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Dynamic processes observed at a gas hydrate outcropping on the continental slope of the Gulf of Mexico

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Abstract A deep-sea time-lapse camera and several temperature probes were deployed on the Gulf of Mexico continental shelf at a biological community associated with a gas hydrate outcropping to study topographic and hydrologic changes over time. The deployment site, Bush Hill (GC-185), is located at 27°47.5′ N and 91°15.0′ W at depths of ~540 m. The digital camera recorded one still image every 6 h for July-October in 2001, every 2 h for the month of June 2002, and every 6 h for the month of July 2002. Temperature probes were in place at the site for the entire experimental period. The data recovered provide a record of processes that occur at gas hydrate mounds. Sediment resuspension over the mound causes significant variation in luminosity of the time-lapse photographs. A marked diurnal pattern can be seen in the temperature and luminosity records. No major change in shape or size of the gas hydrate outcrop at this site was observed during this study. Stable topography of the gas hydrate mound, combined with high bacterial activity and sediment turnover, appears to focus biological activity in the mound area. Frequency and recurrence of sediment resuspension indicate that short-term change in the depth and distribution of surface sediments is a feature of the benthos at the site. Because the sediment interface is a critical environment for hydrocarbon oxidation and chemosynthesis, short-term variability and heterogeneity may be important characteristics of these settings.

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Introduction

Gas hydrate is an ice-like and meta-stable substance that forms when gas molecules are concentrated under high-pressure and low-temperature conditions (Sloan 1998). When the conditions for gas hydrate formation are met (Fig. 1), "guest" molecules such as methane and other hydrocarbons become trapped inside a rigid framework of water molecules. The structure and stability of this matrix is determined by the size of the guest molecules, and the resulting crystal lattice structure that forms. Larger guest molecules enable the hydrate structure to remain stable at higher temperatures. Global abundance of gas hydrated on continental marine margins is thought to be very large, and there is active research concerning its formation, preservation, and dissociation over geologic time (Brooks et al. 1984; Kennicutt et al. 1985; Kennett et al. 2000). Although changes in both temperature and pressure can destabilize gas hydrate deposits, when it approaches the stability horizon (Fig. 1) gas hydrate is more sensitive to increases in temperature than to decreases in pressure, potentially requiring only a few tenths of a degree increase to induce dissociation (Xu and Lowell 2001).

The worldwide gas hydrate reservoir contains a significant amount of carbon, and thus the stability of deep-sea gas hydrate deposits may have important implications for climate change that have been widely discussed (Kvenvolden 1988). Some workers propose that temperature and ocean current fluctuations caused by global warming and other processes may cause the dissociation of deep-sea gas hydrate deposits, perturbing the Earth's carbon cycle (Weissert 2000). There is evidence that large-scale dissociation of gas hydrate deposits in the past led to increased warming and climate change (Dickens 1999; Hesselbo et al. 2000; Weissert 2000; Halverson et al. 2002). A second school of thought proposes that gas hydrate is more stable than predicted, and that the water column is so large and the concentration of hydrocarbons so small that any major outgassing due to gas hydrate dissociation would be oxidized and dispersed before reaching the atmosphere (Kvenvolden 1999; Valentine et al. 2001; Grant and

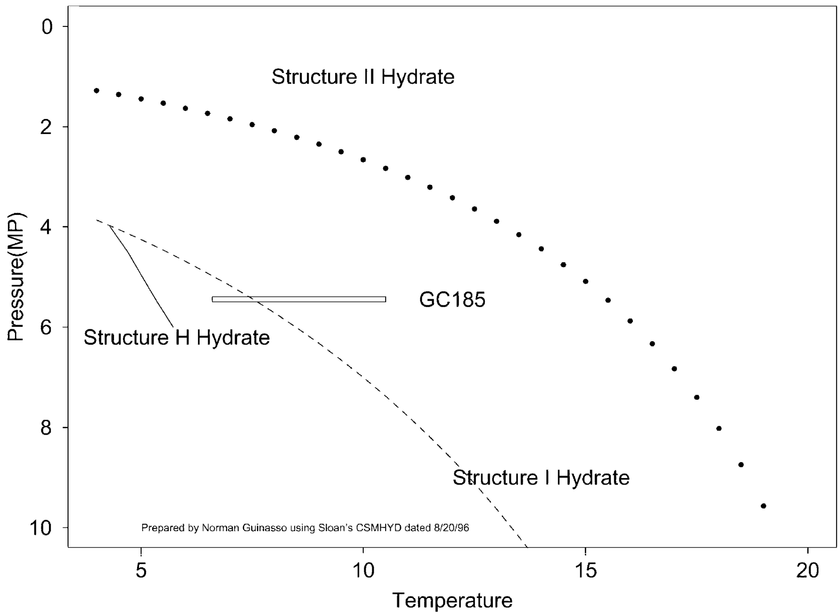

Fig. 1 Gas hydrate stability zone (GHSZ) curves for structure I, II and H gas hydrate. The stability field for each species of gas hydrate is the area below the corresponding curve. Pressure–temperature region for the site of present research, GC-185 (Bush Hill) on the northern continental slope of the Gulf of Mexico, is shown by means of a *box*. For average pressure and temperature at GC-185, structure II gas hydrate is most likely the only stable form of gas hydrate at this site (Guinasso 2002)

Whiticar 2002; Milkov and Sassen 2003). Observations of gas hydrate under natural marine conditions of varying temperature and pressure are needed to help test these theories.

