

HYDROCARBON GASES IN NEAR-SURFACE SEDIMENT OF NORTHERN
BERING SEA (NORTON SOUND AND **CHIRIKOV** BASIN)

Keith A. **Kvenvolden**, George D. Redden,
Devin R. Thor, and C. Hans Nelson

U.S. Geological Survey, Menlo Park, California 94025

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ABSTRACT

Methane, ethane, ethene, propane, propene, **n-butane**, and **isobutane** are common in bottom sediment of the northern Bering Sea. At eight sites the content of methane rapidly increases downward within the first four meters of sediment. These concentration gradients, and absolute methane concentrations, indicate that the interstitial water of the near-surface sediment at these sites may be gas saturated. These gas-charged sediments may be unstable, creating potential geologic hazards and, in certain areas, causing the formation of seafloor craters.

The isotopic compositions of methane **at** four of the sites range from -69 to -80‰ ($\delta^{13}\text{C}_{\text{PDB}}$). This range of values clearly indicates that the methane derives from microbial processes, possibly within the near-surface Pleistocene peat deposits that are common throughout the northern Bering Sea. At one site in Norton Sound, near-surface sediment is charged with CO_2 , accompanied by minor concentrations of hydrocarbons, that is seeping **from** the seafloor. Methane in this gas mixture has an isotopic composition of -36‰ , a **value** that suggests derivation **from** thermal processes at depth in Norton Basin.

The presence **of** sediment charged with methane or CO_2 cannot in general be predicted **from** analyses of surface sediment, which usually contains hydrocarbon **gases** and CO_2 at low concentrations. Sampling beneath a sediment depth of about 0.5 m is generally required to detect **high** concentrations of gas. Acoustic **anomalies** detected on high-resolution seismic records indicate the presence of gas-charged sediment, but gas analyses of sediment samples from areas with these anomalies do not always confirm that high concentrations of gas are there. Conversely, high concentrations of methane are sometimes found at sites where no acoustic anomalies are obvious on high-resolution records.

INTRODUCTION

About twenty years ago Emery and **Hoggan** (1958) described the occurrence of hydrocarbon gases in near-surface marine sediment from Santa Barbara Basin, off southern California. These anoxic sediments contain methane, **ethane**, propane, butanes, pentanes, and hexanes, with methane being one to almost five orders of magnitude greater in concentration than any of the other hydrocarbons. **Geochemical** studies that followed have generally focused on methane and the processes **that can account** for its occurrence and distribution in a **variety** of aquatic sediments (**Reeburgh**, 1969; **Whelan**, 1974; **Martens and Berner**, 1974; **ClayPool and Kaplan**, 1974; **Oremland**, 1975; **Barnes and Goldberg**, 1976; and **Kosiur and Warford**, 1979). Recently **Bernard et al.** (1978) described the distribution of methane, ethane, propane, and propene in sediment **from** shelf and slope sediment in the Gulf of Mexico, and **Kvenvolden and Redden** (1980) reported **on** the occurrence of these gases in sediment from the outer shelf, slope and basin of the Bering Sea. The present study examines **inner** shelf areas of the **Bering** Sea and considers the hydrocarbon gases methane (C_1), ethane (C_2), ethene ($C_{2,1}$), propane (C_3), propene ($C_{3,1}$), **isobutane** ($i-C_4$), and **n-butane** ($n-C_4$) in sediment of the **inner Bering Shelf** in Norton Sound and the adjacent eastern Chirikov Basin (Fig. 1).

Norton Sound is an elongate, east-west trending bay in the western coast of Alaska bounded on the north by the Seward Peninsula, on the east by the Alaskan mainland, on the south by the Yukon Delta, and on the west by the Chirikov Basin. The floor of the sound is very **flat**, and water depths average about **20 m**. **To the west into** the Chirikov Basin water depths increase to about 50 m, especially in the northern part of the basin at the Bering Strait.

When sea level lowered in late Pleistocene time, the floor of Norton Sound and

eastern Chirikov Basin became exposed (Nelson and Hopkins, 1972). During this time fluvial processes and tundra vegetation characterized the area (Hopkins, 1967), and peaty mud was deposited over much of the region. This mud contains 2 to 8 percent organic carbon. As sea level rose during latest Pleistocene time, marine sedimentation resumed. In Holocene time, fine-grained, sandy silt derived mainly from the Yukon River blanketed the area with a cover up to 10 m thick (McManus et al., 1977; Nelson and Creager, 1977). In contrast to the nonmarine sediment, the organic content of the overlying sediment ranges from 0.5 to 1.0 percent (Nelson, 1977).

METHODS

The analytical procedures for this work have been described previously (Nelson et al., 1978; Kvenvolden et al., 1979a). Vibracores and surface samples were taken during three summer field seasons in 1976, 1977 and 1978. Hydrocarbon gases and carbon dioxide were extracted from sediment recovered from the surface and from various intervals in cores. Sediment samples were extruded into 0.95-L double-friction-seal cans which had two septa-covered holes near the top. Helium-purged distilled water was added to each can until a 100-mL headspace remained. Each can was closed with a lid, and the headspace was purged with helium through the septa. The cans were shaken for ten minutes to release gases into the headspace. Exactly one milliliter of the headspace gas mixture was analyzed by gas chromatography using both flame ionization (for hydrocarbons) and thermal conductivity (for carbon dioxide) detectors. Calculations of gas concentrations were determined by peak height measurements on chromatograms. Partition coefficients were used to correct for the different solubilities of the hydrocarbon gases. Concentrations are reported in nL, μ L, or mL per liter of wet sediment.

RESULTS

C_1 is the most abundant hydrocarbon gas found in the first five meters of

sediment in Norton Sound and the eastern Chirikov Basin. Figure 2 shows the geographic distribution of maximum concentrations of C_1 . At eight sites this concentration exceeds 1 mL/L , and at five of these sites (8-4, 8-8, 8-15, 8-21 and 8-22) concentrations exceed 10 mL/L . At the other stations the maximum amount of C_1 measured was less than 100 $\mu L/L$ with two exceptions at 7-33 and 8-6 where it was about 200 $\mu L/L$ at each site. The amount of C_1 found depends to some extent on the depth of core, for concentrations of C_1 generally increase with depth. Thus, surface samples and short cores usually have lower amounts of C_1 than do samples taken from greater depths. The vertical distribution of C_1 at the eight sites mentioned above is shown in Figure 3. For these sites the concentration of C_1 increases by 4 or 5 orders of magnitude within the top four or five meters of sediment. Also shown is the distribution of methane at Sites 7-17 and 8-3. The data for these sites are combined because the sites are at essentially the same location sampled during two different field seasons. Here the C_1 concentrations, especially in deeper samples, are much lower than at the eight sites. The major gas at 7-17/8-3 is not C_1 but CO_2 .

The second most abundant hydrocarbon gas in this area is C_2 ; C_3 concentrations are usually slightly lower and generally parallel C_2 concentration profiles with depth. The geographic distribution of $C_2 + C_3$ is shown in Figure 4. The maximum concentrations of these two hydrocarbons are usually less than 1 $\mu L/L$. At two sites, 8-4 and 8-17, maximum $C_2 + C_3$ concentrations are slightly higher (1.2 and 1.1 $\mu L/L$, respectively), but at Site 7-17/8-3, $C_2 + C_3$ maximum concentration is almost 8 $\mu L/L$. At the eight sites where C_1 show 4-5 orders of magnitude increase in concentrations with depth, $C_2 + C_3$ increases by about two orders, but the profiles of concentration are more variable (Fig. 5) than the C_1 concentration profile (Fig. 3). The concentrations of $C_2 + C_3$ in samples from 7-17/8-3 are much higher than in all other samples.

