Reports

Control of Methane Sediment-Water Bubble Transport by Macroinfaunal Irrigation in Cape Lookout Bight, North Carolina

Abstract. *Methane transport by bubble ebullition through bubble tubes from sediments to overlying waters in Cape Lookout Bight, Outer Banks of North Carolina, occurs only in the absence of burrowing macroinfauna, which indirectly prevent saturation methane concentrations by irrigating surface sediments with dissolved sulfate. Distribution of macroinfauna in the bight is limited to bottom areas not subjected to periodic anoxic conditions.*

Saturation methane concentrations resulting from anaerobic methanogenesis are known to result in the formation of bubbles in the interstitial waters of marine sediments (*1–4*). Bubble ebullition has recently been inferred as a significant methane transport mechanism to overlying water in the Hudson River (*4*), and direct observations of extensive bubbling and water column measurements during June to August 1975 show that it is a major source for overlying waters in Cape Lookout Bight, a small, periodically anoxic basin (Fig. 1) on the Outer Banks of North Carolina.

Saturation concentrations of methane, which result in the formation of methane bubbles in the interstitial waters of marine sediments, build up only when low concentrations of dissolved sulfate occur (*3–5*); therefore, processes that control the distribution of dissolved sulfate should indirectly control the transport of methane to overlying waters by bubble ebullition. During investigations of methane production in organic-rich sediments found in Cape Lookout Bight (*6*), large numbers of bubbles approximately 0.5 to 2 cm in diameter were observed surfacing in a restricted area in the bight's interior. A diving survey conducted at this site (station 1, Fig. 1) revealed that the bubbles were regularly leaving the sediments through large numbers (> 6 per square meter) of randomly distributed, easily visible cylindrical tubes (Fig. 2A) approximately 0.5 to 1.5 cm in diameter, for which the term "bubble tubes" was coined. Sediment sieving to a depth of approximately 30 cm revealed no evidence for any macroinfauna capable of creating such tubes (*7*). Two samples of approximately 75 ml of gas each were collected on separate occasions over randomly chosen bubble tubes within 2 m of

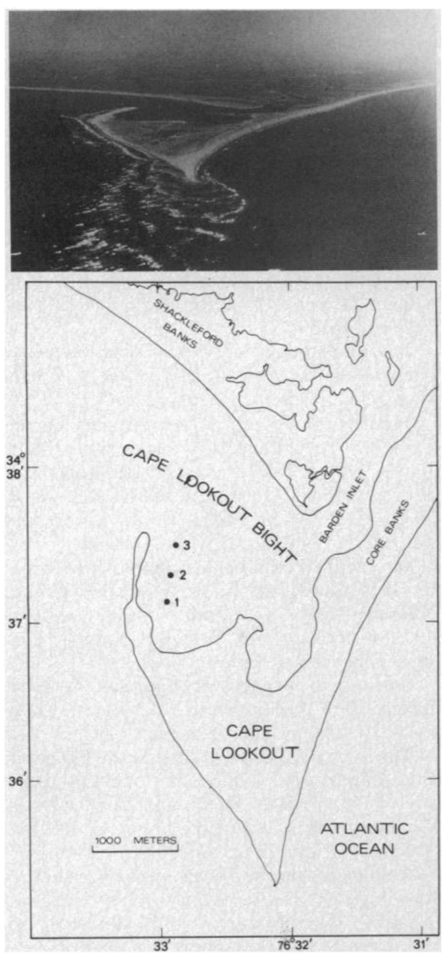

Fig. 1. Cape Lookout Bight study area, Outer Banks of North Carolina. Stations 1, 2, and 3 are indicated on the drawing. The aerial view is from the south. [Photograph courtesy of J. Stivers]

the bottom by a diver holding an inverted Winkler dissolved oxygen bottle. The gas composition of these samples averaged 88 percent methane and 11 percent nitrogen.

Evidence that overlying water near the bottom of this interior area of the bight had been periodically anoxic was provided by the complete lack of an observable brown oxidized layer of sediment as well as the complete absence of macroinfaunal organisms, which maintain a supply of oxygen in their burrows by pumping in overlying water, a process known as irrigation.

