Time series video analysis of bubble release processes at natural hydrocarbon seeps in the Northern Gulf of Mexico

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Abstract

This research quantifies the rate and volume of oil and gas released from two natural seep sites in the Gulf of Mexico: lease blocks GC600 (1200 m depth) and MC118 (850 m depth). Our objectives were to determine variability in release rates and bubble size at five individual vents and to investigate the effects of tidal fluctuations on bubble release. Observations with autonomous video cameras captured the formation of individual bubbles as they were released through partially exposed deposits of gas hydrate. Observations and image processing techniques determined bubble type (oily, gaseous, and mixed: oily and gaseous), size distribution, release rate, and temporal variations (observation intervals ranged from 3 h to 26 d). A semi-automatic bubble counting algorithm was developed to analyze bubble count and release rates from video data. This method is suitable for discrete vents with small bubble streams commonly seen at seeps and is adaptable to multiple *in situ* set-ups. Two vents at GC600 (Birthday Candles 1 and Birthday Candles 2) were analyzed. They released oily bubbles with an average diameter of 5.0 mm at a rate of 4.7 bubbles s^{-1} , and 1.3 bubbles s^{-1} , respectively. Approximately 1 km away, within the GC600 seep site, two more vents (Mega Plume 1 and Mega Plume 2) were analyzed. These vents released a mixture of oily and gaseous bubbles with an average diameter of 3.9 mm at a rate of 49 bubbles s^{-1} , and 81 bubbles s^{-1} , respectively. The fifth vent at MC118 (Rudyville) released gaseous bubbles with an average diameter of 3.0 mm at a rate of 127 bubbles s^{-1} . Pressure records at Mega Plume and Rudyville showed a diurnal tidal cycle (24.5h). Rudyville was the only vent that demonstrated any positive correlation ($p=0.60$) to the 24.5h diurnal tidal cycle. However, these observations were not conclusive regarding tidal effects on bubble release.

1. Introduction

The Gulf of Mexico (GoM) is a well-studied hydrocarbon province of economic significance and scientific importance. This region is a prolific oil producing basin resulting from abundant source rock (Kvenvolden and Cooper, 2003). It occurs on a tectonically passive margin, however, active salt dynamics (Peel et al., 1995) have modified the stratigraphy by extruding through the sedimentary layers creating ridges, knolls, and mini basins (Brun and Fort, 2011) (Fig. 1 A). Salt diapirs serve as trapping structures that hold oil and gas in a reservoir, and also fracture sediments to create conduits for the migration of oil and gas to the sea floor characterized by natural seeps (Planckaert, 2005).

Natural seeps are characteristic features in the GoM where oil and gas are released from reservoirs to the water column in discrete zones (Garcia-Pineda et al., 2010; MacDonald et al., 2015). Hydrocarbon seepage alters the physical, geophysical, and geochemical properties of sediments creating broad distributions of hard grounds such as gas hydrate outcrops and authigenic carbonate mounds (De Beukelaer et al., 2003; Roberts and Aharon, 1994). These hard grounds are associated with a variety of chemosynthetic fauna such as tube worms and mussels (MacDonald, 2004; Sassen et al., 1994).

In this study, bubble release is referred to as focused seepage; that is, active and visible bubble ebullition. Focused seepage comprises a subset of features within a geologic seep zone that can be detected in satellite and hydroacoustic data. Synthetic Aperture Radar (SAR) images show persistent layers of oil (oil slicks) on the ocean surface (Garcia-Pineda et al., 2010; MacDonald et al., 2015), and oil and gas bubbles in the water column are detected by echo sounders that generate distinctive plume shaped features known as flares (Fig. 1 B) (De Beukelaer et al., 2003; Greinert et al., 2006; Klauke et al., 2005; Merewether et al., 1985). Both oil slicks and flares can be traced to their approximate points of origin at the sea floor where oil and gas vent. Focused seepage occurs from distinct vents that are often

associated with authigenic carbonate pavements (Roberts et al., 2010a), shallow gas hydrate deposits and chemosynthetic communities (Sassen et al., 1999).

Detecting and analyzing hydrocarbon release from natural seeps has been studied across the globe and can help quantify the input of methane from the deep sea into the global carbon budget (Kvenvolden, 1993, 2002; MacDonald et al., 2015; Maslin and Thomas, 2003). To date, investigators have estimated the size distribution, behavior, and fate of gaseous bubbles based on measurements taken during short snapshots in time, i.e. seconds to minutes of video footage (Grant and Whiticar, 2002; Greinert et al., 2010; Leifer, 2010; Leifer and MacDonald, 2003; Römer et al., 2012; Römer et al., 2014; Sahling et al., 2009; Sahling et al., 2014; Valentine et al., 2001). State of the art camera systems have also been developed to capture high definition video for accurate bubble size and velocity quantification (Bian et al., 2013; Thomanek et al., 2010; Wang and Socolofsky, 2015). We argue, however, that longer term deployments (days to months) using autonomous camera systems are necessary to capture important processes such as temporal and spatial variability, biological effects, and observational changes in oil and gas content of bubbles.

Detailed time series analysis of gas seepage has shown that there is evident temporal variability in bubble release (Bayrakci et al., 2014; Boles et al., 2001; Leifer and Boles, 2005; Römer et al., 2016; Schneider von Deimling et al., 2011). In these studies, seeps were acoustically monitored (Bayrakci et al., 2014; Römer et al., 2016; Schneider von Deimling et al., 2011), or experiments were conducted at relatively shallow areas (approximately 20 m – 75 m) (Boles et al., 2001; Leifer and Boles, 2005). The camera system introduced in this study is the first of its kind to capture long term *in-situ* video data of gaseous and oily bubbles released in the deep sea environment (850 m -1200 m).