Long-term, in situ observation of gas hydrate sites is logistically challenging due to the water depth and remoteness from land. Gas hydrate is mostly found buried deep in marine sediments, being identified only through seismic detection of bottom simulating reflectors (BSRs; Dickens 2001). The geology of the northern Gulf of Mexico continental slope, including thick sediment columns, salt diapirs, and active hydrocarbon venting through numerous faults, concentrates hydrocarbon gases in shallow sediments, resulting in gas hydrate deposits close to the seawater/sediment interface (Roberts 1995). Gas hydrate has been observed to cap faults and form sizable outcroppings or mounds on the seafloor (Brooks et al. 1984). In this type of setting, accreting gas hydrate deposits may breach the sediment/water interface, and become subject to variable conditions in the benthic environment (MacDonald et al. 1994; Roberts et al. 1999). Under these circumstances, the stability of gas hydrate is challenged by changing temperatures, water circulation, morphology during growth, as well as dynamic interactions with benthic fauna and sediment deposition. Here we analyze several visual and temperature datasets of a seafloor gas hydrate deposit in which the effect of these processes can be observed over periods of weeks and months.

Materials and methods

The study site known as GC-185 (Minerals Management Service lease block number), or Bush Hill, is located southwest of the Mississippi Delta (27°47.5′ N and 91° 30.5′ W) at ~550 m water depth, and contains numerous hydrocarbon seeps, active gas vents, and several gas hydrate formations (MacDonald et al. 1989, 1994). The seep gas issuing from the site contains substantial proportions of propane and ethane, in addition to thermogenic methane, and gas hydrate occurs in structure II form (Sassen and MacDonald 1994). Lenticular gas hydrate deposits capping the seeps provide energy and substrate for biological colonization by bacteria and metazoans (MacDonald et al. 1994). Gas hydrate samples typically contain oil and sediment inclusions (MacDonald 2002).

The site was monitored from July 2001 to July 2002. The monitoring array deployed at the site included a digital time-lapse camera and recording thermistors. The time-lapse camera was a SeaSnap 990 consisting of a modified Nikon CoolPix 990 camera held inside a pressure-housing mounted on an aluminum frame (Fig. 2). Illumination was provided by two 12-V, 50-W halogen lamps. The camera and lights were triggered simultaneously by a Digisnap 2500 remote shutter release. System power was delivered by 12-V batteries in a deep-sea housing filled with mineral oil. Two spherical floats, each with ~9 kg of positive buoyancy, were attached to the top of the camera frame to provide stability.

The temperature probes deployed at the site consisted of two Antares high-resolution temperature data loggers (or thermistors) enclosed in a wand constructed of 2-cm PVC pipe. By measuring changes in the electrical conductivity of the sensor tip, the thermistors record changes in temperature with ±0.1°C accuracy, and can store 65,000 data points in internal memory. The 53-cm-long probes were constructed so that one thermistor sensor tip protruded from each end, allowing us to simultaneously record ambient water and within-hydrate/sediment temperatures. A reflective, numbered marker was attached to the top of each probe by a short length of polypropylene line. Buoyant polypropylene panels painted with scale markers were deployed in the camera's field of view to provide a visual index of scale, and a spatial reference for

Fig. 2 Time-lapse camera that was deployed at Bush Hill, displaying floats, lights, pressure-housing, and battery case. Spherical floats provide compensating buoyancy and a righting moment

the locations of bottom features associated with the hydrate mound.

The camera and temperature probes were first deployed at the site on 18 July 2001 by the *Johnson Sea Link* (JSL) submersible. The camera was positioned facing slightly east of due north, approximately 1 m from the edge of a gas hydrate outcrop with 65 cm of relief and about 2.5 m across. This mound had been pre-selected during previous JSL dives because it was close to a bubble plume, large enough to have distinctive features and support seep epifauna, yet small enough to be fully visible in the camera's field of view (Fig. 3). One 1,024×756 pixel picture was taken every 6 h. The lens aperture was fully closed (F 7.0) to focus the camera over a wide area and a deep field. The auto-shutter was set to change the length of exposure time depending on the light intensity. The zoom was pulled back to provide the widest possible field of view short of a panoramic view. Two plastic markers were positioned on the far side of the mound from the camera to provide scale, and to detect changes in mound height. One marker was about 35 cm square, the other was 15 cm wide and 1 m high, and both markers were anchored by lead weights. The temperature probes were positioned to appear within the camera's field of view, and recorded ambient water temperatures at 30-min intervals. The camera was recovered on 6 June 2002. The batteries were recharged, and the camera sited near the same location on 11 June 2002. The camera was facing an angle slightly farther north than it had been during the preceding deployment. One photograph was taken every 2 h at 2,048×1,536 pixel resolution. New thermistor probes, programmed to record one measurement every 70 s, replaced those deployed in 2001. The camera and thermistors were reclaimed for the final time on 3 July 2002.