Both $C_{2:1}$ and $C_{3:1}$ are present in all samples analyzed. Concentrations are variable, but as a general rule $C_{2:1}$ exceeds C_2 in surface samples and with increasing depth the reverse is observed. At Site 7-17/8-3, C_2 is much more abundant than $C_{2:1}$, with the $C_2/C_{2:1}$ ratio reaching a maximum of 340 at 60 cm depth. A similar relation holds for $C_{3:1}$ and C_3 . At the surface $C_{3:1}$ is usually more abundant than C_3 , and the reverse is true for deeper samples. At 7-17/8-3, C_3 is always more abundant than $C_{3:1}$ being larger by a factor of 47 at 200 cm depth.

The concentrations of $i-C_4$ and $n-C_4$ are lower in concentration than the lighter hydrocarbon gases and in many cases reach the limit of detection of the method, about 2 nL/L. In general the concentrations of $i-C_4 + n-C_4$ are less than 100 nL/L, and the distribution with depth is variable. In samples from **7-17/8-3, concentrations of $i-C_4 + n-C_4$ reach a maximum of 14 μ L/L at a depth of 200 cm.**

Hydrocarbons from C_5 to C_7 are measured in a single **backflush** peak from chromatography and are designated C_{5+} . C_{5+} hydrocarbons commonly occur in low concentrations in surface samples from this area and in core samples from 7-17/8-3.

BIOGENIC METHANE

The occurrence in anoxic sediment of high concentrations of C_1 resulting from microbial decomposition of organic matter is well established (Emery and Hoggan, 1958; Barnes and Goldberg, 1976; Reeburgh and Heggie, 1977; and Kosiur and Warford, 1979). C_1 is both produced and consumed by microorganisms, and models for these processes have been devised (**ClayPool and Kaplan, 1974; Martens and Bemer, 1974; Barnes and Goldberg, 1976; Kosiur and Warford, 1979**). In less reducing sediments of open marine environments, C_1 is also present but at concentrations as much as five orders of magnitude less than those observed in

anoxic marine sediments (Bernard et al., 1978; Kvenvolden and Redden, 1980) .

Although there **is** much less C_1 in sediments of open marine environments, the processes that generate gas are probably similar to those in **anoxic** sediments, but much slower.

At eight sites in Norton Sound and the eastern Chirikov Basin abundances of C_1 increase by four or five orders of magnitude within the first five meters of sediment, reaching concentrations near or exceeding saturation of the **interstitial** water. These shallow sediments are likely **anoxic**, and the C_1 probably is being generated by the decomposition of peaty mud that contains 2 to 8 percent organic carbon, and is buried under marine sediment of lower carbon content (0.5 to 1.0 percent). This sediment cover is thickest near the front of the Yukon Delta and thins to the north (McManus et al., 1977; Nelson and Creager, 1977; Nelson, 1977). The depth of burial of the **peaty** mud may account for the groupings of the C_1 concentration profiles shown in Figure 3. Seven of the sites (6-121, 6-125, 6-131, 8-4, 8-8, 8-15, and 8-21) have profiles that group together. These seven sites are located in the eastern and northern parts of Norton Sound and in the Chirikov Basin near Port Clarence (**Fig. 2**) . In these **areas, peatysediment is buried under about 2 meters** of sandy silt. The seven profiles show maximum concentrations below about 1.5 meters. Therefore, if peaty mud is the source of the methane, the depth of **its** burial accounts for the depth at which high C_1 concentrations are found. In contrast, one C_1 concentration profile (.8-22) reaches maximum values **below** 3 meters. This site was located northwest of the Yukon Delta in the southern part of Norton Sound where the sediment cover is thicker and the peaty mud is more deeply buried. Thus there is a correlation between the depth of buried organic matter and the depth at **which** C_1 concentrations reach high values. At Site 7-17/8-3, C_2 concentrations **follow** a different trend to be discussed below.

That the high concentrations of C_1 at eight sites result from microbiological

processes is supported by both chemical and isotopic data. Higher molecular weight hydrocarbons accompany C_1 , and the ratio $C_1/(C_2 + C_3)$ can be used as a guide to interpret mode of formation. Likewise, the carbon isotopic composition of C_1 can be used to interpret process of formation (Bernard et al., 1976, 1977). Microbial degradation of organic matter produces hydrocarbon gases with $C_1/(C_2 + C_3)$ ratios greater than 1000, and with $\delta^{13}C_{1PDB}$ lighter than -60‰ . **Table 1 shows these parameters** for samples **from** the eight sites. **Clearly, based on the criteria stated above, the C_1 at the eight sites was** derived **from** microbiological processes, and the buried peaty mud, in which the organic carbon has an isotopic composition of -28‰ (Kvenvolden et al., 1979 a,b) is the likely source.

Other sites may exist in Norton Sound and eastern **Chirikov** Basin where C_1 concentrations exceed 1 **mL/L**. Finding these locations will require sampling below about one meter of sediment (**three** meters or more off the Yukon Delta), because the occurrence of high amounts of C_1 at shallow depths is not manifest at the surface. The surface layer of sandy silt either seals the C_1 preventing its migration to the surface or the rate of consumption or diffusion of C_1 in the upper meter **is** very rapid, leading to low concentrations of C_1 at the surface. At two sites, 8-6 and 7-33 (Fig. 2), maximum concentrations of C_1 of 224 and 196 **μ L/L**, respectively, may hint that much higher concentrations are present at greater depths. At Site 7-33, the deepest **sample (Fig. 1)** came from 70 cm. If this sample, containing 196 **μ L/L**, were plotted on Figure 3 it would fall within the envelope of C_1 -concentration profiles of cores in which C_1 exceeds 1 **mL/L** at depth. The case for **Site 8-6** is not so clear. The sample **containing** 224 **pL/L** comes from a depth of 220 cm (Fig. 1). If plotted on **Figure 3, this** value would fall below the envelope of C_1 -concentration profiles. At Site 8-6, peaty mud may be more deeply buried than at other sites in northern Norton Sound. Only deeper sampling can directly verify the presence of higher

Table 1.

$C_1/(C_2+C_3)$ ratios and $\delta^{13}C_1$ values for samples containing C_1 concentrations in excess of 1 mL/L

Site	Maximum $C_1/(C_2+C_3)$	$\delta^{13}C_1^*$ (‰)
8-4	24000	-80 ¹
8-8	71000	nd
8-15	28000	nd
8-21	440000	nd
8-22	88000	nd
6-121	6500	-72 ²
6-125	28000	-69 ²
6-131	5400	-75 ²

* relative to the PDB standard

¹ Kvenvolden et al. (1979a,b)

² Nelson et al. (1979)

amounts of C_1 . At **other** sites in Norton Sound and eastern Chirikov Basin, C_1 concentrations are below 100 $\mu\text{L/L}$ and at many sites below 10 $\mu\text{L/L}$ (Fig. 2).