We address the temporal and spatial variability of bubble release with video collection extending from 3 h to 26 days using an autonomous video time lapse camera (VTLC). The VTLC was deployed in the

Northern GoM at five individual vents for varying periods of time (Table 1), and a robust image processing technique adaptable to diverse deep sea environments was created to quantify bubble release rates. The VTLC was carefully positioned and left on the seafloor to capture bubble exit points and surrounding hydrate outcrops to extend our understanding of the fine scale processes of bubble formation/composition and benthic activity at individual vents.

Our primary objectives were to determine bubble size and release rates and to examine the effects of oil content. Bubble size is influenced by the vent and plume size, diameter of the pore opening, and surfactants coating the bubble (e.g. oil content) (Leifer, 2010). Additionally, external factors such as reservoir fill or hydrostatic pressure on the seafloor can also have an effect on bubble release rates (Hovland et al., 1993; Judd and Hovland, 2007; Torres et al., 2004). Therefore, our secondary objectives were to examine temporal variability in bubble releases and ascertain possible causes such as tidal variation or physical changes to the vents. Our results address the dynamics controlling the complex, natural seep systems in the GoM by describing the fine-scale bubble points and quantifying bubble emission from distinct vents.

2. Study Site

This study was conducted at seep zones located in the ~5x5 km lease blocks Green Canyon 600 (GC600) and Mississippi Canyon 118 (MC118), as designated by the U.S. Bureau of Ocean Energy Management (Fig. 1A). GC600 is an oil producing area that is about 1200 m deep, where prolific oil slicks are chronically visible on the ocean surface (Garcia-Pineda et al., 2010). This area has become an important test bed for research at natural seeps (D'souza et al., 2016; Garcia-Pineda et al., 2010; Roberts et al., 2010b; Wang and Socolofsky, 2015; Wang et al., 2016). We focused on four individual vents at GC600 referred to as Birthday Candles 1, Birthday Candles 2, Mega Plume 1, and Mega Plume 2. The Mega Plume and Birthday Candles areas are separated by approximately 1 km, situated on a salt-supported

ridge trending in a NW-SE direction (Fig. 1B). Two faults that lead to the ridge likely serve as migration pathways for the oil and gas (Roberts et al., 2010b). Mega Plume 1 and 2 are active vents positioned at the NW end of the ridge that expel a mixture of oily and gaseous bubbles. Birthday Candles 1 and 2 are located SE of the Mega Plume vents and characterized by prominent gas hydrate mounds and oily bubble release. Both localities host gas hydrate accumulations that breach the seafloor at the vent sites.

The MC118 site is shallower than GC600, with a water depth of approximately 850 m. The Rudyville vent is found in a small depression at MC118 and released predominantly gaseous bubbles at rapid rates. Oil slicks are infrequently visible at the surface; however, persistent gas seepage is confirmed by repeated mapping of vent activity combining bathymetric and seismic data (Lutken and Welch, 2013; Macelloni et al., 2013; Simonetti et al., 2013; Wilson et al., 2014). This area is underlain by deposits of gas hydrate within fault zones (Dunbar, 2012). Active gas venting with thick bacterial mats and chemosynthetic fauna occurs in association with shallow gas hydrate deposits at both sites (Lapham et al., 2008).

3. Methods

3.1. Camera properties

For the first deployment at Birthday Candles 1, a compact camera (pixel resolution: 640x480, capturing 1 frame every 4 seconds) was used to take pictures of the hydrate outcrop and the associated bubble release. The camera was encased in an aluminum housing mounted on a triangular aluminum frame and held a 12V battery that powered both the front facing LED light and camera (Fig. 2A).

For subsequent deployments at Birthday Candles 2, Mega Plume 1 and 2, and Rudyville, we utilized the newly designed VTLC mounted on a high density polyethylene (HDPE) frame (Fig. 2B-D). The Aquapix VTLC records HD video with a Replay Video XD 1080® mini camera in an anodized aluminum pressure housing (pixel resolution: 1080x1920, field of view: 120° at 29 frames per second). The housing also

contains a 24V lithium battery that can power the camera and a front facing 2400 lumens lamp. The HDPE frame can be adjusted by submersible manipulators to aim the camera towards the bubble emission points. The autonomous VTLC was programmed before deployment to record video clips at fixed sampling frequencies (Table 1), and video data was stored on a 32 GB sd card. A temperature and pressure logger (RbRDuo®) was also attached to the frame to measure background environmental conditions during deployments at Mega Plume and Rudyville (Fig. 2B-E). Once the camera was deployed, no additional communication with the VTLC occurred, and it ran autonomously for the pre-programmed time (Table 1).

3.2. Camera deployments

Birthday Candles 1 site was visited with the *R/V Atlantis* (expedition AT18-2) in November 2010. At this site, oily bubbles were observed escaping from an exposed portion of gas hydrate that was approximately 8 cm x 15 cm. The autonomous camera was deployed on November 26, 2010 with *DSV Alvin* (dive 4655) and positioned approximately 11 cm from the vent for 3.5 h, capturing a still frame image every 4 s (Fig. 2A). Birthday Candles 2 site was visited with *R/V Nautilus* (expedition NA043) on July 2, 2014. For this deployment, we mounted the VTLC on a lander equipped with a benthic acoustic release (2B). The VTLC was deployed and positioned using *ROV Hercules* approximately 35 cm from the vent and programmed to capture 8 seconds of video per hour. Due to benthic release failure we retrieved the camera one year later (June 23, 2015) with the *R/V Pelican* and unfortunately only 5 days of bubble release were recovered.