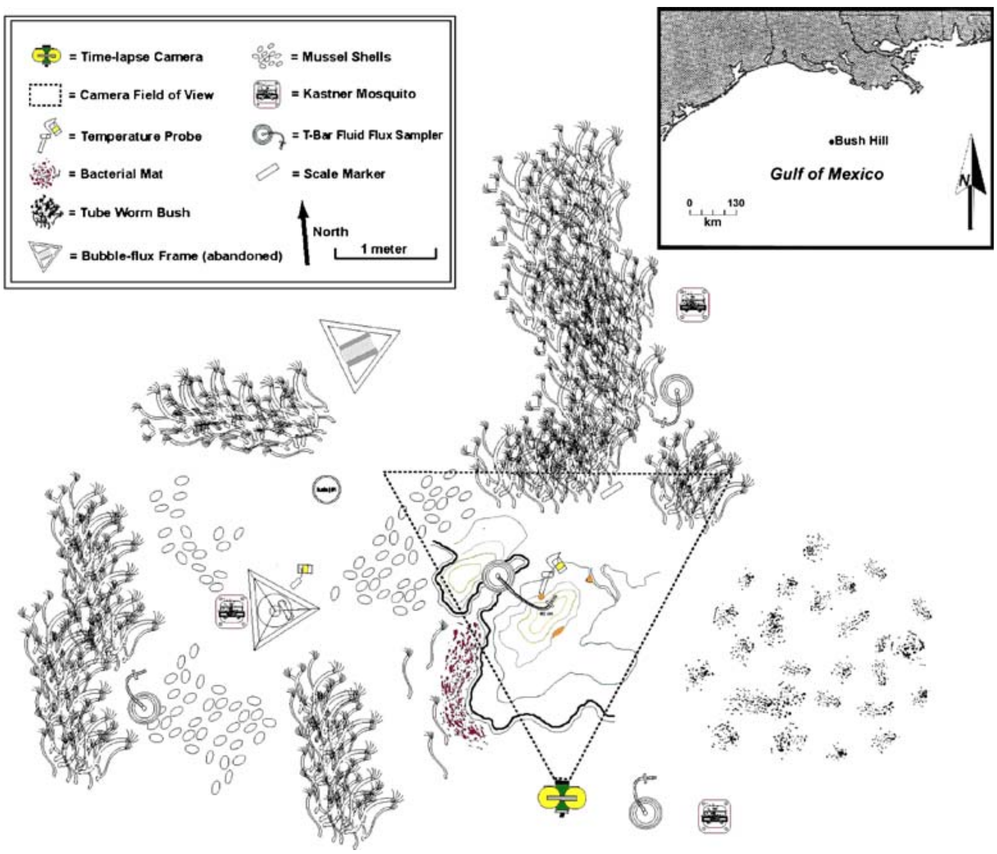

Fig. 3 Map of camera deployment site at Bush Hill (GC-185, see inset map at *top right*) as it appeared in June 2002, made using photomosaics assembled from video footage of submersible overflights. The gas hydrate mound has an irregular shape and about 50 cm of relief. All the equipment shown, except for the bubble-flux meter platforms, has since been recovered

Although no equipment present was capable of determining the exact concentration of particulate matter suspended in the water column, the amount of suspended sediment present in each picture could be quantified by measuring the light from the camera's lamps that backscattered from the near-bottom water column. This phenomenon was analyzed using ImageJ image-processing software developed by the National Institute of Health. The visible portion of the water column above the mound was selected in each frame, with equipment and other persistent objects excluded. A corresponding histogram of image pixels was then created, measuring the luminosity of the highlighted portion on an arbitrary 8-bit scale from complete darkness (zero backscatter) to complete light (all light reflected). Higher luminosity indicates greater amounts of turbidity, and thus greater amounts of suspended material, whereas lower luminosity indicates less turbidity.

Results

The battery power to the camera and lights lasted 91 days during the first deployment, providing 373 images. The field of view for the images included the southern face of the gas hydrate mound, both thermistor probes, scale markers, sediments, several patches of exposed gas hydrate, and bacterial mats and epifauna that colonized the area. The shorter deployment in 2002 lasted 23 days and produced 261 high-resolution images. The internal clock of the camera was verified after recovery and showed negligible (1–2 s) drift. Two separate time-series of water, gas hydrate, and sediment temperatures were recovered by the thermistor probes (Fig. 3). During the longer deployment, each thermistor recorded 15,693 data points over 327 days. The 1-month deployment provided a higher-resolution dataset with 31,171 temperature readings per thermistor. The results are summarized in Table 1.

Despite periodic fluctuations in water temperature, in the range 6.59–9.72°C, no bubbling or dissociation of the solid gas hydrate was observed in any of the photographs, and the mound did not change shape appreciably between July 2001 and July 2002. Image comparisons revealed a slight overall increase in size, and an increase in the number and size of exposed gas hydrate-filled crevices on the flanks and margins of the mound (Fig. 4). The mound had an irregular shape about 2.5 m across and roughly 65 cm of relief. The eastern edge of the mound was buried in sediment, and the southern edge was undercut with a small overhanging ledge. The sediment cap on top of the mound varied in thickness over the time-series, and was constantly redistributed by water movement at the site. The cap was scoured away in some places, exposing gas hydrate to the water while new sediment covered up exposed patches. Overall, the sediment layer appeared to thin substantially over the year of observations.