POSSIBLE BIOLOGIC ORIGIN OF OTHER HYDROCARBONS

Besides C_1 , other hydrocarbon gases are present in these sediments, but quantitatively, they have much less significance than C_1 . The maximum concentrations of $C_2 + C_3$ are in the same range as the minimum concentrations of C_1 . At sites where C_1 increases rapidly with depth (Fig. 3), $C_2 + C_3$ also generally increases (Fig. 5) but much more **slowly** than C_1 . Concentrations of $i-C_4$ and **$n-C_4$ are even lower than concentrations** of $C_2 + C_3$, and the $i-C_4 + n-C_4$ concentrations are erratic with depth. As a generalization, however, the abundances of the higher hydrocarbons, C_2 , C_3 and C_4 , are greater in samples where concentrations of C_1 are larger. Therefore, the processes that produce C_1 may also be responsible in part for the generation of the higher hydrocarbons. Microbiological production and consumption provides a reasonable mechanism to **account** for C_1 at the eight sites where C_1 concentrations increase beyond 1 mL/L. Therefore, microbial processes may also explain the occurrence of the higher molecular weight hydrocarbons, although evidence for this process remains circumstantial. Laboratory experiments have demonstrated the microbial formation of C_2 and C_3 (Davis and Squires, 1954). Thus, there is support for the suggestion that the C_2 and the C_3 hydrocarbons at these sites can come from microbial processes, but there is no precedent in the literature on microbiology for the production of C_4 hydrocarbons.

The presence and distribution of $C_{2:1}$ is probably controlled by biological **processes, but** these processes likely differ from those which **account** for the very high C_1 concentrations. These unsaturated hydrocarbons have been formed by microbial action in the laboratory (Davis and Squires, 1954), and $C_{2:1}$ is produced in soils by bacteria (Primrose and Dilworth, 1976). In the sediment the process seems to take place **uniformly**, because there is no obvious concentration gradient with depth. In surface samples concentrations of $C_{2:1}$ and $C_{3:1}$ are

larger respectively than concentrations of C_2 and C_3 . With depth, concentrations of C_2 and C_3 increase slightly so that below the surface ratios of $C_2/C_{2,1}$ and $C_3/C_{3,1}$ are usually equal to or greater than one.

THERMOGENIC HYDROCARBONS

The above discussion focused mainly on sites where C_1 concentration increases rapidly with depth, and consideration has been given to the heavier

hydrocarbons associated with this C_1 . At one site, 7-17/8-3, however, C_1 concentrations are not unusually high, less than 100 $\mu\text{L/L}$ (Fig. 3), but concentrations of $C_2 + C_3$ (Fig. 5) and $i\text{-}C_4 + n\text{-}C_4$ are unusually large relative to concentrations seen elsewhere in the sediments of this area, or for that matter, anywhere else in marine sediments off Alaska.

Site 7-17/8-3 has been studied in great detail since anomalous hydrocarbon concentrations were first discovered in the water column at the site (Cline and Holmes, 1977). Nelson et al. (1978) showed that the sediments here also contain anomalous hydrocarbon concentrations. Kvenvolden et al. (1979a, b) confirmed the hydrocarbon chemistry and discovered that the major gas component within the sediment and escaping into the water column is CO_2 . The $C_1/(C_2+C_3)$ ratios in sediment at this site are less than 10 and the $\delta^{13}\text{C}_1$ is -36‰ . These numbers differ greatly from those discussed earlier where microbiological processes were inferred.

The hydrocarbons at Site 7-17/8-3 are likely derived from thermochemical processes, judging from the molecular distribution of C_1 , C_2 , and C_3 and the isotopic composition of C_1 . In addition, anomalously high concentrations of $i\text{-}C_4$, $n\text{-}C_4$ and C_{5+} (gasoline-range hydrocarbons) support the mechanism of thermochemical processes (Kvenvolden and Claypool, unpublished). Heat for this process must be available at depth in Norton Basin. The hydrocarbons resulting from the thermal decomposition of organic matter within the basin must migrate along with CO_2 up fault zones to the surface and escape as a seep. Although the hydrocarbon

chemistry indicates that the hydrocarbons at Site 7-17/8-3 likely migrate from depth, the concentration profiles (Figs. 3 and 5) indicate that special conditions of migration must exist. The fact that hydrocarbons are leaking into the water **column** suggests that surface sediments should contain large amounts of these hydrocarbons. On the contrary, surface samples at this site contain very low concentrations of hydrocarbons. In fact, surface samples (0-10 cm) at this site show no evidence of the high concentrations of hydrocarbons deeper in the sediment. The gradients of C_1 (Fig. 3), $C_2 + C_3$ (Fig. 5) and $i-C_4 + n-C_4$ decrease rapidly toward the sediment surface. This rapid decrease and lack of significant quantities of hydrocarbons at the sediment surface can be explained by rapid diffusion of hydrocarbons into the water column from the first few centimeters of sediment or the presence of discrete gas vents that pipe the hydrocarbons through the sediment leaving few hydrocarbons remaining in the sediment. The second explanation is more reasonable, because active gas vents were seen by television in 1978 (Kvenvolden et al., 1979a). The concentration profiles (Figs. 3 and 5) at Site 7-17/8-3 reach a maximum value at about 1 to 2 meters depth and then decrease. This profile suggests that migration **from** greater depths does not involve diffusion of hydrocarbons within the underlying sediment but rather that the hydrocarbons are following distinct conduits such as faults. Near the surface the hydrocarbons are dispersed into the sediment where they **eventually** vent along with CO_2 into the water. That the hydrocarbons from this seep are present in the water **column** has been documented by Cline and Holmes (1977). The waters of Norton Sound and the eastern Chirikov Basin also contain a **regional distribution** of hydrocarbon gases (Cline et al., 1978) whose sources, in part, may be the underlying surface and near-surface sediment.

GEOPHYSICAL EVIDENCE

The presence of gas in near-surface sediments can cause acoustic anomalies

on high-resolution geophysical records where the gas **is** no longer in solution in the interstitial **water** but takes the form of bubbles. **Schubel** (1974), for example, demonstrated how high concentrations of gas affect acoustic properties of sediments. At the eight sites where C_1 concentrations exceeded 1 mL/L and may have reached and exceeded interstitial water solubility, **bubble-phase** C_1 may be present. Acoustic anomalies would be expected on **high-resolution** records **from** these sites if free gas is indeed present.