In contrast, a second dive closer to the bight's entrance, where no bubbles have been observed (station 3, Fig. 1), revealed a brown oxidized sediment layer 0.5 to 1 cm thick and the presence of many burrowing macroinfauna capable of extensive irrigation, including large decapod crustaceans, enteropneusts, and a variety of polychaetes, along with large numbers of burrow holes.

We hypothesized that the irrigation process prevented bubble formation and subsequent ebullition by pumping dissolved sulfate into the highly reducing sediments, the continuous resupply replacing sulfate reduced to hydrogen sulfide. This would prevent methane saturation from occurring near the sediment-water interface (*3*), thus preventing bubble formation in this zone and the maintenance of bubble tubes through ebullition. Recently irrigation has been shown to be a major influence on the interstitial water composition of the upper 15 cm of nearshore Long Island Sound sediments (*8*), where vertical linear sulfate concentration profiles are maintained close to the overlying water value during the late summer months, when macroinfaunal activity is highest. Goldhaber (*9*) has observed irrigation control of sulfate and other dissolved species to depths of more than 50 cm in Gulf of California sediments.

To test this hypothesis we collected a series of three cores on 18 October 1975 along a 1.0-km transect from the bight interior where bubbling was observed (station 1) to near the bight's entrance where macroinfauna were observed (station 3), and at an intermediate point (station 2). Several gravity cores approximately 30 to 50 cm long were collected at each station, allowing only 1 to 2 m of free fall of the cores before impact with the sediments. All cores were immediately examined for evidence of disturbance of the brown oxidized surface layer or visible burrow structures. Similar color characteristics were noted below the interface,

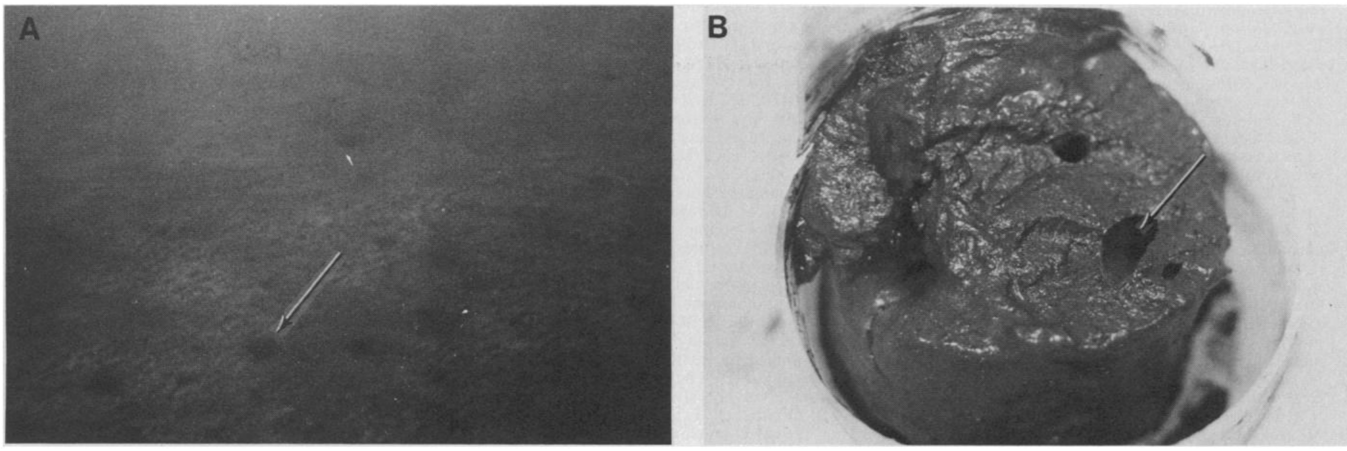

Fig. 2. (A) Arrow points to a bubble tube through which bubbles escape the sediments at depth of 10 m near station 1 in Cape Lookout Bight. The field of view is approximately 1 m in the front of the photograph. Note the sulfur bacteria (*Beggiatoa*), which appear as white flocculent material on the sediment surface. (B) Intact macroinfaunal burrow structures approximately 0.2 to 0.5 cm in diameter found at a depth of 15 cm near the bight entrance (station 3). By pumping overlying water through these burrows, macroinfauna maintain high sulfate concentrations near the sediment-water interface. [Photograph (B) courtesy of J. Kohlmeyer]

with a black zone followed by a lighter gray zone appearing at depths ranging from 35 to 55 cm. Cores selected for further observations were transported within 2 hours to the University of North Carolina's Institute of Marine Sciences in nearby Morehead City, and either checked for evidence of bubble and burrow structures or immediately extruded, centrifuged to separate interstitial water from sediment (*10*), and analyzed for dissolved sulfate by the gravimetric barium sulfate method. Sulfate concentrations plotted against sediment depth at the three stations are shown in Fig. 3.