Despite the lack of gas expulsion from the gas hydrate outcrop itself, a bubble plume on the western side of the mound, less than a meter away but outside the time-lapse camera's field of view, has been releasing natural gas and oil constantly for several years. This area is a part of the gas hydrate mound, since the base of the plume is surrounded by gas hydrate and the outcrop extends for some distance below the sediment on all sides. There is no obvious crevice or fault from which the oil and gas escape. Bubbles appear to issue directly from the gas hydrate mound, which evidently includes a more permeable portion of the deposit. The constant presence of the bubble plume illustrates the active nature of seeps, and while the gas may not be the result of gas hydrate dissociation, it does affect the formation's longevity.

Although little topographic change was observed in the mound, the time-lapse camera captured several ongoing biological and geological processes. *Munidopsis* crabs and gastropods quickly colonized artificial environments such

Table 1 Data recovered from remote sensing equipment

Remote sensing device	Deployment period	Sampling frequency	Data collected	Results
Time-lapse camera	91 days (July–October 2001)	6 h	373 images, 1,024×756 pixels	Intermittent sediment resuspension at tidal frequencies; 1,381 individual organisms representing ~20 species observed
	23 days (June–July 2002)	2 h	261 images, 2,048×1,536 pixels	Gas hydrate appears stable and no dissociation was seen
Temperature probe #1 (in hydrate)	327 days (July 2001–June 2002)	30 min	15,693 data points	Min. water temp.=6.59°C
	23 days (June–July 2002)	70 s	31,171 data points	Max. water temp.=9.72°C
				Avg. water temp.=7.85°C
Temperature probe #2 (in sediment)	327 days (July 2001–June 2002)	30 min	15,693 data points	Min. water temp.=6.59°C
	23 days (June–July 2002)	70 s	31,171 data points	Max. water temp.=9.66°C
				Avg. water temp.=7.86°C

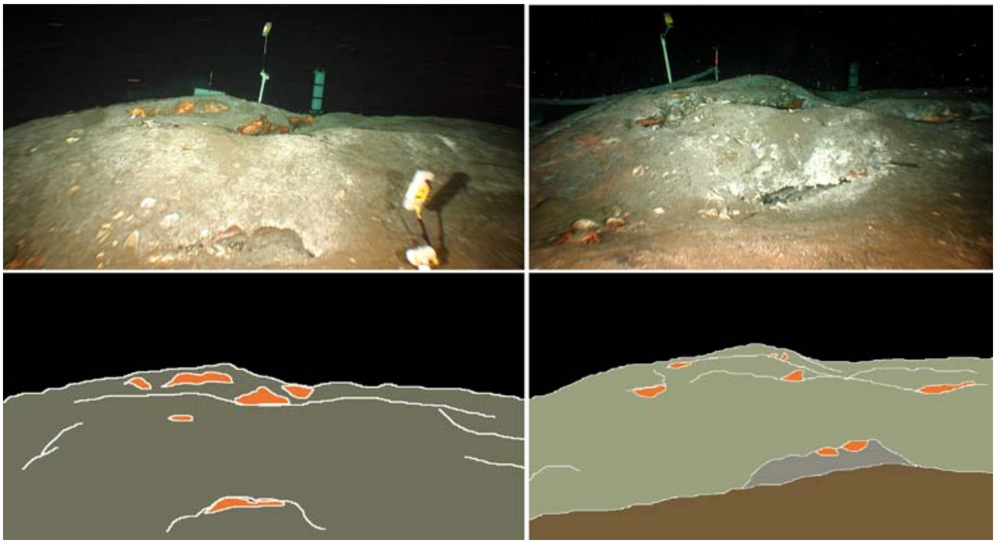

Fig. 4 Time-lapse photographs taken just after first camera deployment (*top left*) and at the end of second deployment (*top right*) exhibit very few changes, aside from a slight shift to the southwest in camera placement. Both photographs and *line drawings* (*bottom*, *left* and *right*) show that the gas hydrate mound has the same shape and exhibits only a slight change in elevation. The undercut area in the foreground has widened and deepened, and the sediment cap covering the mound has been redistributed to cover some hydrate and expose other patches

as the thermistor probes (this biological activity did not appear to affect the temperature record), and the same individuals were seen persistently over several months. Individual asteroids browsed the mound and predatory fish such as *Helicolenus dactylopterus* and *Urophycis cirratus* appeared and reappeared. Schools of *Hoplostethus* spp., often containing 20–30 individuals, were seen above the outcropping on a regular basis, and were among the most common organisms at the site. Large at the base and flanks of the hydrate mound appear to provide shelter for numerous small seep organisms, and may be excavated by biological activity.