Geophysical transects, utilizing 800-J **boom**, 3.5 kHz **subbottom** profiler and 120 **kJ** sparker systems, indicate that near-surface acoustic anomalies are widespread Norton Sound. Figure 6 shows those sites, sampled for hydrocarbon gases, **at** which acoustic anomalies are seen on geophysical records. At three sites (6-125, 8-4, and 8-21), acoustic **anomalies** correspond to samples having high concentrations of C_1 . The acoustic anomaly and associated C_1 at 8-4 were discussed in detail by **Kvenvolden et al. (1979a,b)**. The characteristics of the acoustic anomaly at 8-21 suggest that the cause may be controlled more by the presence of glacial till deposits than by gas. At Sites 7-17/8-3, geophysical records show both near-surface and deeper acoustic anomalies. There the sediment is charged with CO_2 , rather than C_1 , and the CO_2 is escaping **from** the seafloor as a **submarine** seep, observed acoustically and by television (**Kvenvolden et al., 1979a**). At five sites (6-121, 6-131, 8-8, 8-15, and 8-22) on Figure 6, where high concentrations of C_1 were measured, no acoustic **anomalies** were detected. **At** sites 6-121 and 6-131 no geophysical records were obtained; therefore, it is uncertain whether or not acoustic anomalies are **present** at these sites. At Sites 8-8, **8-15, and** 8-22, high-resolution geophysical records show no evidence of acoustic anomalies although the **geochemical** measurements indicate high concentrations of C_1 (Figs. 2 and 4). Apparently the gas concentrations at these sites were not in the proper range to produce anomalies on the records of the **geophysical** systems employed. On the other hand, acoustic anomalies were observed on

records at Sites 8-1, 8-9, and 8-10, but maximum C_1 abundances in cores at these sites were only 6, 4, and **15 μ L/L**, respectively. Concentrations this low are not expected to produce acoustic **anomalies**. In addition, acoustic **anomalies** were found in geophysical records at Sites 6-168, 7-22, and **7-25**, but **sampling at these sites was** not deep enough (Fig. 1) to test the presence of high C_1 or CO_2 concentrations **at** depth.

High concentrations of C_1 in near-surface sediment may cause instability and may lead **to** crater formation whenever the gas vents abruptly into the water column. Nelson et al. (1978) discussed some preliminary engineering information related to the stability of gas-charged sediment in Norton Sound, and Nelson et al. (1979) proposed that the craters found in central Norton Sound **may result from** the rapid escape of gas **from** gas-charged sediments.

SUMMARY

Hydrocarbon gases, methane, ethane, **ethene**, propane, **propene**, **isobutane**, and **n-butane** are **common** in surface and near-surface sediment of Norton Sound and eastern Chirikov Basin. From a quantitative standpoint methane is the most important hydrocarbon gas. At eight sites in this area methane abundances increase with depth in the sediment by four or five orders of magnitude, reaching concentrations near or exceeding saturation of the interstitial water. The highest value measured is about 55 **mL/L**. This methane is probably being generated by microbial decomposition of peat that is buried with mud under a cover of fine-grained, sandy silt derived from the **Yukon** Delta. Maximum ratios of methane to ethane plus propane at the eight sites are large, ranging from about 5×10^3 to 440×10^3 . Carbon isotopic compositions range from -69 to -80‰ (relative to the PDB standard). These molecular and isotopic compositions strongly suggest that microbiological processes are involved in the production of at least methane. Higher molecular weight hydrocarbons **are present in much lower** concen-

trations than methane, but, as a general rule over the area, the trends in concentrations of the hydrocarbons, **at** least through propane, are roughly the same. Therefore, microbiological processes may also be responsible for the hydrocarbon gases heavier than methane.

At one site in Norton Sound the concentrations of all hydrocarbon gases are anomalous. For example, methane is anomalously low in concentration relative to the methane at the eight sites mentioned above. **On** the other hand, ethane, propane, and the butanes are all anomalously high in concentration. The **ratios** of methane to ethane plus propane are less than **10** and the isotopic composition of methane is about -36‰ . The magnitude of these parameters sharply contrasts with the values obtained elsewhere in the area and indicates that thermochemical rather than biochemical processes are at work. The maximum concentration of hydrocarbons from samples at this site is about $100\ \mu\text{L/L}$.

The major **component** is carbon dioxide. The carbon dioxide and hydrocarbons are actively seeping from the sediment into the water column.

A number of geological consequences result **from** the presence of gases in near-surface sediment of this area. Where gas concentrations approach and exceed their **solubilities** in the interstitial water, free gas in the form of bubbles occurs. This gas modifies the acoustic properties of the sediments, and **near-surface** acoustic anomalies are detected on high-resolution geophysical records. Acoustic anomalies were **observed** at three of the eight sites where methane is very abundant and also at the site where carbon dioxide was observed along with hydrocarbons. On the other hand, acoustic **anomalies** were also seen in geophysical records **from** three sites where maximum gas concentrations in core samples were **too low to cause anomalies**. At three other sites there was no geophysical evidence for acoustic **anomalies** although **geochemical** measurements indicated high methane concentrations in the sediment. The presence of high gas concentrations **in near-surface** sediments can lead to sediment instability and the

possibility of seafloor cratering. Finally, the thermochemical hydrocarbons, observed at one site, may have been produced deep within Norton Basin and be migrating to the surface. These hydrocarbons have petroleum-like characteristics and may be indicative of petroleum generation and accumulation **at** depth.

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FIGURE CAPTIONS

Figure 1. **Location** of hydrocarbon gas sampling sites in Norton Sound and **Chirikov** Basin (dots). Sites **are** designated with the last digit of the year when the site was occupied followed by the station number. In parentheses is the interval in centimeters **from which** samples were taken. After the colon is the number of samples analyzed for hydrocarbon gases in that interval.

Figure 2. Distribution of maximum concentrations of C_1 in $\mu\text{L/L}$ and mL/L of wet sediment at each site.

Figure 3. Graph of concentrations of C_1 in $\mu\text{L/L}$ and mL/L of wet sediment vs. depth (cm) for sediment samples **from** cores taken at nine sites in Norton Sound and eastern Chirikov Basin. Site 7-17 and 8-3 are the same location; results are **combined** into one **curve**.

Figure 4. Distribution **of** maximum concentrations of $C_2 + C_3$ in nL/L and $\mu\text{L/L}$ of wet sediment at each site.

Figure 5. Graph of concentrations of $C_2 + C_3$ in nL/L and $\mu\text{L/L}$ of wet sediment **vs** depth (cm) for sediment samples **from** cores taken at nine sites in Norton Sound and eastern **Chirikov** Basin.