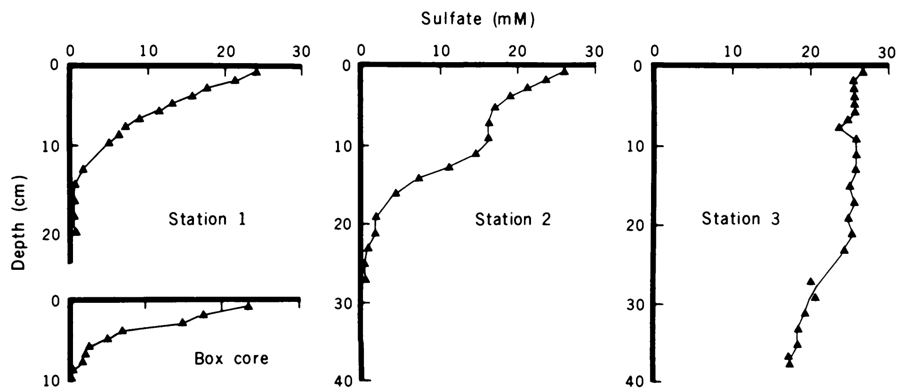

Fig. 3. Concentrations of sulfate in the interstitial waters of sediments at the three stations in Cape Lookout Bight.

The sulfate concentration-depth profile observed in the upper 10 cm of a box core near station 1 in July 1975 is also shown in Fig. 3 for comparison (*11*). Burrow structures observed at a depth of approximately 15 cm in a sister core collected at station 3 are shown in Fig. 2B. Two live polychaetes, both of the family Nereidae and one identified as *Ceratonereis irritabilis*, were recovered in the upper 11 cm of the station 3 core processed for sulfate distribution.

At coring station 1 a steep negative gradient in sulfate resulting from its reduction to hydrogen sulfide indicated little or no influence of irrigation and probable maintenance of the concentration profile by a combination of diffusion and reduction (*12*). At station 2, where a brown oxidized surface layer was observed, a steep concentration gradient with depth also occurred (*13*). At station 3, where many burrow structures appeared and live irrigating organisms were found, a vertical linear sulfate concentration profile with values near those in the overlying water was maintained to a depth of approximately 24 cm by extensive irrigation, although active sulfate reduction was indicated by a strong odor of hydrogen sulfide and by the presence of jet black iron monosulfides. The lack of bubble ebullition from sediments in this area of the bight appears to be caused by the high concentrations of sulfate, which indirectly prevent saturation methane concentrations (*5*) and thus prevent bubbles from forming near the sediment-water interface.

In summary, methane transport to overlying waters in Cape Lookout Bight by bubble ebullition occurs only in the absence of macroinfauna, which maintain high pore water sulfate concentrations in the upper 20 to 30 cm of sediments through irrigation. The correlation between active bubbling periods in the summer and early fall and high methane concentrations in bottom waters (*14*) suggests that bubble transport is a major, seasonally regulated methane source for Cape Lookout Bight waters. The distribution of irrigating macroinfauna is controlled by requirements for continuously oxygenated overlying water, which is in turn controlled by mixing and respiration processes in the water column.

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References and Notes

W. S. Reeburgh, *Limnol. Oceanogr.* **14**, 368 (1969).
2. J. R. Schubel, in *Natural Gases in Marine Sediments*, I. R. Kaplan, Ed. (Plenum, New York, 1974), pp. 275–298; ——— and E. W. Schiemer, *Mar. Geophys. Res.* **2**, 61 (1973).
3. C. S. Martens and R. A. Berner, *Science* **185**, 1167 (1974).
4. D. E. Hammond, H. J. Simpson, G. Mathieu, in *Marine Chemistry in the Coastal Environment*, T. Church, Ed. (American Chemical Society, Washington, D. C., 1976), pp. 119–132.
5. Low methane concentrations (< 0.1 mmole/liter) in the presence of sulfate may be explained by consumption of methane by sulfate-reducing bacteria [R. O. Barnes and E. D. Goldberg, *Geology* **4**, 297 (1976); W. S. Reeburgh, *Earth Planet. Sci. Lett.* **15**, 337 (1976); C. S. Martens and R. A. Berner, in preparation], lack of methane production during sulfate reduct A. Nissenbaum, B. J. Presley, I. R. Kaplan, *Geochim. Cosmochim. Acta* **36**, 1007 (1972); G. E. Claypool and I. R. Kaplan, in *Natural Gases in Marine Sediments*, I. R. Kaplan, Ed. (Plenum, New York, 1974), pp. 99–139; C. S. Martens and