Orange and white *Beggiatoa* bacterial mats covering the mound grew and retreated over the deployment period, often producing white flocculent material that would build up into drifts and then disperse due to currents or biological activity. Bacterial mats can retreat into the sediment (Sassen et al. 1993). However, they were able to reemerge fully within a 2-h period, and environmental features such as temperature, time of day and sediment suspension appeared to have no impact on this behavior. Benthic organisms such as sea stars, gastropods and crustaceans disturbed the bacterial mats as they moved across the mound, but these bare patches soon recovered, often within hours. The only patch that did not recover during the deployment period was an area of heavy orange *Beggiatoa* growth on the western face of the mound that was apparently scoured away by turbulent currents. This occurred on 18 June 2002, and that spot was the only part of the mound not entirely filled in by the end of the record on 3 July 2002. The activity of these animals produced no evident changes in the size or shape of the gas

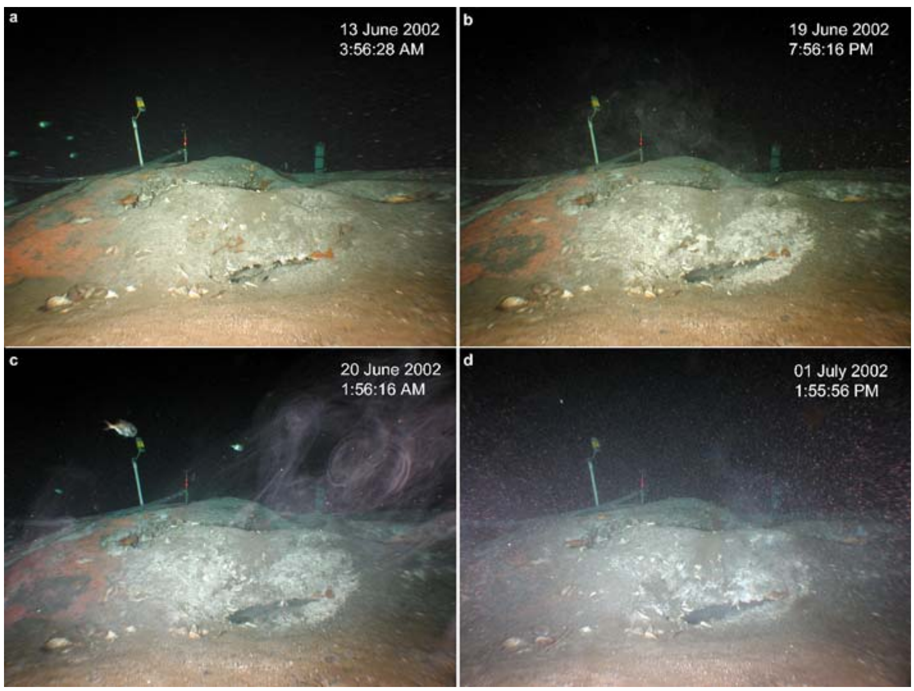

Fig. 5 Selection of photographs of gas hydrate outcropping illustrates the levels of sediment resuspension observed at the study site. Values range from very little (**a**), to mild (**b**), to vigorous (**c**, **d**). Dates and times are Central Standard Time

hydrate deposit. None of the biological activity was sufficient to produce sustained resuspension of the sediment that covered the gas hydrate deposit.

However, significant levels of sediment resuspension were observed in both sets of time-lapse images, at times obscuring the entire frame, indicating a number of turbulent events during which the luminosity of the water

