Reports

Deep Methane Maxima in the Northwest Caribbean Sea: Possible Seepage Along the Jamaica Ridge

Abstract. *Methane concentrations as great as 30,000 nanoliters per liter were measured on two cruises in the northwest Caribbean Sea. Such concentrations are three orders of magnitude higher than Bunsen solubilities would predict. Although shallow maxima may result from in situ microbial activity, the deeper maxima appear to result from massive seepage (estimated at 1 × 10^8 to 10 × 10^8 liters per day) along the Jamaica Ridge.*

Although methane is perhaps the most thoroughly studied reduced gas in the ocean, there is much uncertainty concerning its geochemistry. Scientists at the Naval Research Laboratories (*1*) and Texas A & M University (*2*), among others, have determined that the ocean is a source of methane to the atmosphere. Several authors (*3*) report that shallow methane maxima are common in the Atlantic Ocean and the Gulf of Mexico. The maxima that have been found in these areas are near or in the major pycnocline (50 to 200 m) and are about twice the atmospheric equilibrium concentrations (35 to 50 nl/liter for subtropical zones). We have shown (*4*) that methane maxima can be several thousand nanoliters per liter in shelf regions of the northwest Gulf of Mexico. Shallow maxima have been attributed to advection off the shelf or to in situ production. Although production of methane in situ has been postulated by a number of investigators, all known methane-producing bacteria are obligate anaerobes (*5*). Thus, it is speculative to posit the existence of methane-producing bacteria in the oxygen-loaded waters of the ocean, although recent work has demonstrated fairly well that advection off shelf regions cannot supply shallow maxima (*3*, *4*).

In November 1976, we received water samples from a depth profile in the Cayman Trough area of the Caribbean Sea in about 6300 m of water. A surprising methane concentration of > 1000 nl/liter in the 250- to 600-m depth interval was measured. One year later we resampled water at this station and several other stations on a transect from the Cayman Trough toward the Mississippi Delta aboard the research vessel *Gyre*. All samples were obtained with Niskin and Nansen bottles. The gaseous hydrocarbon concentrations were determined immediately after collection by helium stripping, trapping in a liquid-nitrogen cold trap, and analysis with a gas chromatograph having a flame ionization detector or by use of an equilibration technique when methane concentrations were high (*2*). These data are presented in Figs. 1 and 2.

We believe that methane distribution in the Cayman and Yucatan basins (Fig. 3) is controlled by topography and water circulation. The circulation and structure of the waters of the Caribbean have been extensively studied (*6*). The surface circulation is from the Atlantic through the passages of the Antillean Arc, exiting to the Gulf of Mexico through the Yucatan Strait. Most of the Caribbean waters enter through passages in the Lesser Antilles with sill depths shallower than 1200 m. Although four ridge systems divide the Caribbean into five basins, these divisions have little effect on the westerly flow of surface waters down to the depth of the subantarctic intermediate water (700 to 850 m), and probably several hundred meters deeper. East-west sections through the Caribbean (*6*) clearly show the cores of high-salinity subtropical underwater (50 to 200 m) and low-salinity subantarctic intermediate water as they spread westerly across the Caribbean. The deep waters of the Caribbean are believed to be North Atlantic deep water supplied through passages in the Greater Antilles (for example, the Windward and Aregada passages) that have sill depths less than 2000 m.

It is unlikely that the maxima we studied in the Cayman and Yucatan basins are related to processes in the eastern Caribbean. Scranton (*7*) and Lamontagne and co-workers (*1*) presented five profiles from the eastern Caribbean (see Fig. 3) that show no methane concentrations greater than 150 nl/liter, and most profiles had concentrations considerably less than 100 nl/liter. All of their measurements were made at stations in the southern Venezuela Basin and represent water that moved across the Antillean Arc (*6*). Thus, it is unlikely that the methane maxima we studied in the western Caribbean are the result of additions from east of the Jamaica Ridge.