The Mega Plume site was visited in November 2012 with the *R/V Falkor* (expedition F006B). Approximately 1 km NW of Birthday Candles, a composite of flares in the water column was located with the ship's swath mapping system (Kongsberg EM 302 Multibeam Echosounder). For Mega Plume 1 we deployed the VTLC next to a hydrate outcrop at that measured 11 cm x 4 cm on November 14, 2012

with the *ROV Global Explorer* (dive 04) (Fig. 2C). The VTLC was positioned approximately 40 cm from the vent and was deployed for 48 h, during which 15 s video clips were taken every 5 min (Table 1). For Mega Plume 2, we re-visited this site in March 2014 with the *R/V Pelican* (expedition PE14-14) and *ROV Global Explorer* (dive 01) to deploy the VTLC for 26 days (March 9 to April 4, 2014). The VTLC recorded 10 s video clips every 30 min, and was positioned approximately 50 cm from the bubble release points (Fig. 2D). This VTLC was recovered with the *DSV Alvin* (dive 4690) aboard the *R/V Atlantis* (expedition AT26-13).

Finally, the Rudyville site was visited with the *E/V Nautilus* (expedition NA028) in June 2013. The VTLC was positioned about 45 cm away from this vent with the *ROV Hercules* (dive H1261) on June 24, 2013 (Fig. 2E). For this deployment we mounted the VTLC on a lander equipped with a benthic acoustic release, similar to the one used for Birthday Candles 2. The lander was retrieved with the *ROV Global Explorer* (dive 5) on the *R/V Pelican* (expedition PE14-14) on March 12, 2014. The VTLC was programmed to record 10 s video clips every hour, however, we only recorded 5 days of data (June 26 to July 1, 2013) due to equipment failure.

3.3. Measuring bubble size

The images captured by each camera showed bubbles in a two-dimensional plane imaged at less than 50 cm from the camera's lens (Table 1). A significant level of accuracy was forfeited due to parallax, *in-situ* camera positioning, and timing (e.g. limited ROV bottom time). Additionally, we were only able to obtain bubble size measurements from Birthday Candles 1, Mega Plume 1, and Rudyville. At Birthday Candles 2 and Mega Plume 2 we did not have a known reference measurement (i.e. measuring stick in field of view or in line with bubbles) to convert pixels to mm. At Birthday Candles 1 we used measurements obtained from the *DSV ALVIN* video for scale calibration of bubble size measurements (Fig. 2A). At Mega Plume 1 and Rudyville, we were able to determine the pixel-to-mm conversion by inserting a graduated

measuring stick into the bubble stream (Fig. 2C) or placing the measuring stick in line with the bubble stream (Fig. 2E).

The pixel-to-mm conversion was adjusted separately for each data set, and after converting pixels to mm ImageJ® was used to estimate bubble dimensions by measuring their major and minor axes. To decrease error, bubble sizes were measured approximately 6 cm above the bubble emission points in multiple images. The smallest measurable bubble was ~1mm. For Birthday Candles 1, 971 bubbles were measured from the 231 images analyzed. For Mega Plume 1, a total of 1766 bubbles were measured from 176 images analyzed. Finally, for Rudyville, 1002 bubbles were measured from 80 analyzed images.

To obtain volume measurements, we estimated the radius of a sphere by calculating the major and minor axes of a spheroidal bubble following Sam et al. (1996):

$$r = \sqrt[3]{\frac{(a^2b)}{8}} \quad (1)$$

where a is the semi-major axis, b is the semi-minor axis, and r is the radius of a spheroid bubble. From each bubble we estimated r in equation 1, and calculated the volume of the sphere (bubble) ($V=4/3\pi r^3$) (Table 1). Although natural gas can contain higher hydrocarbons, we assumed a gas composition of 100% CH₄ in our calculations. In the northern GoM, concentrations of higher hydrocarbons typically account for less than 10% of gas, by volume (Bernard et al., 1976; Brooks et al., 1974; Kvenvolden, 1995). Based on this assumption, we determined the amount, n , of gas within this volume V , using equation (2) that corrects for the compressibility factor of methane at the given depth and pressure:

$$PV = nRTZ \quad (2)$$

where P is the absolute pressure in MPa, V is the volume of the bubble in cm³, R is the universal gas constant equal to 8.314 cm³*MPa*mol⁻¹*K⁻¹, T is the temperature of the water in K, and Z is the

compressibility factor of CH_4 which was calculated using van der Waals equation of state based on the given pressure and temperature ($Z=0.73$ at Birthday Candles and Mega Plume and $Z=0.79$ Rudyville). Water temperatures averaged at 4.5°C (S.D. 0.02) at GC600 and 5.6°C (S.D. 0.07) at MC118.

The rise speed of bubbles can be affected by various hydrodynamic properties. These include bubble size, natural bubble oscillation, currents, and rate of emission, upwelling effects, and the bubble interface mobility, i.e. “dirty” vs. “clean” bubbles (Grant and Whiticar, 2002; Leifer, 2010; Leifer and Judd, 2002). In addition, pressure change, bubble oscillation and gas exchange can cause bubble size to increase after leaving the origin point (Greene and Wilson, 2012). Therefore, to minimize discrepancies, we measured bubble sizes approximately 6 cm above the release points. Furthermore to minimize additional error in bubble counts, the bubble release rates were determined independent of bubble size.