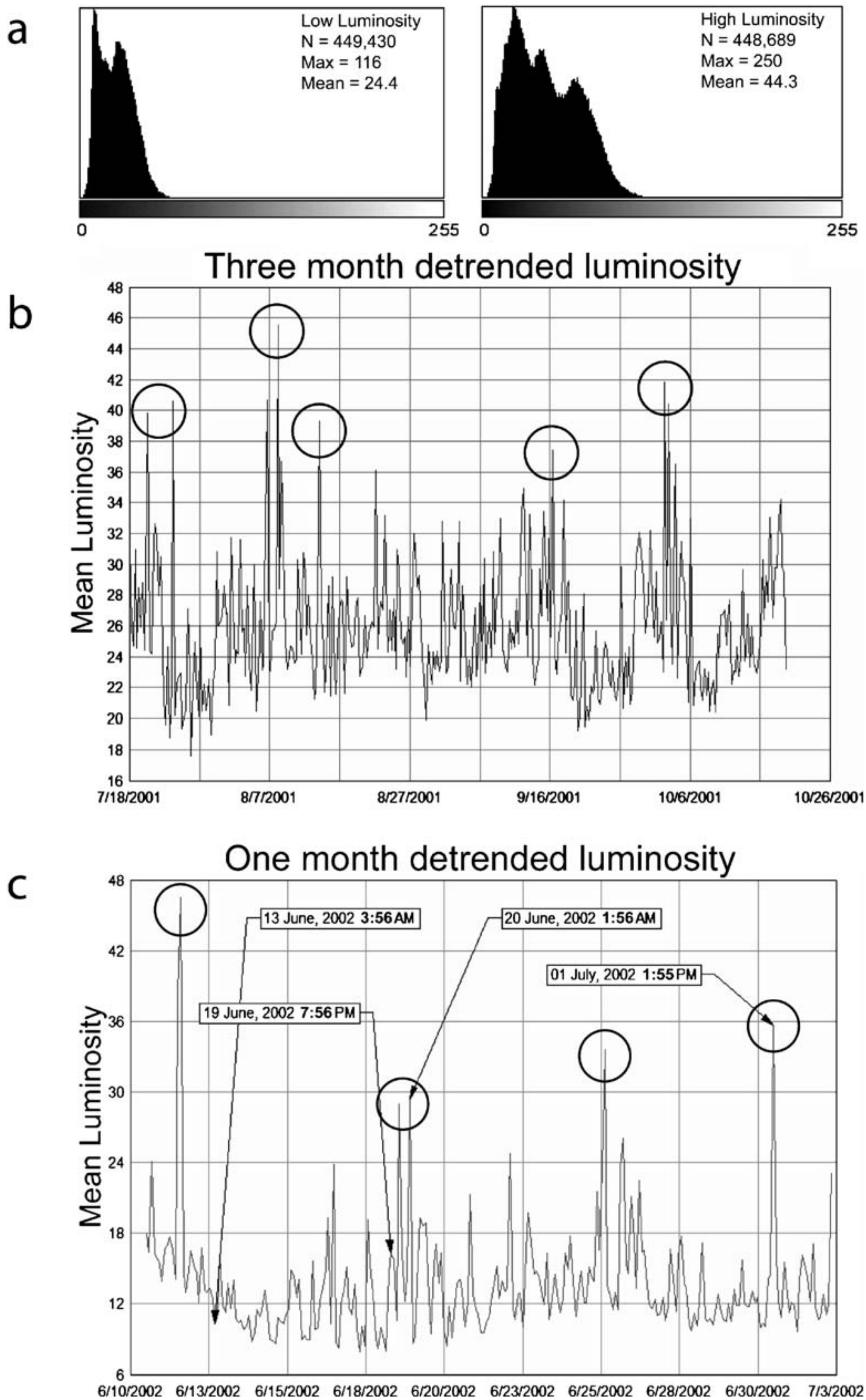

Fig. 6 **a–c** ImageJ software was used to generate histograms of pixel intensity (0–255) in the visible portion of the water column above the hydrate mound, and measure luminosity of time-lapse images as shown in examples in **a**. Low luminosity (*left histogram*) indicated a darker image with relatively little particulate material; higher luminosity (*right histogram*) indicated a lighter image, and thus more particulate matter. Mean luminosity of each recorded image is plotted for 3-month (**b**) and 1-month (**c**) time-series. Both datasets were detrended to compensate for dimming of the camera lights due to battery discharge. The *encircled peaks* are maximum luminosity events. The *labeled arrows* (**c**) indicate selected images shown in Fig. 5

volume visible above the mound fluctuated significantly; it increased in proportion to the amount of suspended sediment (Fig. 5). The luminosity data for each image (Fig. 6a) were detrended and plotted for the 3-month (Fig. 6b) and 1-month photographic time-series. Results showed structured variability with distinct peaks of high luminosity. The luminosity time-series were analyzed for periodicity using Matlab software. Similar analysis was performed on the temperature data. The temperature record exhibited peaks at a 23.9-h (K1) period during both deployments, indicating tidal influences (Fig. 7a). Additional, higher-frequency tidal peaks were visible in the data from the year-long deployment. Although the turbulent events appeared to reoccur on a cyclic time scale, the power spectrum analysis showed no significant (>95% confidence) evidence of periodicity in the 3-month time-lapse record, and a great deal of random noise. When some of the high-frequency noise was smoothed out of the 1-month time-lapse record, a significant peak at the K1 period was revealed (Fig. 7b).