R. A. Berner (3)], and inhibition of methane production by dissolved sulfide [Th. E. Cappenberg, *Microbiol. Ecol.* **2**, 60 (1975)].
6. Previous observations of anoxic conditions in Cape Lookout Bight were reported by R. Menzies. G. Rowe, and L. Atkinson [*Int. Rev. Gesamten Hydrobiol.* **53**, 77 (1968)]. The organic-rich sediments accumulate in the bight as a result of decreases in current velocity of waters entering either through Barden Inlet or the open-ocean entrance bordering Shackleford Bank.
7. P. E. Cloud [*Am. J. Sci.* **258A**, 35 (1960)] has discussed the abiotic characteristics of "gas trackways" observed in modern and ancient carbonate sediments. The possibility that macroinfauna occupy the bight interior during winter months has not been ruled out and it is conceivable that vacated burrow structures could be maintained by bubble ebullition during summer months. Small puffs of sediment accompanied many bubbles observed exiting bubble tubes.
8. M. B. Goldhaber, R. C. Aller, K. Cochran, J. Rosenfeld, C. S Martens, R. A. Berner, *Am. J. Sci.*, in press.
9. M. B. Goldhaber, thesis, University of California, Los Angeles (1974).
10. E. Sholkovitz, *Geochim. Cosmochim. Acta* **37**, 2043 (1973). Centrifuge separation of interstitial waters from anoxic sediments was successfully used to study sulfate and other dissolved ions in the Santa Barbara Basin.
11. The box corer was inserted by a diver. Its design and use are described by Goldhaber *et al.* (8).
12. Kinetic reaction-diffusion models utilized to describe interstitial water distributions of sulfate can be found in R. A. Berner, in *The Sea*, E. D. Goldberg, Ed. (Wiley, New York, 1974) vol. 5, pp. 427–450; M. B. Goldhaber and I. R. Kaplan, in *ibid.*, pp. 569–655.
13. The structure in the station 2 sulfate depth profile may be a relict feature from previous irrigation episodes.
14. Methane concentrations in Cape Lookout Bight bottom waters averaged 40 μl/liter during periods of active bubble transport in summer and early fall and 2 μl/liter during the late fall, when bubbling had ceased.
15. I thank F. Sansone and E. Powell for assistance with core collection, identification of macroinfauna, and chemical analyses, and my colleagues in the Marine Sciences Program in Chapel Hill and at the Institute of Marine Sciences, Morehead City, for helpful information and discussions about the study site. D. Frankenberg, M. B. Goldhaber, L. K. Benninger, and R. C. Aller provided constructive critical reviews of the manuscript. Research supported by NSF grant DES75-06199 (Oceanography Section) and by a grant from the University of North Carolina Marine Sciences Council.

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Meteoroid Storms Detected on the Moon

Abstract. *Seismometers on the moon have detected several brief periods of enhanced meteoroid-impact activity, believed to represent encounters of the moon with "clouds" of objects in the kilogram range. The latest and most active encounter, in June 1975, is interpreted as a meteoroid cloud of diameter 0.1 astronomical unit and total mass 10^{13} to 10^{14} grams.*

Impacts of masses greater than about 50 g generate lunar seismic disturbances that are detected by the Apollo passive seismometer network. Thus, the moon acts as a sounding board for meteoroids and the seismic data yield information on the mass and spatial distribution of these large particles in space. In this report we describe time variations in the number of meteoroids hitting the moon. The large fluctuations observed suggest that some massive fragments are not randomly distributed in space, but are concentrated in clouds that sweep past the earth-moon system.

