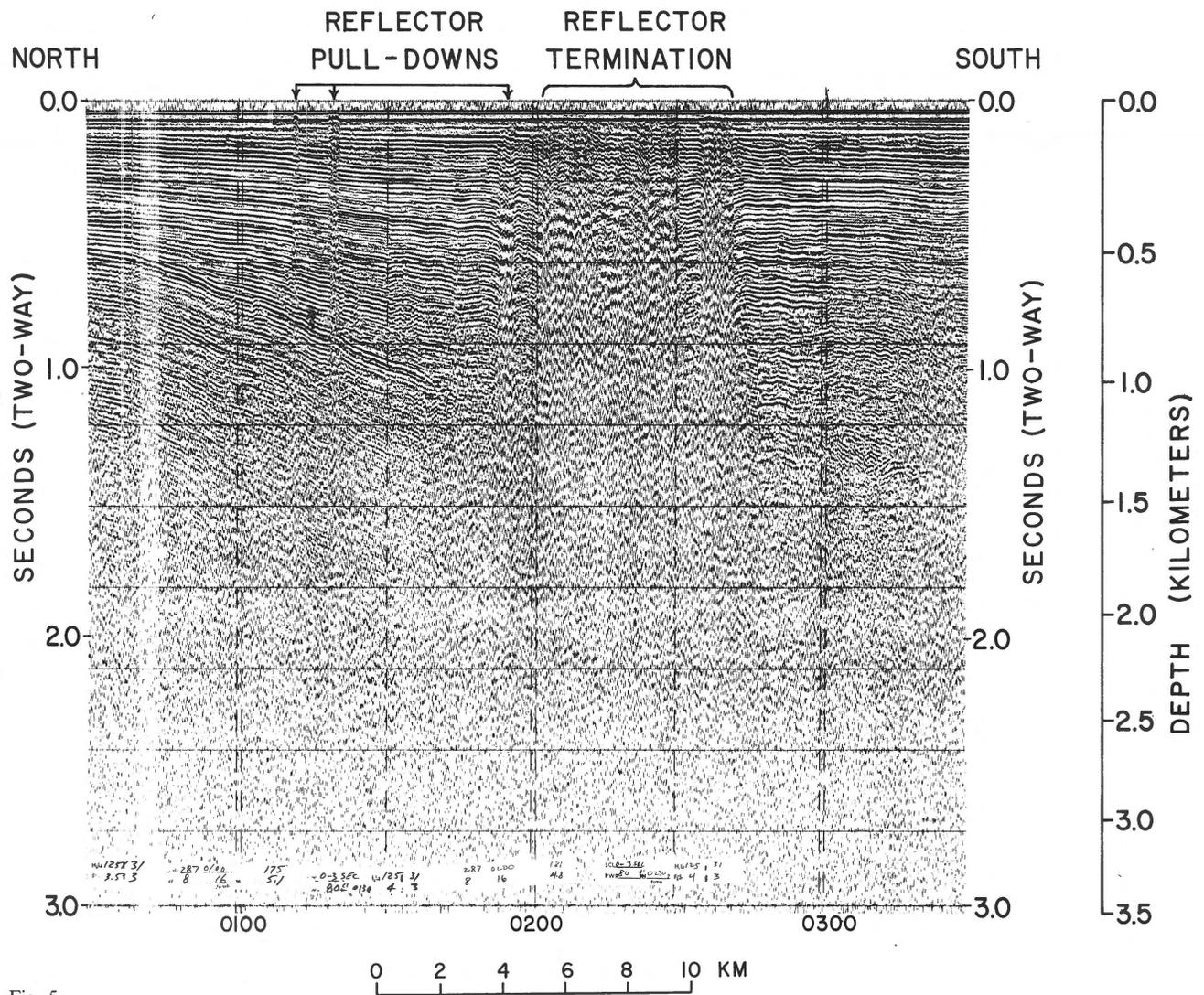
Fig. 5
Seismic reflections (air gun) record across the Norton Sound gas-seep zone. Location of line shown in figure 3. This record shows two types of acoustic anomalies indicative of gas in the sediment: Reflector terminations an reflector pull-downs.