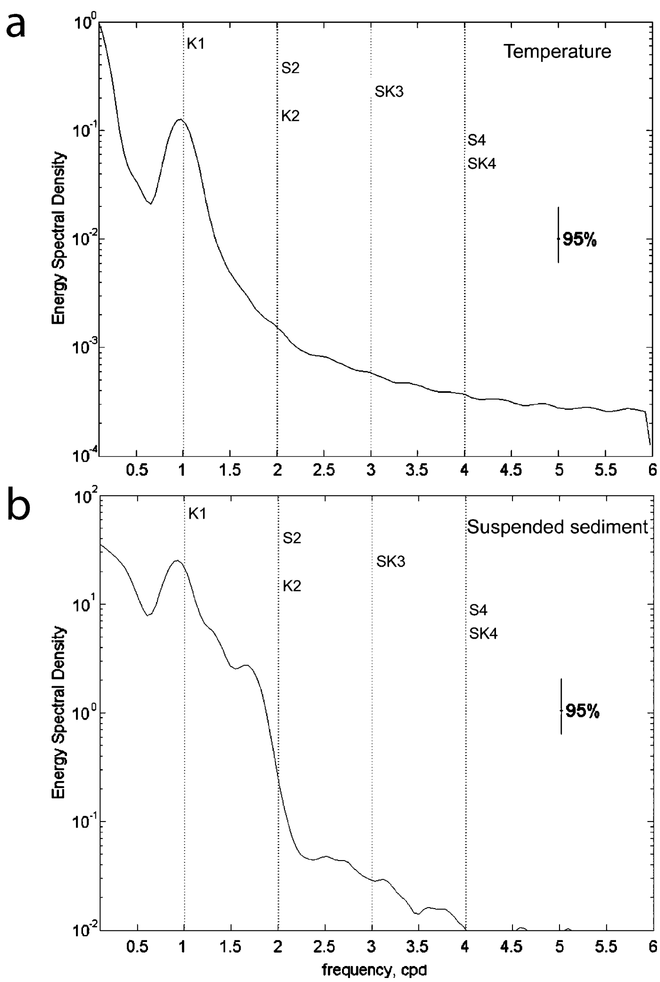

Fig. 7 **a, b** Power spectrum analyses of the temperature (**a**) and suspended sediment (**b**) data during the 1-month deployment period. These periodograms chart the frequency of temperature spikes and intense turbulent events at the Bush Hill site. A peak with significance greater than the 95% confidence interval is seen at the 23.9-h (K1) interval in both records, indicating some periodic tidal or inertial influence on sediment resuspension

There was a marked variability in the strength of these occurrences in both records. Some sediment resuspension events were more powerful than others, lifting greater amounts of material and exerting more visible changes on the gas hydrate outcrop environment. The most extreme turbulence lifted detritus as large as 0.5 cm in diameter into the water column, and almost completely obscured the camera's field of view, resulting in outlier luminosity values that were 2 standard deviations above the mean. Such events were generally of short duration, visible only in a single time-lapse frame, such as those on 24 July, 6, 8 and 14 August, 30 September and 1 October 2001, and on 12 and 26 June and 1 July 2002. However, some of the events of intermediate power lasted for longer intervals. These occurrences lifted only smaller sediment particles into the water column, and the luminosity values derived from the time-lapse images did not deviate as greatly from the mean. One period of intermediate sediment resuspension lasted 24 h from 10 to 11 September 2001, and another was maintained for 18 h from 18:00 on 26 June to 12:00 on 27 June 2002. None of the outlier events or longer-term occurrences correlated significantly with outliers or trends in the temperature data.

Discussion

Insulation by sediment and bacterial mats may delay gas hydrate disassociation but it does not indefinitely preserve a gas hydrate mound (MacDonald et al. 2003). The lack of change in the shape or size of the gas hydrate outcrop observed in this study, despite temperatures that exceeded the threshold necessary for dissociation of structure I hydrate by nearly 1°C, indicates a greater stability than previously described in laboratory studies and prior in situ observations (MacDonald et al. 1994). The irregular crevices that undercut the mounds, and the distribution of sediment on and around them, support the theory that outcroppings form beneath the sediment and push upward as they increase in size. The mound retains some of the sediment in the form of a thin "cap" that drapes over the gas hydrate. As the mound is pushed up from beneath by further gas hydrate formation, it begins to crack and is undercut by exposure to seawater. MacDonald et al. (1994) have proposed that the buoyancy of a large gas hydrate mass formed at the seafloor interface might cause it to detach and float upward and leave a pockmark on the seafloor. This putative process would potentially raft the constituent methane upward into the water column (Paull et al. 2003). Although a slope failure or other disturbance might well detach hydrate pieces, as Paull et al. (2003) have suggested, our time-series observations did not show that large, exposed masses will necessarily detach due to buoyancy alone. Indeed, the observations suggest destruction of hydrate deposits occurs as seawater penetrates the fissures formed as the mound breaches the seafloor, dissolving hydrate formally protected by sediment layers.

The large number and diversity of organisms observed at the mound, in the absence of any bait or other artificial inducement, indicates that gas hydrate provides a stable environment and possible food sources for deep-sea organisms. Previous results indicate that many benthic predators derive substantial amounts of nutrient carbon from seeps (MacAvoy et al. 2002). Our findings show that gas hydrate deposits can be a focus for biological activity, but that the activity has no obvious impact on their long-term persistence. Mat-like colonies of the bacteria *Beggiatoa* are ubiquitous at cold seeps (Nikolaus et al. 2003), and may be uplifted as the gas hydrate mound grows. Alternatively, they may grow on top of the sediment cap after the outcrop breaches the seafloor.

Temperature probes and current meters, in association with bubble-flux meters measuring expelled gas, have shown that as temperatures increase there is a corresponding increase in flow from existing bubble streams, and that upward temperature spikes are often associated with north/south currents (Roberts and Carney 1997). Although the thermal energy of these currents can have an impact on the stability of gas hydrate, the velocity and force of the currents are generally not sufficient to suspend sediment or alter seafloor features in a direct way. Deep currents in the Atlantic and Pacific oceans have been recorded at speeds of 50 cm s^{-1} and higher in marine canyons (Gardner 1989a; Gardner et al. 1984). There are also records of benthic storms that cause substantial amounts of turbulence and resuspension at the sediment/water interface, even at 4,000 m depth, possibly due to the pressure changes and mass transport associated with surface storm systems (Gardner and Sullivan 1981). During a previous study in 1997, a current meter mooring was deployed in 547 m of water at 27°46.95′N, 91°30.28′W, adjacent to the Bush Hill site (Guinasso 2002); two Oregon Environmental Inc. 9407 vector-averaging current meters were attached to the mooring, one 10 m above the bottom, the other 300 m above the bottom. They recorded a 10-min average segment every hour for 9 months. The results showed that currents were below 10 cm s^{-1} 93% of the time, and exhibited marked power spectrum peaks near 12 and 24 h (Fig. 8). Since the inertial period at this latitude is 25.7 h, the conclusion was that the daily peak could contain inertial as well as tidal signals.