Although a number of investigators

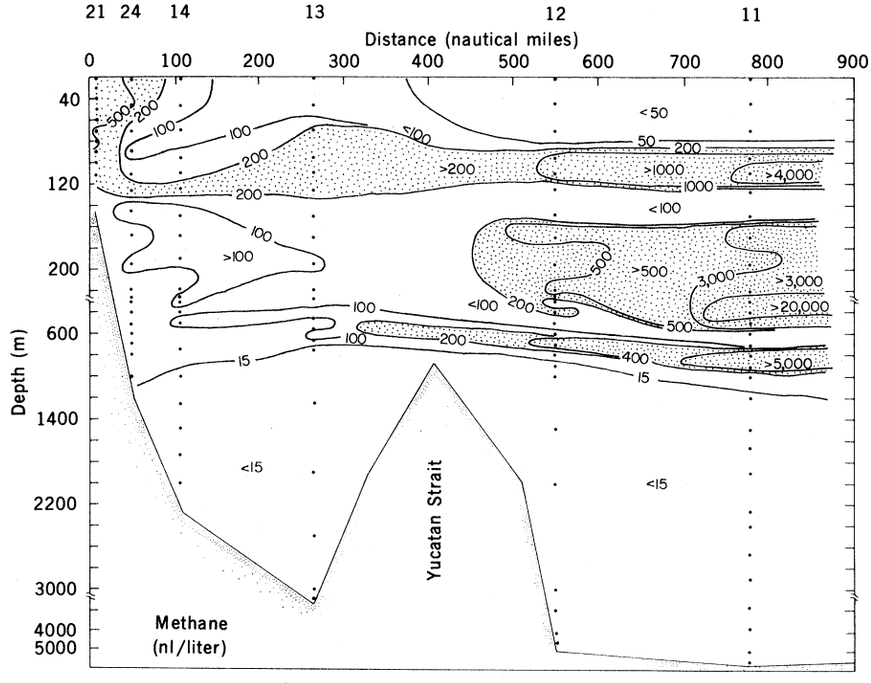

Fig. 1. Methane profile along cruise track from the northwest Caribbean Sea to the Mississippi Delta. Distance from left to right represents nautical miles from the Mississippi Delta. Stippled areas represent concentrations greater than 200 nl per liter of seawater.

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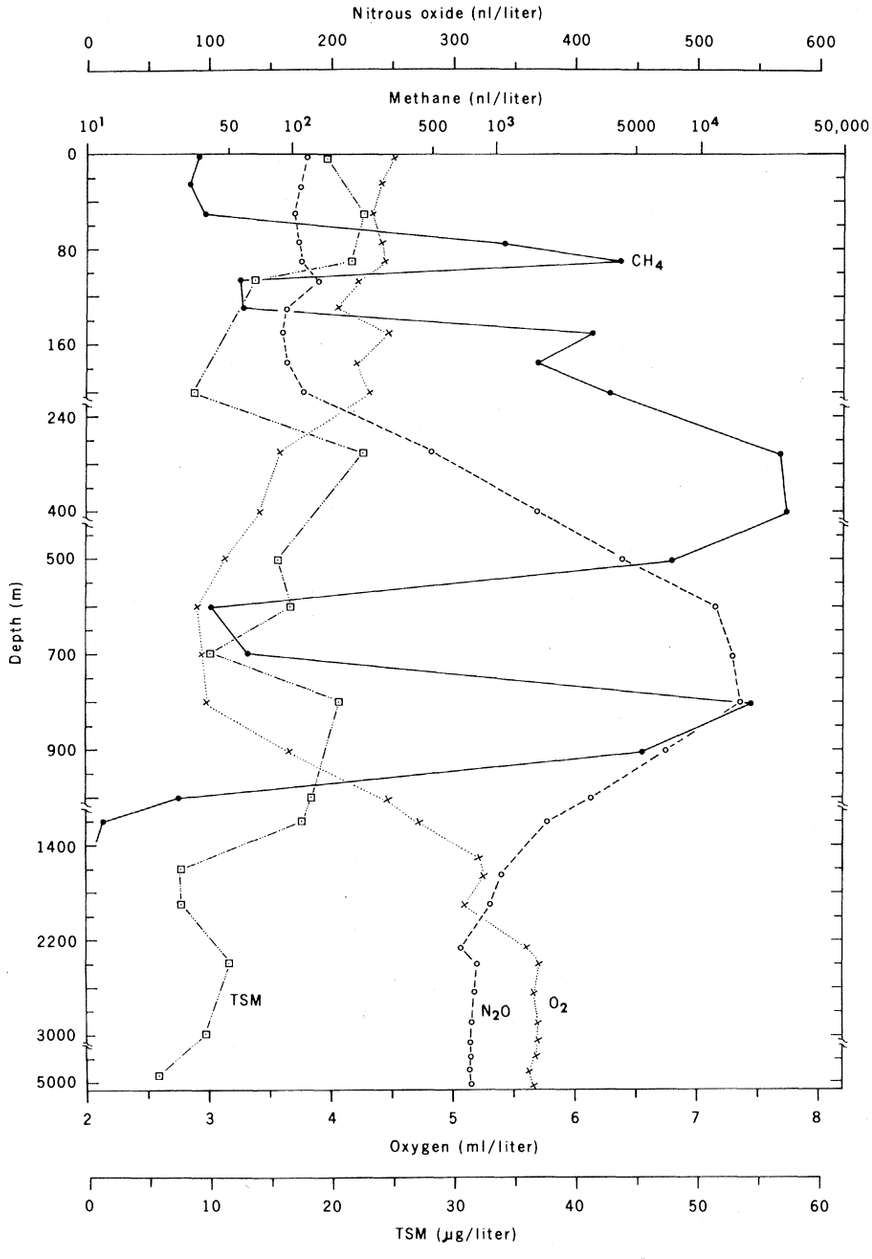