The depth to a given reflector could then be determined using the equation for the depth (thickness) versus reflection time curve derived from the sonobuoy measurements:

$$D = 0.80T_v + 0.167T_v^2$$

It was then possible to construct average velocity curves for both the normal zones and the gas-charged zones using:

$$\overline{V}^2 = \frac{4D^2 + x^2}{T_v^2}$$

where T_v = corrected vertical reflection time to a given reflector in the normal zone and to that same reflector in the pulled-down (gas-charged) section. These average-velocity curves can then be used to compute interval velocities in each zone. This treatment assumes that all of the distortion (pull-down) of the marker reflectors is due to a reduction in compressional velocity.

In actual practice, reflectors were picked at time increments of 0.1 s, and these intervals were carried through the entire chain of calculations. Figure 10 is an example of such an analysis of the pull-down zone over the gas seep shown in figure 6. The analysis extends only to a subbottom depth of 640 m; the extent and character of the acoustically anomalous zone beneath the seep area prevents accurate picking of pulled-down reflectors below that depth. However, the general trend of the average and interval velocity curves for the gas-charged zone beneath the seep suggest that the entire section above basement (about 1.3 km) probably contains
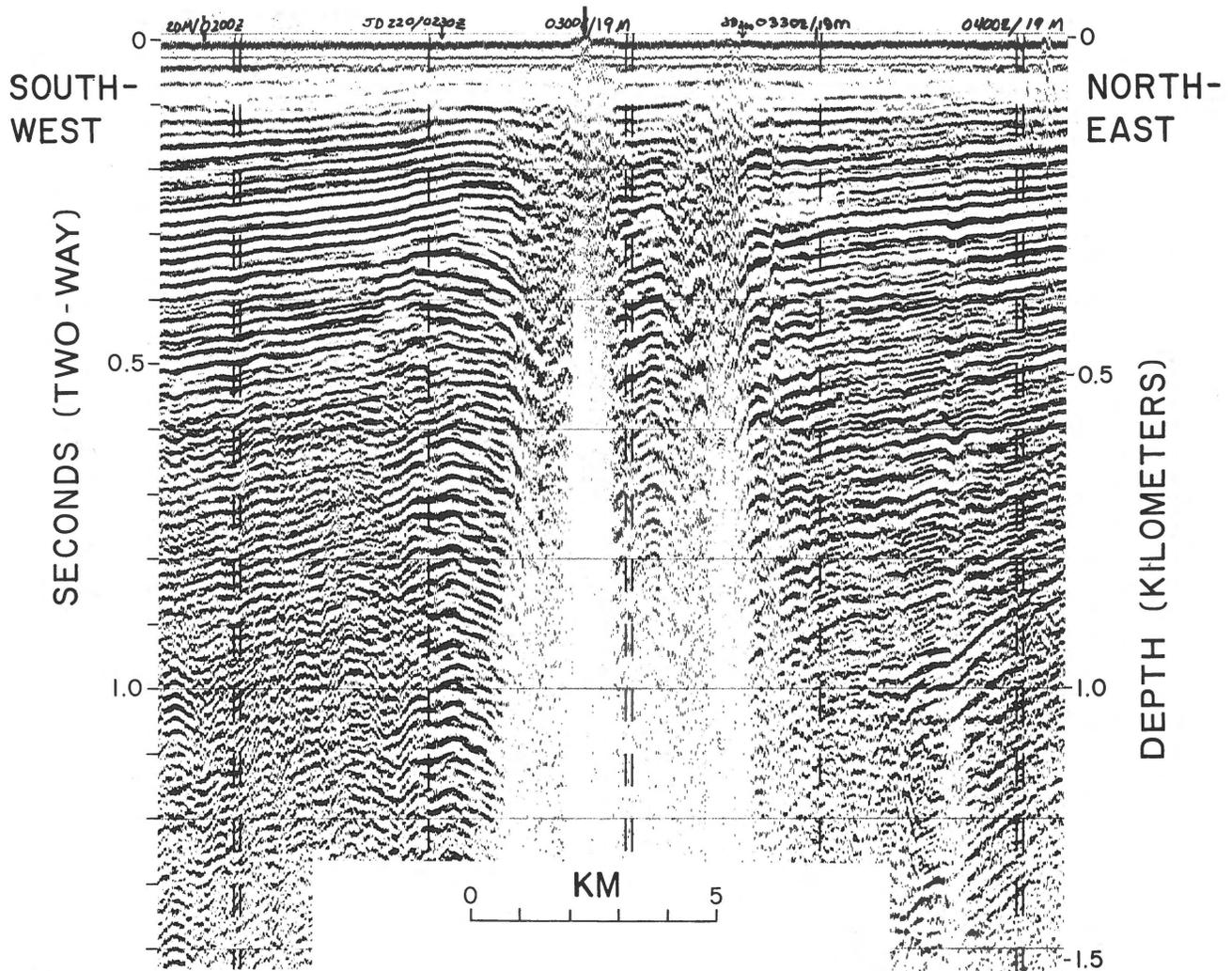
Fig. 6