When the shear stress exerted on the seafloor by bottom currents exceeds a critical value, determined on the basis of grain size, density, interstitial water, deposition history and bioturbation, resuspension can occur (Gardner 1989b). This work suggests that resuspension of fine silt and mud of the type found at hydrocarbon seeps could occur at velocities as low as 11–12 cm s^{-1}. If the organic detritus recently deposited by seep-dwelling organisms, and the flocculent material produced by certain *Beggiatoa* mats are taken into account, the critical velocity could drop as low as 7 cm s^{-1} (Lampitt 1985). Given these low thresholds, and the additional turbulence due to the topography of the gas hydrate outcrop, the current velocities recorded by the current meters adjacent to the site are strong enough to lift sediment into the water column. The rapid temperature

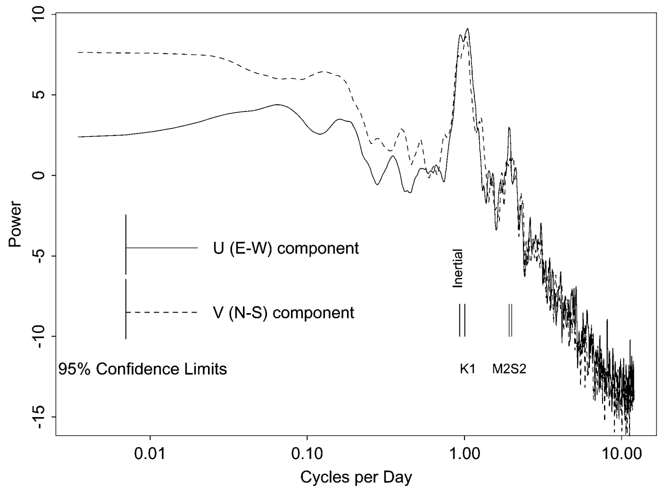

Fig. 8 A power spectrum analysis of cycles of water movement recorded by the lower current meter deployed in 547 m water depth adjacent to Bush Hill in 1997. Significant peaks were seen at the K1 (daily), and M2 and S2 tidal intervals, indicating a tidal component to the bottom currents. The similarity of the inertial current interval to the K1 tidal interval at this latitude means that the daily peak may include both signals (Guinasso 2002)

changes that accompany the tidal currents could also affect resuspension at the seep site. It has been suggested that the density inversion created when cold water rapidly moves over warmer pore water in the sediment could promote resuspension of overlying sediment through buoyancy effects (Gardner 1989a,b).

The frequency peak that occurs at the K1 interval in both sediment suspension and temperature records suggests that tidal or inertial currents are at least one driving force that promotes sediment resuspension at this site. Low-velocity currents could cause turbidity through acceleration due to local topography or strengthening by temperature inversions. However, there are many higher-frequency sediment resuspension events that do not correlate with tidal intervals. These could be explained by intermittent bursts of higher-velocity currents such as those recorded during 1997, which move at speeds of 10–20 cm s^{-1} and have sufficient power to suspend sediment and detritus. However, the highest levels of turbidity do not correlate significantly with any observed temperature maxima or minima that would suggest a major water movement event. Sediment can also be disturbed by gas hydrate decomposition or gas expulsion (De Beukelaer et al. 2003; Leifer and MacDonald 2003), but these would also be preceded by an increase in temperature, which was not present in the data.

Another possible explanation could be fluid or gas venting unrelated to gas hydrate decomposition, which occurs in the area around the gas hydrate outcrop. Previous studies of gas flux at the Bush Hill site (Roberts et al. 1999) have suggested that increases in gas flux from gas hydrate are correlated with temperature increases at a tidal frequency. However, the decomposition of gas hydrate as a result of minor, short-term changes in bottom water temperature has not been validated by more recent investigations of thermal conductivity in gas hydrate (MacDonald et al. 2005). Because sediment disturbance at seep sites has a number of potentially significant implications, further study is required to determine the nature and causative agents of the resuspension events at GC-185.

The frequent sediment resuspension during the observation period indicates that the thickness and local distribution of surface sediments are subject to continuous, and possibly rapid, change. Patches of exposed gas hydrate were often cleared of sediment cover following turbulent events, possibly increasing the rate of gas hydrate dissolution in those areas, and contributing to crevice formation and gas hydrate mound colonization. Sediment resuspension events appear to be a major feature of the benthos at this site. The sediment/water interface is a vital environment for many benthic species, and the location of most essential chemosynthetic and oxidation reactions. Disruption and reorganization of this interface could have substantial impact on the biochemical processes of the seep community. Sediment resuspension due to water movement could also increase the availability of food for filter feeders, transport the organic material produced by gas hydrate mound communities beyond the immediate vicinity of the seep, distribute bacterial cells from site to site, aid in the larval dispersal of seep organisms, and assist in the burial of tubeworm roots that is necessary for their sulfide uptake. The wide range of possible effects these turbulent events could exert on the biology and geology of the gas hydrate outcrop make them one of the most important environmental processes observed at this site.

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