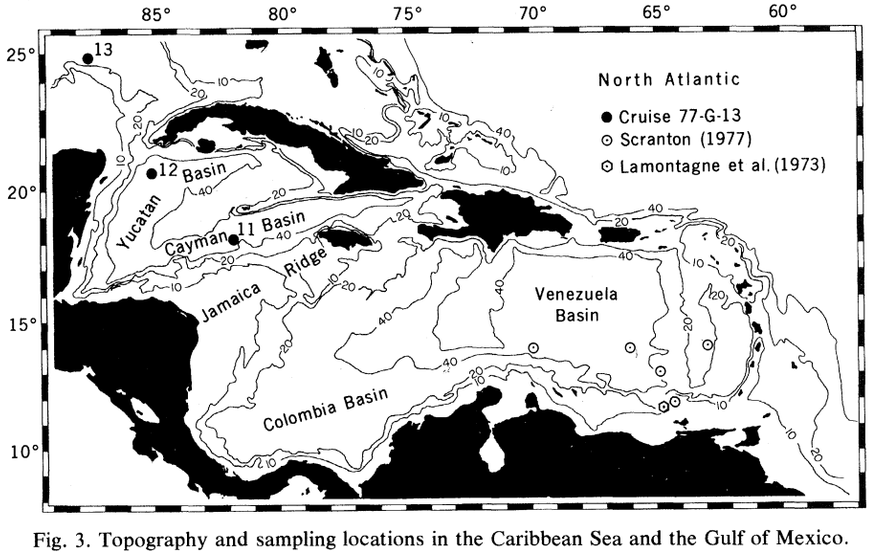

Fig. 3. Topography and sampling locations in the Caribbean Sea and the Gulf of Mexico.

Fig. 2. Methane, nitrous oxide, dissolved oxygen, and total suspended matter (*TSM*) depth profiles at station 11.

have postulated in situ production of methane in the water column (*3*, *4*), we do not believe that the deep methane maxima we studied could result from in situ activity. The methane concentration of ~ 26,000 nl/liter at 200 and 300 m from station 11 (Fig. 3) represent ~ 14 μg of carbon per liter. This is greater than the particulate organic concentration (POC) (4 to 15 μg of carbon per liter) at these depths. Since POC has been postulated to be the source of in situ methane (*4*), it is unreasonable to believe that bacterial degradative processes utilizing the scarce POC could produce methane maxima in the deep ocean without corresponding maxima in total suspended matter (TSM), POC, chlorophyll, or adenosine triphosphate (ATP). No such maxima were found.

The most probable source of the methane maxima in the western Caribbean basins is extensive gas seepage along the Jamaica Ridge. Although this ridge system has a sill depth of approximately 1500 m, large sections extend to depths of 1000 m or less and the system is necessarily in the upcurrent direction of the methane maxima. This seepage may be intermittent or affected by seasonal circulation patterns, since similar maxima in the northwest Caribbean were not observed during a cruise in April 1979.

The methane in the maxima appears to be microbially produced rather than generated by a thermogenic hydrocarbon gas. Bernard *et al.* (*8*) recently discussed the characterization of natural gas in terms of $C_1/(C_2 + C_3)$ ratios and carbon isotope compositions. The gas seeping from the ridge appears to be predominately methane, with only small amounts of the higher hydrocarbons. Although ethane values ranged up to 90 nl/liter in the core waters with large concentrations of methane, the C_1/C_2 ratios were high (> 200). The ratio was highest where the methane concentration was greatest, indicating a depletion of ethane relative to methane in the maxima in the less saturated waters. The C_1/C_2 ratios are similar to those of gases collected from bubbling gas seeps (a possible mechanism for methane additions to overlying waters) on the continental shelf in the northwest Gulf of Mexico (*9*). A significant petrogenic source for the gas seepage cannot be ruled out, since Brooks *et al.* (*10*) showed for a seep on the south Texas shelf that measurements of molecular compositions in the over-

lying water column indicated a biogenic source whereas measurements of dissolved gases in the underlying sediments indicated a petrogenic source.