Single-channel reflection (air gun) record across the Norton Sound gas seep area. Location of line shown in figure 3. Reflector termination zone and marginal pull-downs are clearly shown.

enough gas to significantly lower compressional velocity.

The interval velocity curve can also be used as a qualitative indicator of gas concentration in the sedimentary section. The gas-seep pull-down analysis (Fig. 10) shows that compressional velocity reaches a minimum of 1.21 to 1.24 km/s between 250 and 440 m subbottom depth. This represents a decrease of about 35 percent from the velocity one would expect at that depth in a normal sedimentary section. If the interval velocity curve could be constructed for the entire section down to basement, it might exhibit several minima similar to the ones shown in figure 10. These minima are probably an expression of a change in sediment or rock type that allows gas to be concentrated in those horizons.

POSSIBLE SOURCES OF GAS

The distribution of acoustic anomalies (Figs. 3 and 4) suggests that near-surface accumulations of gas are most common in the western part of Norton Sound northwest of the Yukon River delta. What appear to be gas-free zones along the southern and eastern shores of Norton Sound (Figs. 3 and 4) result from lack of seismic records over these very shallow water areas. Such is not the case for western Chirikov Basin where seismic-reflection coverage is good (Fig. 2); there are simply few occurences of acoustic anomalies.

The possible sources of the gas are still being investigated. The gas seep south of Nome is the only well-substantiated source of low molecur weight hydrocarbon gases and carbon
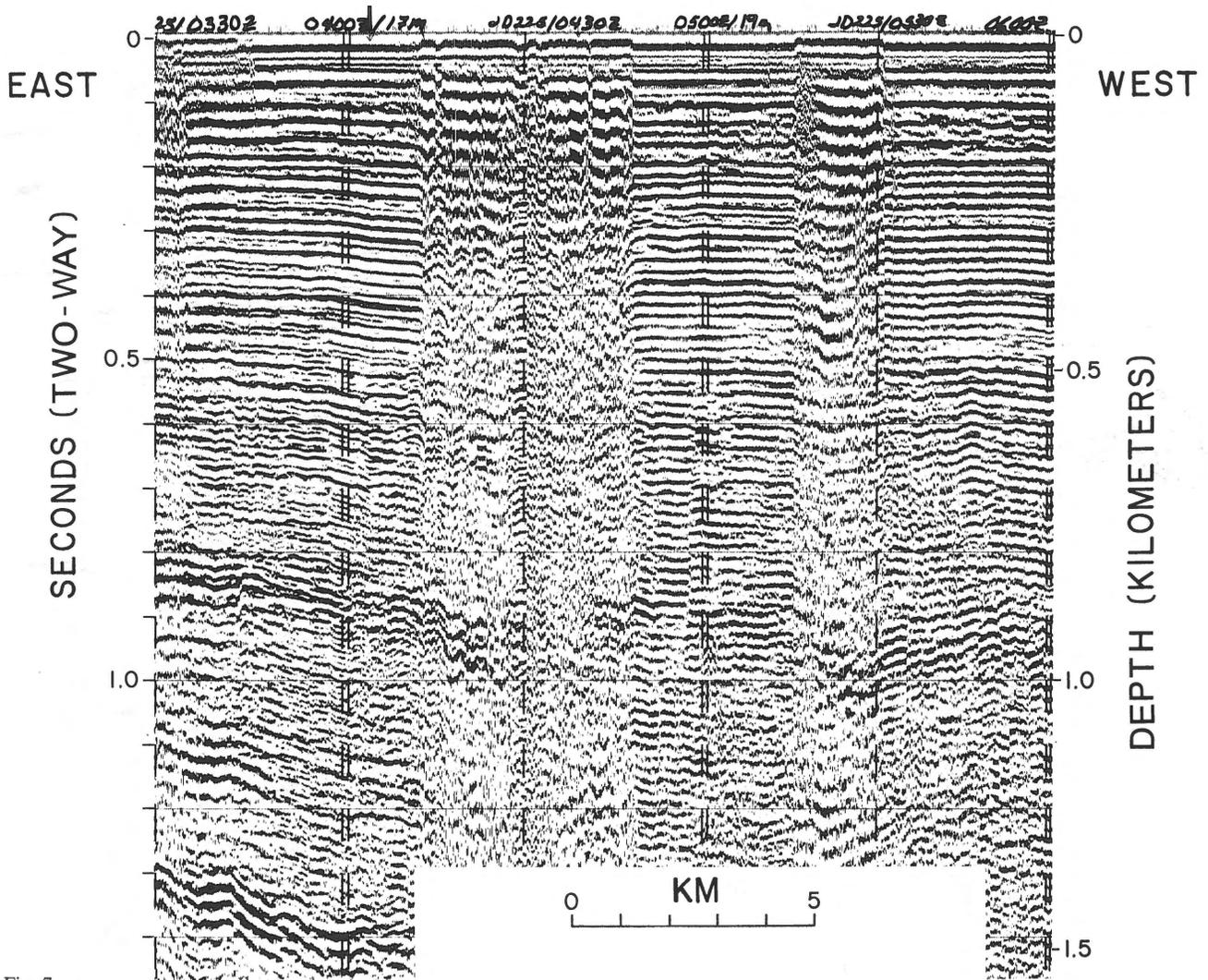
Fig. 7

Single-channel seismic-reflection (air gun) record from central Norton Sound showing 'normal' reflector zones and typical reflector termination anomalies. Location of line is shown in figure 3.

dioxide indicative of a deep thermogenic origin (CLINE & HOLMES, 1978; NELSON ET AL., 1978; KVENVOLDEN ET AL., 1979).

Carbon isotope measurements on the CO_2 and CH_4 components yielded $\delta^{13}C$ values (relative to PDB) of -0.27 and -3.6%, respectively (KVENVOLDEN ET AL., 1979). HOLMES and CLINE (1979) have used these data to estimate the source depth of these seep gases. A $\delta^{13}C$ value of -3.6% is characteristic of methane from a depth of about 2500 m (GALIMOV, 1969). This depth greatly exceeds basement depth (850-1450 m) beneath the seep, suggesting that the gas has migrated to the seep area from the deeper central part of Norton basin. The southerly dip of beds and unconformities as well as numerous faults observed on the reflection records over the seep support such an interpretation.