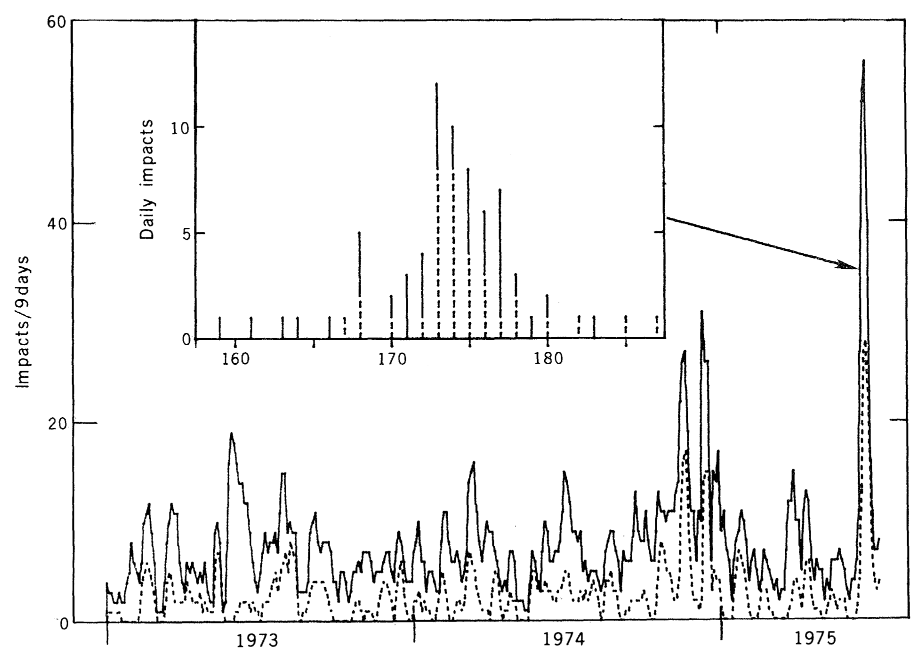

Fig. 1. Occurrence of meteoroid impacts detected by the Apollo seismic network. Each data point is the number of events in a 9-day window, with the window stepped 3 days per data point. The solid line represents all impacts and the dashed line represents only small impacts (see text). Shown in the inset are the daily numbers of impacts during the period from 7 June 1975 (day 158) to 6 July 1975 (day 187), which includes the most active interval. Solid and dashed lines are used as in the main figure. The data have been compiled from *Passive Seismic Experiment Long Period Event Catalog* (13).

The passive seismic network, deployed by the Apollo astronauts, consists of four stations arranged in an approximately equilateral triangle 1100 km on a side with two stations 180 km apart at one corner. Each station consists of a set of three long-period (1 hertz and below) seismometers sensitive to motion in orthogonal directions and one short-period (1 hertz and above) seismometer sensitive to vertical motion. Each instrument can detect ground motions of about 0.05 nm at the peak of its response. A more detailed description of the instruments is found in Latham *et al.* (1).

The mass distribution of meteoroids has been measured by several earth-based methods (2), by satellite detectors (3), and from the lunar seismic data (1, 4). The latter yield mass distribution estimates that are lower by about an order of magnitude than those determined by earth-based methods. The mass distribution estimated by Duennebier and Sutton (5) from lunar short-period seismic data was very close to earth-based estimates in the mass range around 1 g. However, a correction in amplitude calibration for the Active Seismic Experiment (6) reduces their flux estimate by about an order of magnitude, making it an order of magnitude lower than the earth-based observations. In all known methods of meteoroid flux estimation, however, the parameter measured is difficult to relate to the mass of the impacting body.

Dainty *et al.* (7) used the lunar seismic data to determine the direction of approach of meteoroids in near-earth space. They concluded from studies of the variation in numbers of events observed as a function of phase of the moon that most meteoroid orbits lie near the plane of the ecliptic and that the orbits have aphelia between 2 and 5 A.U. In this report we note large temporal fluctuations in the numbers of impacts observed and interpret this observation in terms of the spatial distribution of meteoroids.

Between 1 January 1973 and 13 July 1975 (924 days), the long-period components of the passive seismometer array detected 815 signals interpreted as representing meteoroid impacts. These signals are similar to the signals from impacts of the lunar module and Saturn-rocket boosters. They differ from those