The most probable mechanism for addition of the methane to the overlying water column is bubbling seepage—as has been extensively observed in the Gulf of Mexico (*9, 10*). The total methane contributed to the overlying waters by this seepage could amount to 1×10^8 to 10×10^8 liters per day considering that the total transport of water across the Jamaica Ridge is approximately 31×10^6 m^3/sec (*6*) and that the integrated excess methane in the upper 1200 m is in the 500 to 5000 nl/liter range.

Other gases measured in the northwest Caribbean showed no anomalous depth trends. The concentration of nitrous oxide (N_2O) was fairly uniform (160 to 190 nl/liter) in the upper 200 m and increased to a maximum of ~ 550 nl/liter at 800 m, which coincides with the core of the antarctic intermediate water. Similar profiles have been presented by Yoshinari (*11*) for the North Atlantic and the Caribbean, showing that the maximum concentration of N_2O corresponds to the minimum concentration of oxygen. The large methane maxima in Fig. 2 coincide somewhat with small increases in TSM. Suspended matter may also be added to the water column as the current moves across from the Jamaica Ridge.

The deep methane maxima in the northwest Caribbean are of interest not only because of the unusual geological processes that create them but because they may provide tracers for Caribbean Current waters. This system of currents is important since it flows through the Yucatan Strait to form the Loop Current in the Gulf of Mexico and exits through the Florida Straits to contribute to the Gulf Stream. No methane profiles have been obtained for the core of the Loop Current or the Gulf Stream waters. If the seepage along the Jamaica Ridge is a relatively constant addition to the waters flowing over that sill, then the deep methane maxima may be useful tracers of these current systems if methane is fairly conservative in its action as a tracer. It was shown in (*2*) that in polar regions deep waters formed with a concentration of ~ 70 nl per liter of methane are depleted to ~ 10 nl/liter by the time they reach the deep basins of the ocean. Methane depletion is evident in the water deeper than 1000 m in the Cayman and Mexico basins (Fig. 1).

The mechanism and rate of methane utilization in the ocean is unknown. Most deep profiles, however, indicate that the greatest utilization occurs at depths above 500 m, with the half-life for methane below this depth being hundreds of years. Such large additions of methane in the 80- to 1000-m depth interval may provide an ideal condition for studying methane consumption in the water column.

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Electrical Origin of the Outbursts on Io

Abstract. *The outbursts seen on Jupiter's satellite Io have been described as volcanic eruptions. They may instead be the result of large electric currents flowing through hot spots on Io and causing evaporation of surface materials. A strictly periodic behavior would then be expected.*

In the course of the Voyager 1 mission photography of Jupiter's satellite Io, at least seven violent eruptions were identified, apparently throwing material to heights up to 270 km and emanating from caldera-like markings. The eruptions were regarded as volcanic in origin by the various scientific teams that had the primary responsibility for the analysis of the data (*1, 2*). Thus one of the teams writes, "Probably the most spectacular discovery of the Voyager mission has been the existence of active volcanoes on Io, erupting material to heights of several hundred kilometers above the surface" (*1*, p. 961).

A volcanic interpretation of the eruptions seemed favored by several associated circumstances. Fluid flow patterns that may represent lava flows are seen in association with some of the calderas. Infrared observations show increased temperatures in these locations (*3*). A paper on the tidal energy dissipation in Io, published shortly before the observations (*4*), suggested that much internal melting in Io can be expected and that volcanic features on the surface should be anticipated.

Nevertheless, the volcanic interpretation presents great difficulties. For material to be thrown to the heights observed, it must have been propelled to velocities up to 1 km/sec. Volcanic events can expel materials with high velocities only with the aid of volatile substances. On the earth, water and carbon dioxide are the chief volatiles involved. If the activity on Io was as incessant as it appears now to be, then in a small fraction of geologic time all the volatiles would have been driven off and would no longer be available as propellants. Indeed, the spectroscopic evidence indicates an absence of water in the atmosphere of Io.

Sulfur or sulfur compounds have been mentioned (*1*) as a possible propellant. Although there are good indications that sulfur is abundant on Io, neither elemental sulfur nor any of its compounds are likely to be suitable for causing such eruptions. The volatile compounds of sulfur would be expected to have been lost, together with the other volatiles. In any case, whatever the compound, the atomic weight of sulfur, 32, virtually rules it out as the propellant to achieve such velocities. Only in very special circumstances is it possible for solid particles to gain speeds in excess of the speed of sound in the propelling gas. In most actual circumstances applicable to a volcano, expulsion speeds would be less than the speed of sound in the propelling gas (*5*). For a gas of the molecular weight of diatomic sulfur or sulfur dioxide to have a speed of sound of 1 km/sec, it would have to be heated to 6000 K. Even for the molecular weight of hydrogen sul-

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