The location of many of the other reflector termination zones, particularly in Norton Sound, coincides with known occurrences of buried tundra-derived peat deposits that formed during low sea-level stands in the Quaternary (NELSON & CREAGER, 1977). Biogenic methane generated in these peat beds could cause the observed anomalous acoustic responses (KVENVOLDEN ET AL., 1979); the peat layers themselves could also act to trap petroleum-derived gases migrating upward. A velocity analysis similar to the one discussed for the seep zone was performed for an acoustic anomaly associated with a suspected peat deposit. Although the reflector-termination anomalies usually associated with this type of gas accumulation make it difficult to trace reflector pull-downs, preliminary results suggest that the gas has accumulated in near-surface horizons up to a few tens of meters thick. Compressional velocity in these layers is approximately 1.5 km/s, about 7 percent less than in the surrounding gas-free sediment.
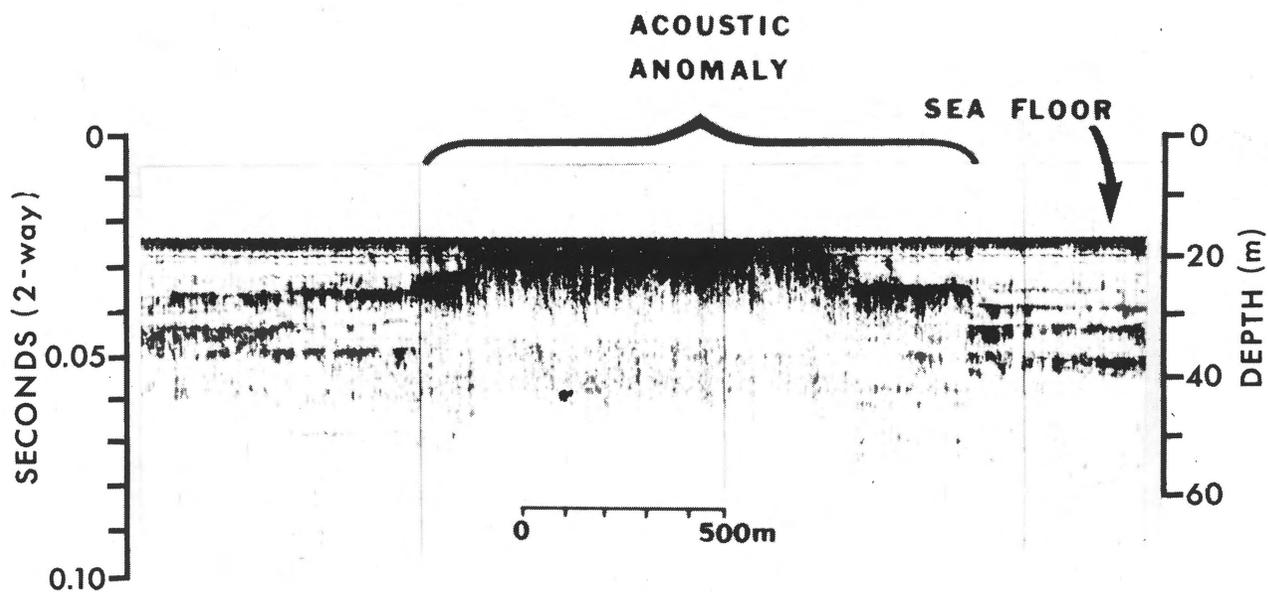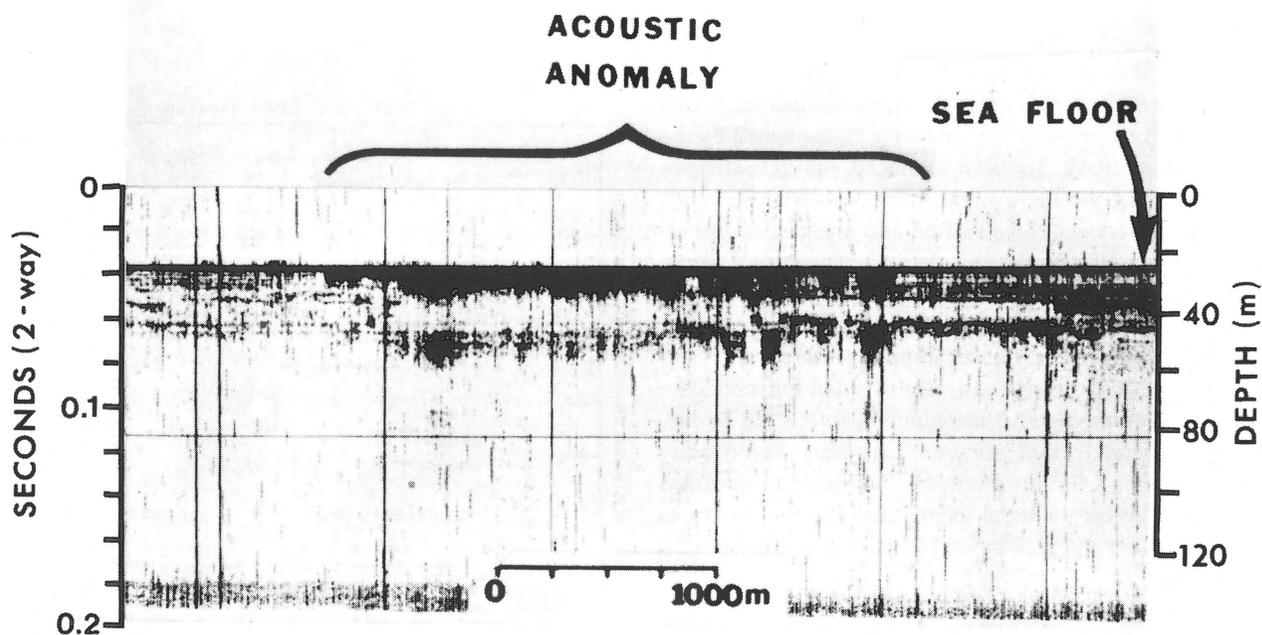
Fig. 8
High-resolution boomer records showing acoustic anomalies over the gas seep area south of Nome (A), and gas-charged peaty-mud zones (B).
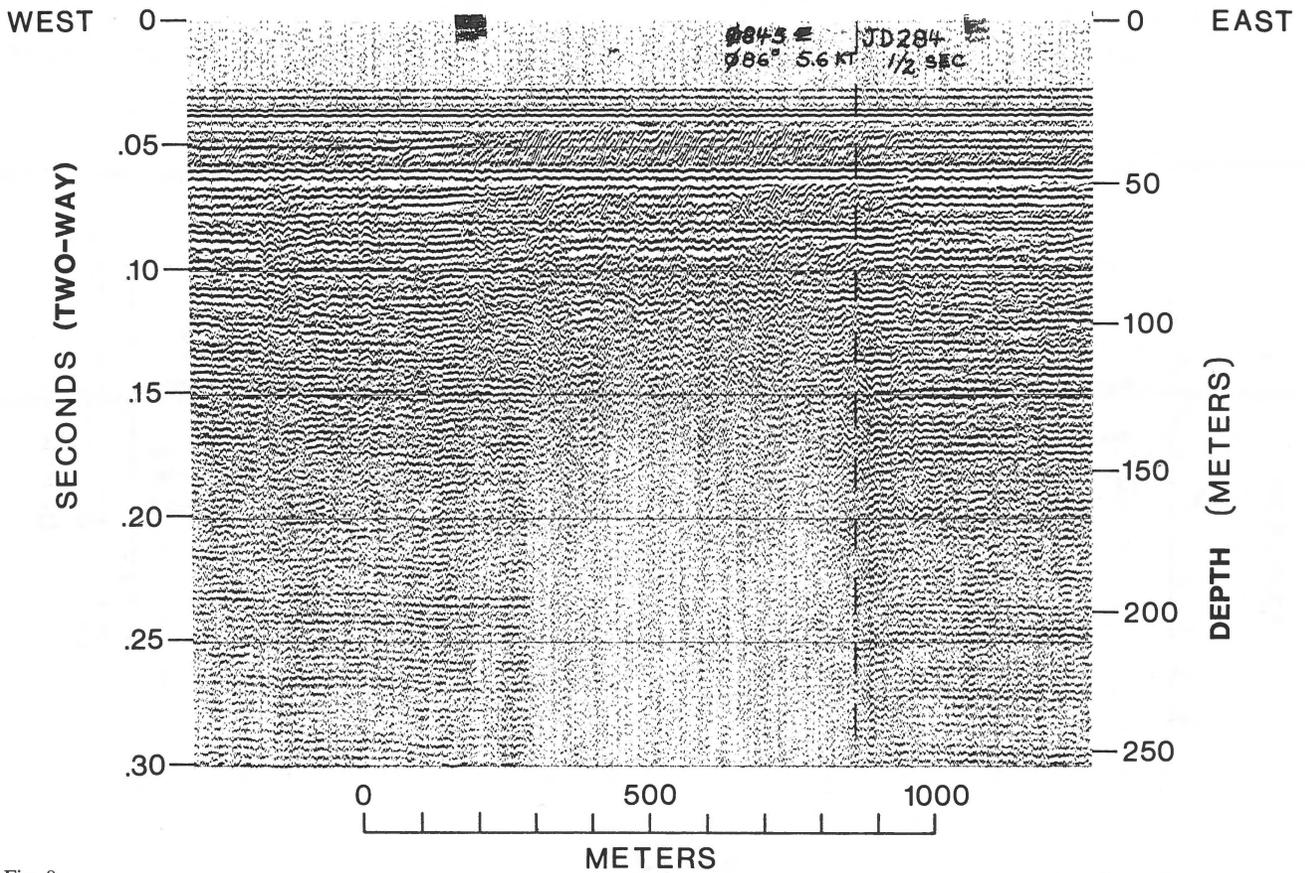Location of lines shown in figure 4.