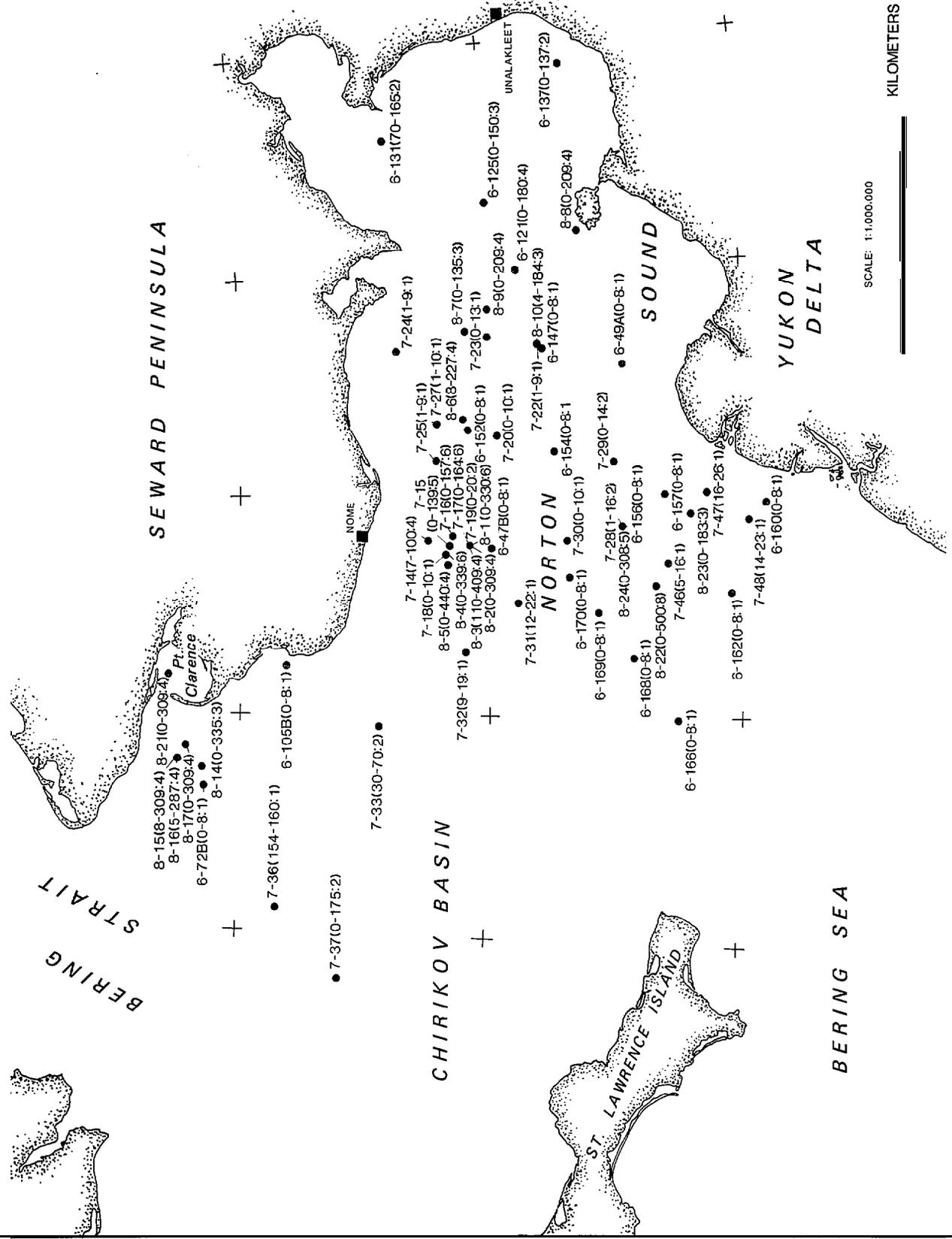
Figure 6. Distribution **of** acoustic **anomalies** and sites with high concentrations of gas.

69°

65°

±4°

ALASKA



SEWARD PENINSULA

CHIRIKOV BASIN

NORTON SOUND

SOUND

YUKON DELTA

BERING SEA

KILOMETERS

SCALE: 1:1,000,000

Pt. Clarence

NOME

UNALAKLEET

ST. LAWRENCE ISLAND

8-15(8-309:4) 8-21(0-309:4)
 8-16(5-287:4) 8-17(0-309:4)
 6-72B(0-8:1) 8-14(0-335:3)

7-36(154-160:1) 6-105B(0-8:1)

7-37(0-175:2)

7-33(30-70:2)

7-14(7-100:4) 7-15 (0-139:5) 7-27(1-10:1)
 8-5(0-440:4) 7-16(0-157:6) 8-6(8-227:4) 8-7(0-135:3)
 8-4(0-339:6) 7-17(0-164:6) 8-7(0-13:1) 7-23(0-13:1)
 8-3(110-408:4) 7-19(0-20:2) 6-152(0-8:1) 8-9(0-209:4)
 8-2(0-309:4) 8-1(0-330:6) 6-152(0-8:1) 7-20(0-10:1)
 6-47B(0-8:1)

7-31(12-22:1) 7-22(1-9:1) 8-10(4-184:3) 6-147(0-8:1)
 6-170(0-8:1) 7-30(0-10:1) 6-154(0-8:1)

6-169(0-8:1) 7-28(1-16:2) 7-29(0-14:2) 8-49A(0-8:1)
 8-24(0-308:5) 6-156(0-8:1)

6-168(0-8:1) 8-22(0-500:8) 7-46(5-16:1) 6-157(0-8:1)
 8-23(0-183:3) 7-47(16-26:1) 6-162(0-8:1)

7-48(14-23:1) 6-160(0-8:1)

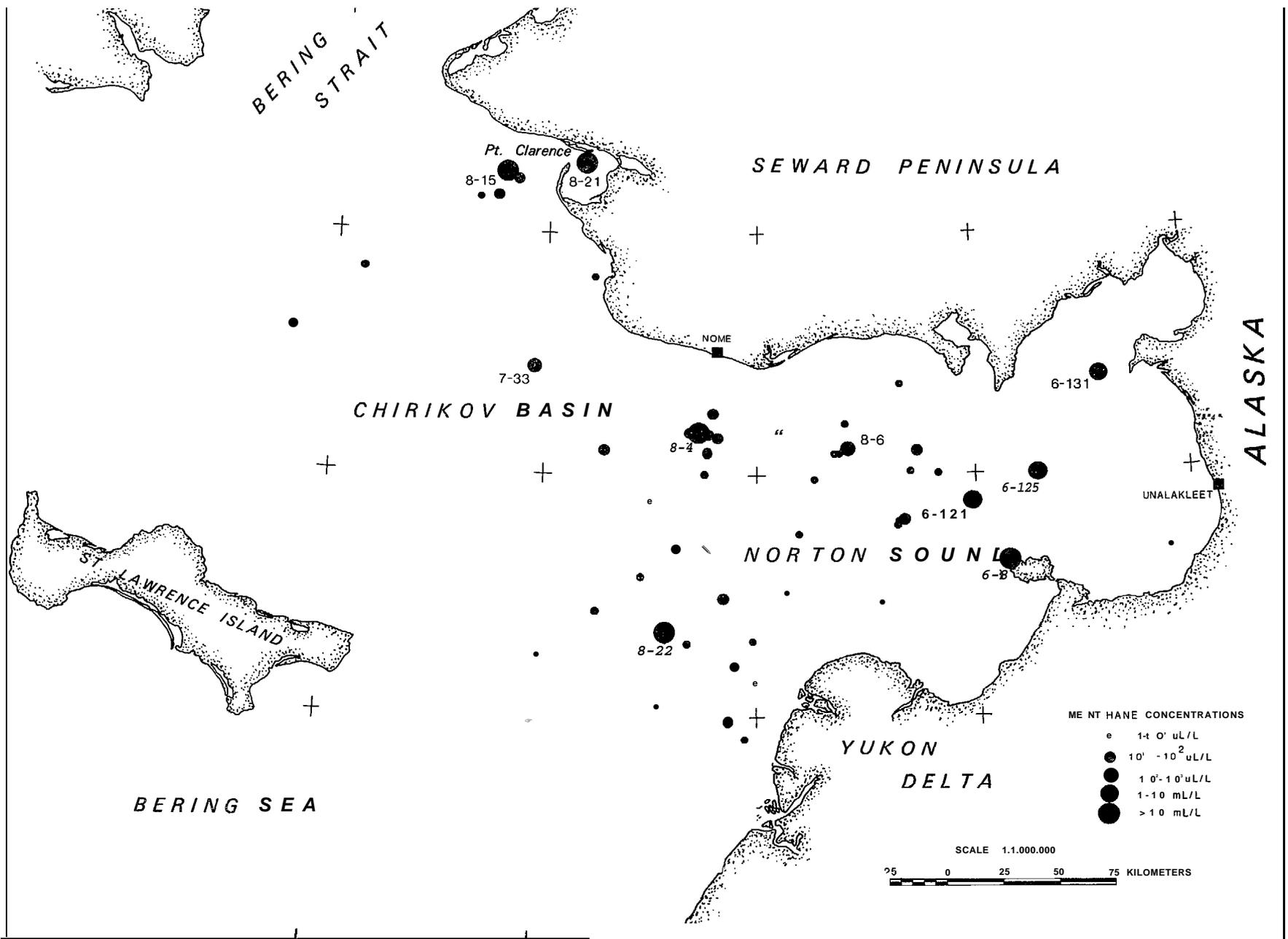
6-13(170-165:2)