3.4. Semi-automatic bubble counting algorithm

A semi-automatic bubble counting algorithm (SABCA) was developed to analyze bubble count and release rates from the video data. For each deployment, we sampled the bubble flow by recording a sequence of video clips at set intervals (e.g. 10 s video every h) (Table 1). Prior to running the automated bubble counting algorithm, the data must be manually prepared and certain variables defined through the following steps: 1) digitize the video clips to still frame images; 2) determine the optimal position of a cropped window within the frame for bubble counting (white box Fig. 3A); 3) within the cropped window, specify the counting region (horizontal lines in Fig. 3B,C,D); 4) estimate the rising speed and height of bubbles, measured in pixels, within this counting region; 5) assign appropriate thresholds. These variables must be adjusted and cross-checked throughout the data set to ensure consistency prior to running the automated bubble counting procedure.

Digitizing the video clips to still frame images provides analysis of multiple images that make up a clip (e.g. 10 second clip at 29 frames per second has 290 still frames). To determine a time series of the

entire deployment time (e.g. 5 days) we averaged the bubble release from each still frame, resulting in one value per clip. For example in the case of Rudyville, we sampled a 10 second clip every hour for 5 days (Table 1), the result showed a time series of one value per hour for 5 days; and in the case of Mega Plume 2, we sampled a 15 second video clip every 30 min for 26 day^s (Table 1), resulting in a time series with a data point every 30 min for 26 days.

The cropped window varies between sites and is determined based on the optimal area for counting bubbles within the video frame from each camera deployment. This adaptation is what makes this method viable under various *in-situ* conditions. The cropped window remains the same for deployment as long as the camera does not move. Once the cropped window is determined, the counting region is assigned. The counting region defines the horizontal line or lines over which the algorithm will count the bubbles (e.g. white lines 3E). We include multiple lines (e.g. 1-60 lines in pixels) to minimize error caused by overlapping bubbles, bubbles exiting the frame, and shadows. The approximate bubble pixel height and rising bubble speed is used to determine how fast bubbles move through the counting region. We assume a constant rise speed for all bubbles within one dataset. These values must be cross-checked for consistency over multiple images within the dataset to determine the interval between images analyzed by the automated algorithm. A properly chosen interval between images ensures that a completely new set of bubbles is analyzed between consecutive images (e.g Fig. 3B-C). This is especially important for slower rising bubbles (e.g. Birthday Candles 2) to avoid double-counting or oversampling bubble counts between consecutive frames. Our data set sampled at 29 frames per second, which was sufficient to include faster moving bubbles without under sampling (e.g. Mega Plume 1 and 2, and Rudyville).

Finally, the cropped window is converted to grey scale and corresponding pixel values of consecutive images were subtracted to remove the unchanging background (e.g. sediments, gas hydrate, bacterial mats, and water column). The resulting image delineates the change between frames (i.e. bubble

movement) as bright spots (Fig. 3D). The intensity of bubble spots in the processed image varied for multiple reasons: 1) bubble size, 2) motion blurring, and 3) oil content or shadows that caused contrast differences. Larger bubbles had less distinct edges than small bubbles and motion blurring occurred when the video was digitized to separate frames. Therefore, to qualify the bubble counts and de-noise the data, three thresholds were defined based on the pixel value of bright spots: high, medium, and low (Fig. 3E). The values for the thresholds were adjusted manually for each separate site, and depending on the lighting in the videos once consecutive images have been subtracted. This created a range of thresholds from strict (high) to less strict (low) to adjust for any brightness variations and noise (Fig. 3F).

Once each manual step was appropriately addressed the automated bubble counting algorithm (eq. 3) could be run:

$$B = \left[\sum_{r=1}^R (\sum_{i=1}^I {}_t c_{ri}) \right] \times F / (R \times I) \quad (3)$$

where B is the average bubbles per second for the given video clip at threshold t , R is the number of horizontal pixel lines in the counting region, I is the number of frames, ${}_t c_{ri}$ is the bubble count on line r of image i , for threshold t , and F is the number of frames per second. (The full Matlab© code for SABCA is publically available on GRIIDC doi: 10.7266/N7M906N3). To test accuracy of the algorithm, sub sections of the data were manually counted and compared to automated results. The manual cross check was conducted on 2 second excerpts of 20 randomly selected video clips spanning the deployment time, resulting in a total of 1180 images analyzed per deployment.

3.5. Extrapolation

To calculate the annual release in mol yr^{-1} we used the release rates derived from equation 3 and the amount of gas per bubble (mol) (Table 1). These values are based solely on the gas constant at depth; therefore extrapolating annual amounts of CH_4 is most reliable for the gaseous-type vent (Rudyville). At

the mixed-type vents (Mega Plume 1 and 2) we must assume a significant error when extrapolating annual CH_4 values because a mixture of both oil and gas were released simultaneously. Extrapolating annual CH_4 amounts was not applicable at the oily-type vent (Birthday Candles1 and 2). In terms of total carbon release, rendering methane flow in mol values is an underestimation since higher hydrocarbons are not considered.

Table 1 also includes a range for mass flow of pure gas and pure oil in T yr^{-1} from each vent. These values are based on the density of pure CH_4 as a function of temperature and pressure for the low end, and the density of oil (600 kg m^{-3} in accordance with Smith et al. (2014) Table B.2 analyzing a vent at similar depth $\sim 1070 \text{ m}$) for the high end of the range. We are only able to report the range between pure oil and pure gas since we currently do not have accurate estimates of the percentages of oil to gas ratios.