WEST 0 — EAST 0

Fig. 9
Minisparker (800 joules) record from Norton Sound showing reflector-termination anomaly with near-surface diffractions. Location of line is shown in figure 3.

The absence of acoustic anomalies (gas-charged sediment) in western Chirikov Basin can probably be explained by the types of Quaternary deposits produced during extensive glaciation during the Pleistocene (GRIM & MCMANUS, 1970); the boundary between the glaciated and unglaciated terrain corresponds closely with the western limit of acoustic anomalies in figures 3 and 4. The Quaternary glacial and glaciomarine sediments deposited in Chirikov Basin do not have a high potential for biogenic gas generation because advance and retreat of the ice sheets evidently destroyed or prevented the growth of tundra-derived peats common to Norton Sound. Also, the relatively thin section of Tertiary sedimentary deposits beneath Chirikov Basin has not attained thickness sufficient to subject the basal sediments to the temperatures and pressures for the generation of hydrocarbon gases.

SUMMARY

The distribution of acoustic anomalies indicates that almost 7000 km² of seafloor in Norton Sound and Chirikov Basin is underlain by sediments containing gas sufficient to affect
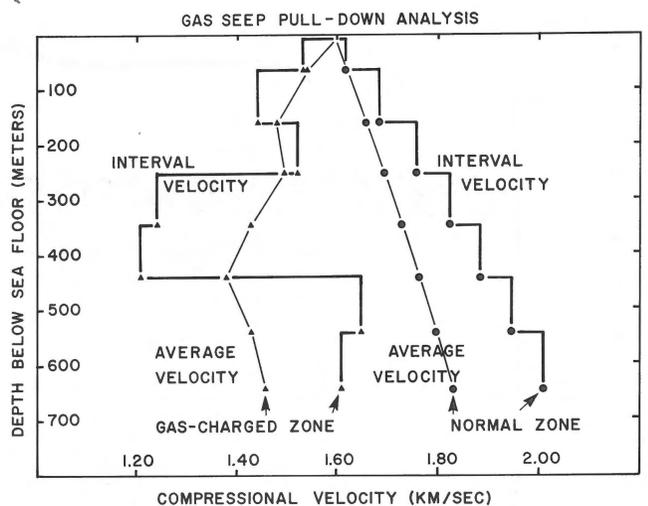

Fig. 10
Velocity analysis of reflector pull-down zone beneath the Norton Sound gas seep (Fig. 5). The two right-hand curves show average and interval velocity versus depth in the gas-free reflector sequence outside the seep zone. The two curves on the left are for the gas-charged section beneath the seep itself.

sound transmission trough these zones. A method of indirectly determining compressional velocity in the gas-charged zones gave values 7 to 35 percent lower than would be expected for gas-free sediment. The cause of one of the anomalies, that associated with the Norton Sound gas seep, is well documented. Here thermogenic gases are seeping to the surface along a system of basin-margin faults. Although other undiscovered seeps of the thermogenic gas may exist in Norton Sound or Chirikov Basin, most of the acoustic anomalies in this area are probably caused by biogenic gases generated in buried peat layers. Further detailed processing and analysis of the seismic data will possibly permit quantitative estimates to be made of the amounts of gas present in these acoustically anomalous zones.