6-125(0-150:3)

6-12(10-180:4)

8-8(0-208:4)

6-137(0-137:2)



ALASKA

64°

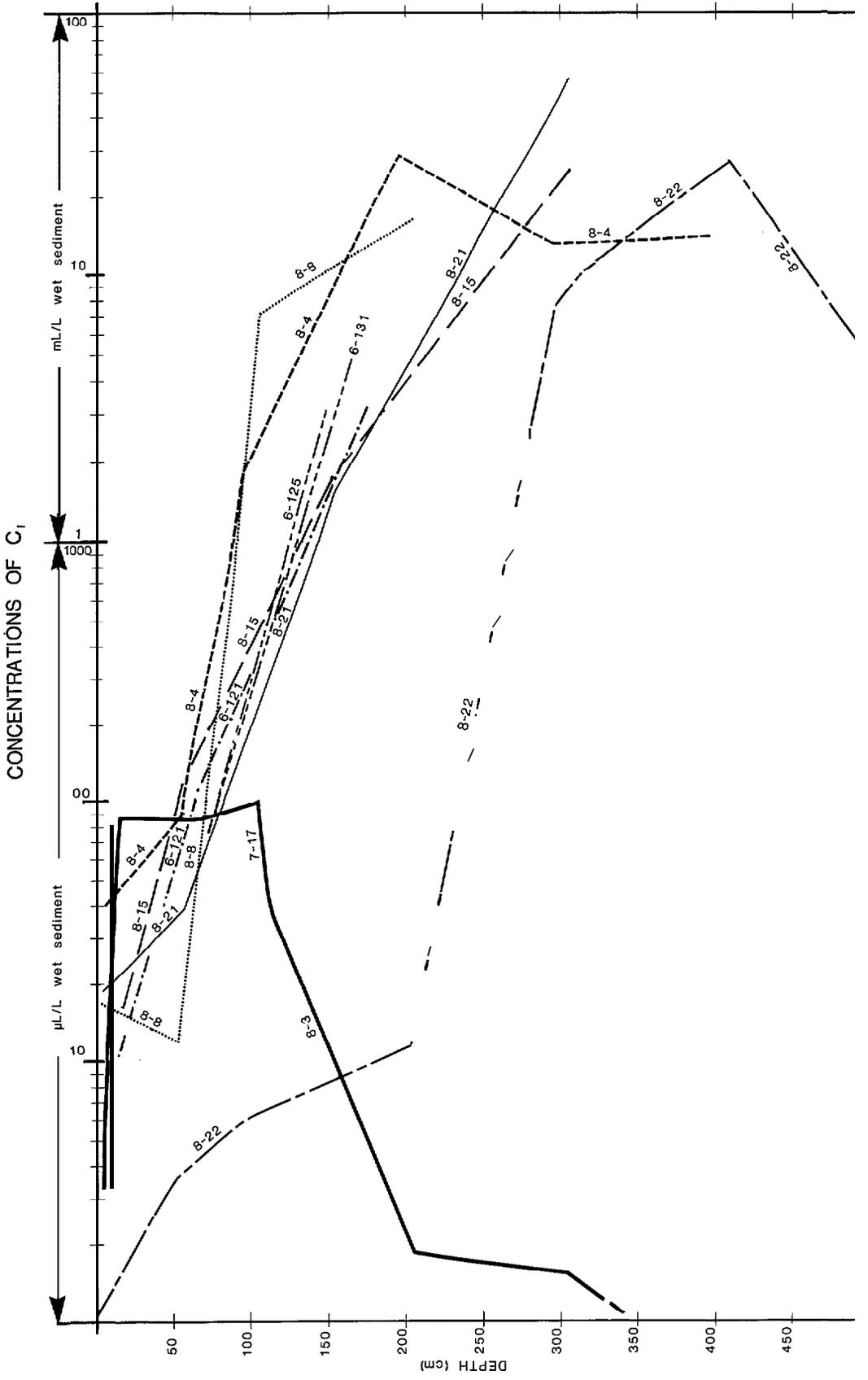
62°

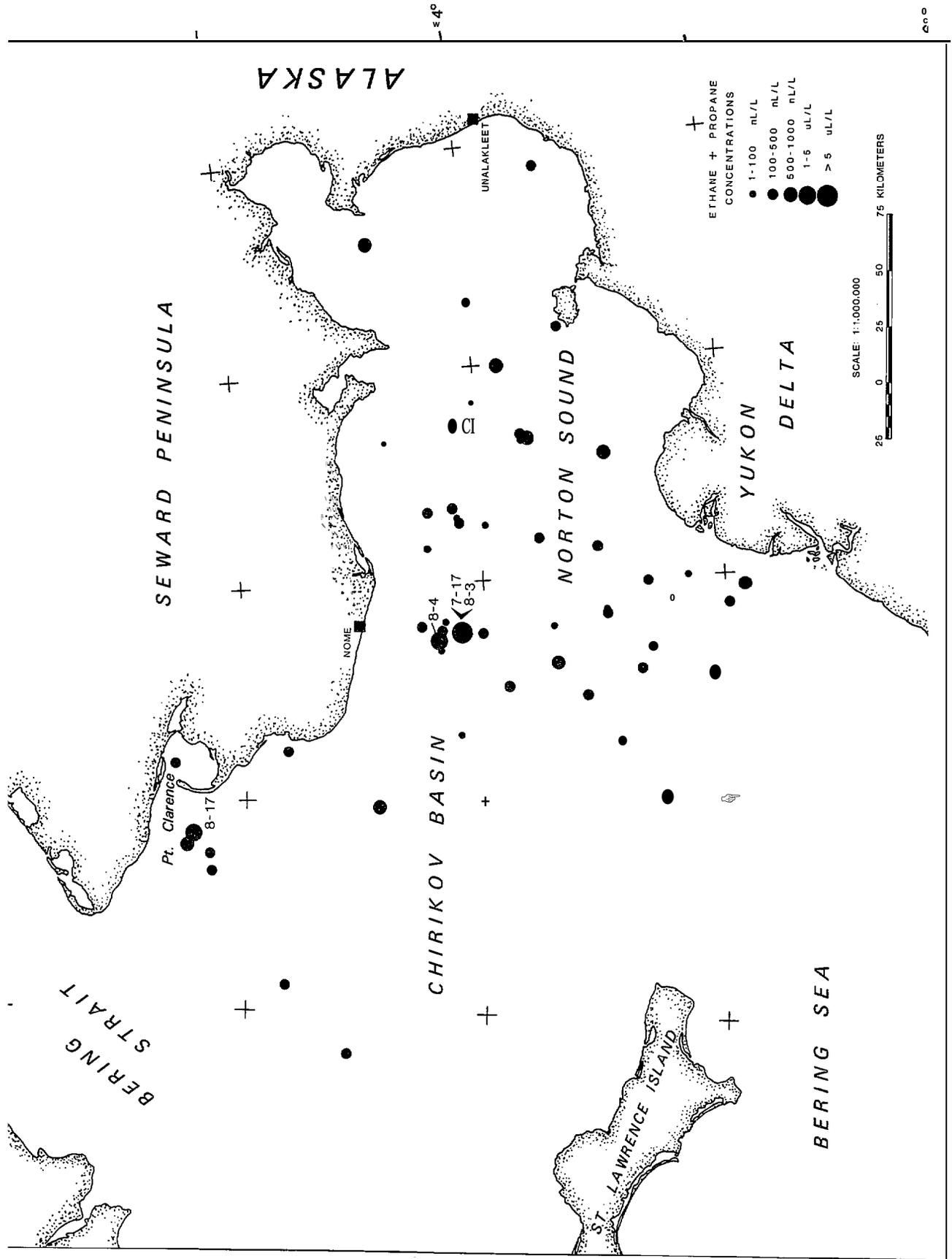
MERCURY CONCENTRATIONS

- 1-10⁰ uL/L
- 10¹-10² uL/L
- 10⁰-10⁰ uL/L
- 1-10 mL/L
- > 10 mL/L

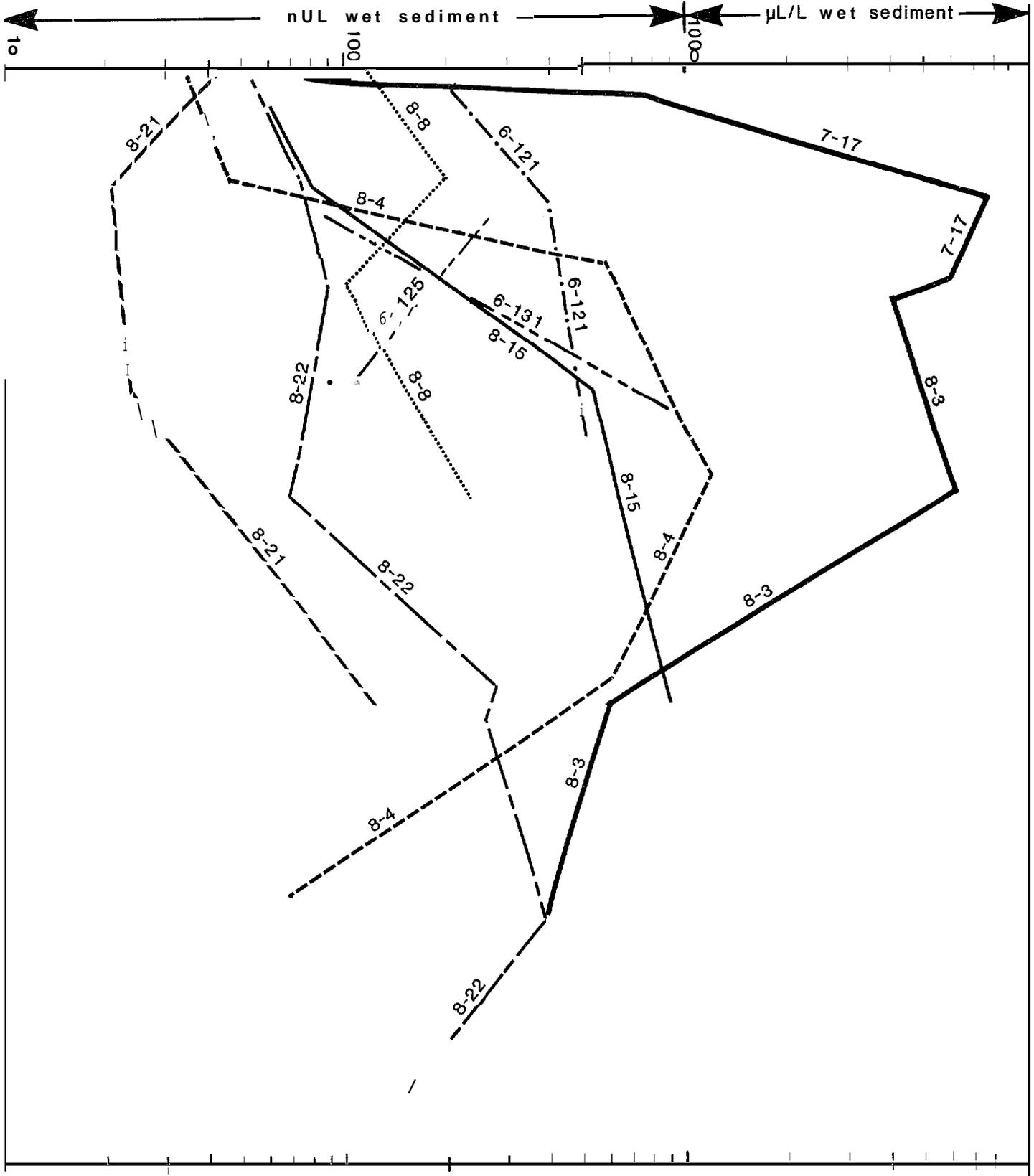
SCALE 1:1,000,000







CONCENTRATIONS OF $C^* + C_3$



The papers that follow cover a decade of interdisciplinary research on Holocene sedimentation in the northern Bering Sea. The U.S. Geological Survey environmental assessment studies in this region result in interfacing studies of a number of marine geologic, physical oceanographic, **geochemical**, and **geotechnical** specialists. This **epicontinental** shelf research focuses on a poorly known, but significantly large type of environment of northern North America. Although nearly half of the continental shelf area of the United States is made up of **epicontinental** shelves that surround Alaska, most studies of Holocene shelf sedimentation in north America have focused either on the narrow, tectonically active Pacific coast shelves or the Atlantic continental margin shelves. The general lack of information on modern **epicontinental** shelves is a severe handicap to understanding the extensive ancient rock record of these types of environments, for example, **the** Mesozoic of **the** interior of western **North** America.

We feel it is most useful for modern and ancient comparative studies to incorporate our papers into this volume containing the significant body of European work on the North Sea. The environment of the northern Bering Sea is similar in many ways to that of the North Sea. Both shelf areas are dominated **by** strong currents constricted by land masses. As a result, **large sand ridges** and sand-wave fields are common, and significant **reworking**, resuspension, and relocation of Holocene sediment masses is apparent on both shelves. storm waves are common to all shelf areas, but large storm surges and strong **storm-**driven currents are more restricted, occurring mostly in broad shallow embayments such as those found **in** the North and Bering Seas. Wide variation in tidal range and sediment input **in** different parts of the basins is also

characteristic of both regions and results in similar Holocene sediment types and distribution patterns in the two areas.