4. Results

We analyzed VTLC HD video datasets for five distinctive vents at three different sites (Table 1). Each vent consisted of a small cluster of pore openings from which bubbles escaped (Fig. 4). These pore openings were sometimes modified with chimney-like tubes of gas hydrate that would increase in length before breaking free. Our video footage confirmed that the individual pore openings were persistent on a daily to monthly scale. However, the bubble release rates from the pore openings varied in activity (bubbling or not bubbling) over a time-scale of hours. Of the vents studied, we found that gaseous bubbles had smaller diameters and more rapid release rates. Conversely, oilier bubbles had larger diameters, and slower release rates.

4.1. Vent characteristics

At Birthday Candles 1 and 2, dark brown oily bubbles were slowly released from tubes at the edges of gas hydrate mounds (Fig. 4A-B). We classified Birthday Candles 1 and 2 as an oily-type vents (Fig. 5). Mega Plume 1 and 2 vents consisted of a mixture of oily bubbles and gaseous bubbles released from small tubes in hydrates cropping out from the sediments (Fig. 4C-D). Over the deployment period, the bubbles varied between an oily, brown appearance to a gassy and clear aspect. These bubble types were sometimes released simultaneously and also individually (e.g. only gassy bubbles). Therefore, we classified this vent as a mixed-type vent (mixture of oil and gas) (Fig. 5). Rudyville consisted of a row of small release tubes that protruded from the hydrate outcrop (Fig. 4E). These bubbles were all gassy (clear in color); we classified this as a gas-dominated vent (Fig. 5). No oil was observed escaping from Rudyville during the 5 days of video observation.

After surveying a prospective deployment area with the ROV, the VTLC would be positioned to incorporate an active bubble stream. In all cases, bubble release was restricted to the local areas where pore openings were visible in the gas hydrate outcrop. However, at the more active vents such as Mega Plume 1 and 2 and Rudyville, the pressure of the ROV landing would temporarily induce a stronger bubble flow that would continue for several hours after the ROV had departed from the deployment site. Additionally, transient bubble streams would sometimes appear in the area surrounding the targeted vent. Of particular interest was an intense burst of gas bubbles observed at Mega Plume 2. This gas blowout occurred only once during the entire deployment and lasted approximately 2 h (white oval in Fig. 4D). Bubble counting analysis was applied to the main gas hydrate outcrops where bubble release persisted for the duration of the deployment.

Localized chemosynthetic fauna (tubeworms, mussels, and clams) were common in the seep areas around the vents. Mobile fauna observed at each vent included Provanidae, demersal fish (*Dicrolene kanazawai*), deep-sea eels (*Synaphobranchus* spp.), red crabs (*Chaceon* spp.), shrimp (*Alvinocaris* spp.),

gastropods (Pleurotomariidae), and bivalves (Vesicomyidae). Fish and crabs were seen interacting with the bubble streams. Fluctuations in bacterial mat coverage of the surrounding sediments were also apparent over the deployment times. At Birthday Candles and Mega Plume sites, there were large numbers of the polychaete *Hesiocaeca methanicola* (ice worms) burrowing within the gas hydrate and overlying sediments. Within a 100 cm² area of hydrate outcropping, we typically observed 5-10 ice worms in a given video clip. Their behavior included browsing the exposed surfaces and moving into and out of their burrows, which often extended several cm into the gas hydrate mass. Considering the extensive gas hydrate occurrences in this area of the Northern GoM, we posit that the total number of ice-worms to be quite large. Their bioturbation of the overlying sediments and active excavation of gas hydrate material is potentially a significant factor in the long-term stability of shallow gas hydrates.

4.2. Bubble measurements and rates

Bubble size distribution is shown in Fig. 6, and average bubble diameter is plotted with the standard deviation in Fig. 7. Bubble sizes were compared to the size of the two primary vents studied by Wang et al. (2016), which they designated Sleeping Dragon (Lat: 28° 51.1421 N, Long: 88° 29.5109 W) and Confetti (Lat: 27° 22.1954 N, Long: 90° 34.2624 W). Sleeping Dragon was a vent located near Rudyville, and Confetti was arguably the same vent as Mega Plume 1 based on vent descriptions in Wang et al. (2016) and Wang (personal communication). Fig. 7 shows our measurements for each vent including the high resolution measurements of Wang et al. (2016) for comparison.

To determine bubble release rates, three different thresholds were considered in order to address noise. The general trend was that the looser thresholds had a larger standard deviation because of increased noise (e.g. magenta contour in Fig. 3). With the manual bubble count cross check, we concluded that bubble release in the strict and medium thresholds were the most reliable (Fig. 8). In Table 1 we report the values of the medium threshold.

The volume and gas amount (moles) was calculated separately for each bubble size measurement and then averaged for more accurate results. For the mass flux we used the density of methane gas based on temperature and pressure (Birthday Candles: 109 kg m^{-3} , Mega Plume: 110 kg m^{-3} , Rudyville: 71.3 kg m^{-3}), and the density of oil (600 kg m^{-3} , derived from Smith et al. (2014) Table B2). By calculating the mass flux rate of CH_4 and oil, we provided a range of hydrocarbon flow from gaseous to oily (Table 1).