REFERENCES

Cline, J.D. & M.L. Holmes 1977 Submarine seepage of natural gas in Norton Sound, Alaska – Science 198: 1149-1153.
—— 1978 Anomalous gaseous hydrocarbons in Norton Sound: Biogenic or thermogenic? – Proc. Offshore Tech. Conf. (Houston): 81-86.
Cooper, A.K. 1978 Hydrocarbon prospects for the frontier abyssal areas of the Bering Sea – Oil Gas J. (Oct. 23): 196-201.
Craft, C.I. 1973 Detecting hydrocarbons – for years the goal of exploration geophysicists – Oil Gas J. (Feb. 19): 122-125.
Galimov, E.M. 1969 Isotopic composition of carbon in gases of the crust – Int. Geol. Rev. 11: 1092-1104.
Grim, M.S. & D.A. McManus 1970 A shallow seismic-profiling survey of the northern Bering Sea – Mar. Geol. 8: 293-320.
Holmes, M.L. & J.D. Cline 1978 Geological setting of the Norton basin seep – Proc. Offshore Tech. Conf. (Houston): 73-80.
—— 1979 Source depth and geologic setting of the Norton basin gas seep – J. Petrol. Tech. 31: 1241-1248.
Holmes, M.L. & M.A. Fisher 1979 Sonobuoy refraction measurements from Norton basin, northern Bering Sea – Am. Assoc. Pet. Geol. Program & Abstr. Annuel Convention (Houston): 104.
Kvenvolden, K.A., C.H. Nelson, D.R. Thor, M.C. Larsen, G.D. Redden & J.B. Rapp 1979 Biogenic and thermogenic gas in gas-charged sediment of Norton Sound, Alaska – Proc. Offshore Tech. Conf. (Houston): 479-486.
Lindsey, J.P. & C.I. Craft 1973 How hydrocarbon reserves are estimated from seismic data – World Oil (Aug. 1): 23-25.
McManus, D.A., K. Venkatarathnam, D.M. Hopkins & C.H. Nelson 1974 Yukon River sediment on the northernmost Bering Sea Shelf – J. Sed. Pet. 44: 1052-1060.
Nelson, C.H., D.M. Hopkins & D.W. Scholl 1974 Cenozoic sedimentary and tectonic history of the Bering Sea – In: D.W. Hood & E.J. Kelley (eds.): Oceanography of the Bering Sea (Univ. Alaska, Inst. Marine Sc.: 485-516.
Nelson, C.H. & J.S. Creager 1977 Displacement of Yukon-derived sediment from Bering Sea to Chukchi Sea during Holocene time – Geology 5: 141-146.
Nelson, C.H., K. Kvenvolden & E.C. Clukey 1978 Thermogenic gases in near-surface sediments of Norton Sound, Alaska – Proc. Offshore Tech. Conf. (Houston): 2623-2633.
Nelson, C.H., D.R. Thor, M.W. Sandstrom & K.A.Kvenvolden 1979 Modern biogenic gas-generated craters (sea-floor 'pockmarks') on the Bering Shelf, Alaska – Geol. Soc. Am. Bull. Part I 90: 1144-1151.
Savit, C.H. 1974 Bright spot in the energy picture – Ocean Industry (Feb.): 60-65.
Walton, F.W., R.B. Perry & H.G. Greene 1969 Seismic reflection profiles, northern Bering Sea – Environmental Science Services Administration, Operational Data Report C & GS DR-8: 26 pp.