The first paper on the late Pleistocene to Holocene sedimentation points out that two very different sequences of transgressive **deposits** can develop within the same shelf region. In **Chirikov** Basin, Pleistocene peaty mud is covered by typical, but extremely thin, basal and inner shelf transgressive sand units. The strong currents and circulation of water masses, however, prevent deposition of a modern mud blanket to complete a normal transgressive sequence. Instead, currents rework the surface sediment into a distribution that conforms to the strong geostrophic flow patterns rather than a **wave-**generated gradation from coarse-grained deposits in shoreline regions to **finer-grained** deposits in offshore regions.

The seafloor of Norton Sound is overlain by Pleistocene peaty mud but, in contrast to **Chirikov** Basin, it lacks transgressive sand layers. Here marine transgressive sequences consist of mud **interbedded** with thick storm sand layers which grade **upsection** to thinner storm sands and then to **bioturbated** mud **facies**. Progradation of the modern Yukon prodelta reverses this sequence in southern Norton Sound so that storm sand layers are found in the uppermost Holocene sediment. Patterns of late Pleistocene-Holocene sedimentation in both **Chirikov** Basin and Norton Sound are different from those in southern Bering shelf where a classic wave-generated seaward-fining is found in Holocene deposits. Thus, when interpretations are made of ancient **epicontinental** shelf sequences, deposits in current-dominated settings like the North Sea and the northern Bering Sea must be **considered** because gradations in sediment texture and thickness may have little relation to shoreline location or depth-related variations in wave energy.

The second paper analyzing **microfauna** in shelf deposits of the northern

Bering Sea shows that **biostratigraphical** changes and **paleoecological** patterns may aid in reconstruction of **epicontinental** shelf environments. In Chirikov Basin there is a vertical change from freshwater to marine **facies**. In Norton Sound the same change is evident, but nearshore and offshore **faunal** assemblages can be distinguished in thicker transgressive deposits. In the **late** Holocene sediment, however, a reversal back to brackish water environments is encountered because of formation of the present active delta lobe in southern Norton Sound.

Sedimentary structures in Norton Sound described in the third paper also mirror the effects of the transgressive and progradational history. Nearshore physical structures occur at the base of the sequence and grade upsection to bioturbated mud; the uppermost sequence, however, changes to well-developed nearshore structures in southern Norton Sound where the delta progrades over the offshore sequences **laid** down in the earlier Holocene. Because of the delta progradation in southern Norton Sound, well-developed physical structures in surface sediment grade offshore to highly bioturbated deposits as might be expected in onshore to offshore sequences. The high degree of **bioturbation** nearshore in northern Norton Sound, however, it is unexpected near shorelines and reflects low sedimentation rates caused by resuspension and **advection** of most Holocene sediment from this region by the Alaska Coastal Water. Because of the large freshwater discharge from the Yukon River into southern Norton Sound, **bioturbation** there is similar to that found in local coastal embayments and estuaries **elsewhere, even** though Norton Sound is an open-shelf region. Again, this is an example to be kept in mind when interpreting ancient **epicontinental** shelf deposits.

The fourth paper, describing the Bering shelf sand body types and their processes of formation, provides new information to trace petroleum reservoirs

in ancient shelf systems. The sand bodies of the Bering shelf, although similar to one another **in** their linearity, size, and sediment types, can be separated into genetic types based on subtleties of grain size, sedimentary structure, morphology, and orientation. Recognition of **leeside** sand bodies formed of very fine sand may help to distinguish large sand bodies deposited far offshore and not parallel to shorelines, from the more common and generally **coarser-grained**, shore-parallel sand bodies of the inner **shelf**.

Several of the process-oriented papers that follow the first four papers describing sedimentary features show that development of different sand body types is a result of a wide variation in **hydrographic** setting and sediment input on the Bering shelf. In the modern inner shelf area, out to water depths of 10-15 m, the sea floor is typically affected by wave energy. **Along** southern Seward Peninsula, however, a complex pattern of **bedforms** related to wave and unidirectional currents is evident. Interplay of current-formed features with ice scour in this subarctic environment adds to the complexity of **bedforms** in this region. The result is a mosaic of oscillation and unidirectional current ripples, ice-gouge features, and a complex pattern of varying sediment types.

The inner shelf off the Yukon delta complex of southern Norton Sound contrasts with that of the rocky headland and coastal plain coast of the Seward Peninsula. It is dominated by **deltaic** sedimentation and a seasonal set of **fluvial**, hydrographic, and ice processes. In winter, river discharge is almost totally lacking and extensive shorefast ice develops. The wide apron of shorefast ice results in much further extension of distributary channels offshore from the delta than is the case in temperate or tropical deltas. The sub-ice channels serve as sediment conduits during maximum discharge conditions in late spring and summer. Thus, extremely large

quantities of sediment enter the sound in a very short period of time and accumulate rapidly in southern Norton Sound. Major storms in the fall rework, resuspend, and remove large quantities of sediment from Norton Sound.

Occasional extremely large storm-surge events cause progradation of major sand sheets from the delta shoreline out over southern Norton Sound.

Quantitative measurements of significant reworking and resuspension of bottom sediment during storms have been made in northern Norton Sound using **GEOPROBE** instrumentation. The **longterm** in situ measurements of currents and suspended sediment made with the GEOPROBE in the **benthic** boundary-layer provide new information that has broad implications for any **epicontinental** shelf region. The continuous monitoring of shear velocities proves that storm-related currents are the major process in the constricted shallow waters of **epicontinental** shelf regions like northern Bering Sea. Measurements also show the importance of continual **advective** suspended sediment transport over northern Bering shelf and sediment resuspension and transport during spring tidal conditions.

In contrast to the more classic wave and current processes outlined in several papers, new concepts of epicontinental shelf processes are suggested by the **geotechnical, geochemical,** and geophysical studies. **Poorly** consolidated mud of restricted quiet-water lagoons and sheltered, but **open-shelf embayments,** contrasts with other regions of highly **overconsolidated** sediment; there, fetch of the open sea permits strong cyclic loading on shallow bottom sediment by large open-shelf waves. Biogenic gas trapped beneath Holocene mud of Norton Sound can create poorly consolidated zones and regions of gas-charged sediment traced by acoustic anomalies in geophysical records. New studies also show that cyclic wave loading during major storm surge events may have the potential to liquefy the very fine sand of the Yukon

delta region. Thus, liquefaction may be a very important process in conjunction with strong, storm-generated currents to develop the prograding storm-sand sheets and extensive scour observed on **epicontinental** shelves like Bering Sea.

Our research on Bering shelf suggests that sedimentary processes on shallow **epicontinental** shelves include synergistic effects of wind, tidal, and barotropic-driven currents and also poorly understood effects of instability due to sediment gas-charging and cyclic wave loading. Future interdisciplinary research on **epicontinental** shelves is required to define the relative importance of these factors in sediment transport.

We hope that this set of papers on the Bering **epicontinental shelf** will show some similarities and contrasts with the North Sea as well as provoke some new thoughts regarding Holocene sedimentation processes common to all **epicontinental** shelf settings. Large new studies are being instigated in other **epicontinental** shelves like the east China Sea and it appears that **commonalities** of Holocene transgressive sedimentation and modern sedimentary processes are present. Once this modern data base is provided from a **wide** variety of settings like the east China, Bering and North Seas, new refined interpretations can be applied to similar ancient environments.

Hans Nelson