Considering the release rates of Birthday Candles 1 and 2 (Table 1) we conclude that these larger, oily bubbles (Fig. 6, 7) were released at relatively slow rates (Fig. 8A-B). At Mega Plume 1 and 2, the release rates were significantly faster than at Birthday Candles (Fig. 8C-D). The average bubble size was also smaller at this mixed-type vent (Fig. 6, 7). These sites are separated by 1km and presumably the bubble emission mechanisms and migration pathways are similar (Roberts et al., 2010b). Therefore, we conclude that oily bubble size was larger and released at slower rates at these two sites. Rudyville may have different migration pathways and emission mechanisms than Birthday Candles and Mega Plume, yet it is interesting to note that at Rudyville the bubbles were smaller (Fig. 6, 7), contained no oil and released at faster rates (Fig. 8E).

4.3. Pressure differential and bubble release

A second objective of this study was to investigate variations in bubble release rates over intervals of several days and to test whether it conforms to tidal pressure cycles. Generally the release rates showed continuous high-frequency variability within a min-max range of 5 bubbles per second at Birthday Candles 2, 71 bubbles per second at Mega Plume 1, 173 bubbles per second at Mega Plume 2, and 172 bubbles per second at Rudyville. The Mega Plume sites also displayed gradual, low frequency trends (Fig. 9). Periodic variation was only readily apparent at Rudyville (Fig. 9D). Synoptic pressure records were only available for Birthday Candles 2, Mega Plume 1, Mega Plume 2, and Rudyville. To test the correlation between tidal pressure and bubble release rates, the data were divided into four groups: low

slack tide, rising tide, high slack tide, and falling tide. A Pearson's Correlation test was then used to compare bubble rates among these groups. For the deployments at Birthday Candles 2, and Mega Plume 1 and 2, the Pearson's test indicated no positive correlation between bubble release rates and pressure. However, at Rudyville there was a weak positive correlation with the rising and falling tide ($p=0.48$ and $p=0.60$, respectively). This correlation weakened with falling pressure (Fig. 9D). Generally bubble release rates did not depict a strong trend of increasing or decreasing bubble release over time, but portrayed small fluctuations.

The range between maximum and minimum pressure was 0.3 dbar at Birthday Candles 2 (over 5 days), 0.8 dbar at Mega Plume 1 (over 2 days), 3.7 dbar at Mega Plume 2 (over 26 days), and 0.6 dbar at Rudyville (over 5 days). Because the pressure changes in these areas were small and correlation with tidal periods was only detected at Rudyville general conclusions regarding periodicity in release rates are not supported. Other factors such as sediment loading, migration pathways, hydrate formation, permeability, and porosity may have influenced observed variation in ebullition rates (Kannberg et al., 2013; Leifer and Boles, 2005; Liu and Flemings, 2009).

5. Discussion

This study is the first attempt of long term camera deployment at individual vents in the deep sea. To achieve *in-situ*, long-term deployments, the VTLC has reduced precision in measurements compared to lab set ups and ROV-dependent systems in order to increase battery endurance, data capacity, and camera autonomy. The VTLCs were deployed close to gas hydrate outcrops to observe individual pore openings from which the bubbles were released, multi-day changes in the environment (e.g. bubble bursts and "pop up" streams), and behavior of various benthic organisms (e.g. bacterial mat coverage, and ice-worm activity). The method presented in this paper is limited to discreet vents where small

bubble streams are escaping, which is commonly seen at natural seep sites. However, it would not be appropriate for large fields of bubble release.

Long-term seepage observation provides a more exact determination of the variability of bubble release compared to short snapshots in time, which may miss transient events or disturbance effects resulting from the presence of a submersible. For example, bubble emissions were prone to short-lived increases in rate and oil content when the ROV contacted the bottom and a transient vent appeared during the Mega Plume 2 deployment (white oval in Fig. 4D). If release rates were extrapolated from these observations alone, we would have quite different understanding of bubble flow rates in the GoM. In the context of the 26 days, we can confirm that this site consists of oily and gaseous bubble release (mixed-type vent). Additionally, the biological components of the seep zone react to the ROV when it sits on the sea floor. During the 26 day deployment, white bacterial mats were not visible until approximately 3 days after disturbance caused by the ROV, and they did not reach the thick coverage seen in Fig. 4D until approximately 5 days after initial deployment. Finally, long-term deployment allows us to analyze possible effects of tidal pressure changes. These factors combined can set the stage for continuous research regarding the processes that affect hydrocarbon migration.

5.1. Considerations for long-term deployment

As Leifer et al. (2003) discuss, there is often a sacrifice when moving from a controlled set up in the lab to the field (i.e. power being a limiting factor at sea compared to camera set up in the lab). Additional challenges are met when moving from ROV-dependent camera and lighting systems to autonomous systems. Even though more elaborate ROV-dependent camera systems have been used to observe bubbles with higher frame rates, modelled illumination, and smaller lens apertures (Bian et al., 2013; Leifer et al., 2003; Thomanek et al., 2010; Wang and Socolofsky, 2015; Wang et al., 2016); our results were well within the range that these more elaborate methods measured. For example our bubble size

measurements at Mega Plume 1 and Rudyville were comparable (average and standard deviation) to multiple measurements by Wang et al. (2016) who used a ROV dependent high-speed stereoscopic imaging system at approximately the same locations (Wang and Socolofsky, 2015) (Fig. 7).

Furthermore, the SABCA counts bubbles independent of size and was developed to accommodate *in-situ* positioning of the camera for long term video acquisition. It is adaptable to a variety of settings and does not require a uniform background to facilitate edge detection (Thomanek et al., 2010). This makes our method more versatile for *in-situ* camera deployments where carefully staged set-ups and high-intensity lighting are difficult to achieve.

We assigned three different threshold values: strict, medium, and loose to address the inherent noise in the data. Noise can be caused by shadows, motion blur, and movement caused by small organisms or any other movements that are not bubbles. Due to the versatility of the *in situ* set up, we have to be able to address these challenges in order to avoid missing small bubbles (loose threshold) and simultaneously cutting out noise (strict threshold). Assigning thresholds gives a range of possible release rates with a general trend of increasing standard deviation with a looser threshold becomes looser, where more noise is picked up (Fig. 8). With a manual cross check we confirmed that the strict and medium thresholds are more reliable than the loose threshold. Table 1 and Fig. 9 present the results of bubble release using the medium threshold.

Under-sampling could be an issue for the VTLC if the bubble speeds are extremely fast. In our data sets we were able to manually confirm that the 29 per second frame rate of the VTLC was in fact able to accurately track bubbles through the frame (fastest bubble release rates analyzed in this study was 127 bubbles per second, Table 1). Increasing the camera's frame rate would be something to consider for future adaptations of the VTLC. The issue of over-sampling bubbles is explained in the methods section during the set up for the SABCA. In cases of slow moving bubbles (e.g. Birthday Candles 2), frame

intervals are assigned in order to avoid double counting bubbles. For example the SABCA algorithm will read in every four frames as opposed to every frame, in order to avoid double counting bubbles.

5.2. Temporal variation of bubble size and release

We did not observe any significant variation among bubble sizes during the deployment intervals. Bubble size ranges fell within a normal distribution (Fig. 6). We compared bubble sizes and rates between the vents (Birthday Candles 1 and 2, Mega Plume 1 and 2, and Rudyville), and concluded that oily bubbles tended to be larger and moved at slower speeds. Although there may be other factors affecting bubble size and speed such as vent and orifice size (Leifer and MacDonald, 2003), our observations confirmed differences in bubble motion based on whether the bubbles are *clean* (gaseous) or *dirty* (covered by oil or other surfactants) (Leifer, 2010).

Previous studies have shown that tidal pressure fluctuations influence the flow rate of CH₄ gas because hydrostatic pressures affect the underlying geological structures (Krabbenhoeft et al., 2010; Netzeband et al., 2010). In general these findings found decreased bubble flow at high tide, and increased bubble flow at low tide (Bayrakci et al., 2014; Boles et al., 2001; Leifer and Boles, 2005; Liu and Flemings, 2009; Schneider von Deimling et al., 2010). In our study, Rudyville was the only vent where we were able to detect a positive correlation between bubble release and pressure change, developing a lag of ± 6 hours as neap tide approached (Fig. 9D). This may be explained by the fact that Rudyville was the shallowest of the vents studied (850 m) and therefore more sensitive to pressure differences due to larger tidal fluctuations relative to the water depth. The relative lack of oily components in the bubbles might also be a factor making the release rates more sensitive to pressure variation. However, in contrast to previous findings, we observed increased flow at high tide, and decreased flow at low tide. In general, the correlation of tides and bubble release were inconsistent among the different vents analyzed and no firm conclusion can be stated based on our dataset.

On a larger scale, bubble release is affected by the presence of gas hydrate, pressurization of oil and gas in reservoirs, and differential loading of sedimentary layers (Clayton and Hay, 1994; Leifer and Boles, 2005). The GoM has high sedimentation rates and is strongly influenced by salt tectonic activity (Roberts et al., 2010b). Our study sites are located in the gas hydrate stability zone, which results in large gas hydrate accretion near the seafloor due to continuous migration of hydrocarbons (Torres et al., 2004). As we have demonstrated in our video data, and confirmed with site reconnaissance, the individual pores in bubble vents generally pass through gas hydrate outcrops. This implies that gas hydrate is porous enough to allow bubble flow through the crystalline microstructures, as has been found in previous studies (Klapp et al., 2010). Gas hydrate outcroppings will affect the local compressibility of the seafloor and might alter the ebullition mechanisms.

Hydrate mounds form when a continuous flux of hydrocarbons thickens local areas of gas hydrate (e.g. Fig. 2B), causing it to breach the sediments (Römer et al., 2014). As the gas hydrate thickens it becomes a more substantial barrier, eventually forcing oil and gas to find alternative pathways, which explains why bubbles tend to escape from the sides of mounds (Lapham et al., 2014). This system has been described by Römer et al. (2012) in the Black Sea and is observed at Birthday Candles 2 and other seep sites in the GoM, such as Bush Hill (MacDonald et al., 1994).

5.3. Bubble flow rate comparisons

Our estimated annual flow rate of gas and oil are comparable to those of other studies that measured mass flow from individual vents in the GoM, but used different methods for bubble quantification. Wang et al. (2016) determined average bubble rates at Sleeping Dragon (MC118) to be 105-158 $\text{m}^3 \text{yr}^{-1}$ (compared to our 188 $\text{m}^3 \text{yr}^{-1}$ at Rudyville, Table 1) and at Confetti (GC600) an average bubble rate of 79-121 $\text{m}^3 \text{yr}^{-1}$ (compared to our 62-101 $\text{m}^3 \text{yr}^{-1}$ at Mega Plume 1 and 2, Table 1).

Variation in bubble venting can be best explained by migration pathways (Leifer and Boles, 2005) and by mechanisms that sequester or block the release of hydrocarbons into the water column (Klapp et al., 2010). We posit that the accumulation of gas hydrate is a major factor in the sequestration of hydrocarbons, as is consumption by biogeochemical processes. Additionally, we cannot ignore the diffusive flow into the water column that cannot be captured with the VTLC. Finally, we caution against extrapolating information from release rates of individual vents to the entire GoM, especially based on short data sets. As we have demonstrated with our multi-day video data, there is significant variability of bubble release and bubble characteristics at individual vents. In order to estimate total flow rates in the GoM, we would need to analyze multiple vents within different seep zones, and detailed hydroacoustic surveys over larger areas would be necessary to resolve the number of vents in a seep zone.

6. Conclusion

We developed a reproducible and adaptable image processing method to quantify bubble release rates in various deep-sea environments and estimated bubble size and flow rates. By collecting high definition video footage over extended periods of time (3 h -26 d), we can account for temporal variability of bubble composition and release rates.

VTLC's were deployed at five individual vents; four at GC600 and one at MC118. We conclude that in areas where more oil is present, the bubble size is larger and bubble speed is slower (Table 2). This is attributed to various factors including pressure, migration pathways in the sediments, and gas hydrate mounds. There is high variability in the activity of seeps, and the vents studied have been classified into three types: oily, mixed, and gaseous. We consider these classifications to cover the range of typical vent types found in the GoM.

With extended video deployments, we defined a bubble size distribution and quantified a range of bubble release rates. This paper is the start of an intensive study focusing on the dynamics of natural

hydrocarbon seeps and the geophysical processes that take place during the release of oil and gas bubbles from the sediments into the water column.

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Tables and Figures

Table 1: VTLC deployment location, date, and autonomous settings and measurements. Annual release in $\text{m}^3 \text{yr}^{-1}$ is at depth. Areas where we did not have sufficient data is indicated with (--). Gas amount for Birthday Candles 1 and 2 is not applicable (oily type vent). Annual mass flow is based on values for pure gas and pure oil indicating the range.

*Annual mass for Birthday Candles 2 is based on sizes from Birthday Candles 1.

** Annual mass flow for Mega Plume 2 is based on sizes from Mega Plume 1.

Release rate (bubbles s ⁻¹)	Avg. bubble diameter (mm)	Bubble volume at depth (mm ³)	Gas amount per bubble (mol)	Annual release (mol yr ⁻¹)	Annual release (m ³ yr ⁻¹)	Annual mass flow (T yr ⁻¹)
4.68 (std. 0.315)	4.96 (std. 1.300)	78.4 (std. 77.01)	n/a	n/a	10.8	<i>gas - oil</i> 1.12 - 6.48
1.28 (std. 1.002)	--	--	n/a	n/a	2.62*	<i>gas - oil</i> 0.29 - 1.57*
49.1 (std. 12.43)	3.87 (std. 1.187)	40.2 (std. 49.49)	2.91 x 10 ⁻⁴ (std. 3.584 x 10 ⁻⁴)	4.50E+05	62.2	<i>gas - oil</i> 6.84 - 37.3
81.1 (std. 28.54)	--	--	--	--	101**	<i>gas - oil</i> 11.3 - 61.3**
127.3 (std. 34.00)	3.01 (std. 1.994)	46.8 (std. 155.7)	2.18 x 10 ⁻⁴ (std. 7.245 x 10 ⁻⁴)	8.73E+05	188	<i>gas - oil</i> 13.4 - 113

Site	Vent	Depth (m)	Latitude	Longitude	Deployment date	Sampling frequency	Data range	VTLC distance from seep (cm)	Vent type
GC600	<i>Birthday Candles 1</i>	1215	27° 21.858 N	90° 33.822 W	26. Nov 10	1 frame/s	3.5 h	11	oily
GC600	<i>Birthday Candles 2</i>	1200	27° 22.853 N	90° 33.736 W	02. Jul 14	8 s video/h	5 d	35	oily
GC600	<i>Mega Plume 1</i>	1222	27° 22.204 N	90° 34.256 W	14. Nov 12	15 s video/ 5 min	2 d	40	mixed
GC600	<i>Mega Plume 2</i>	1222	27° 22.206 N	90° 34.254 W	9. Mar 2014	10 s video/ 30 min	26 d	45	mixed
MC118	<i>Rudyville</i>	850	28° 51.136 N	88° 29.531 W	24. Jun 13	10 s video/h	5 d	50	gaseous

Fig. 1: A: Study sites MC118 (850 m deep) and GC600 (1200 m deep), separated by 260 km. Contour line spacing: 10 m. Rudyville vent is located at MC118. Birthday Candles 1 and 2 and Mega Plume 1 and 2 are located at GC600. B: shows 3D rendering of sea floor and hydroacoustic signature of bubble plumes in the water column at GC600. The hydroacoustic data was collected on the R/V Falkor (expedition F006B). Mega Plume (b) is located to the NW and Birthday Candles (a) approximately 1 km to the SE.

Fig 2. Camera positioned in front of vents. **A** Birthday Candles 1 at GC600, 3.5 hr deployment. **B** Birthday Candles 2 at GC600, 5 day deployment. **C** Mega Plume 1 at GC600, 2 day deployment. **D** Mega Plume 2 at GC600, 26 day deployment. **E** Rudyville at MC118, 5 day deployment. **B** and **E** cameras are attached to benthic released landers.

Fig. 3: Schematic depicting the image processing method. **A** Original image from which a cropped window is determined and converted to gray scale. Cropped window is subtracted from the consecutive image (**B** – **C**) to negate constant background and identify bubbles (shown here as bright spots **D**). Three thresholds (high, medium, and low) are assigned to the bubbles to account for bubble size, motion blurring, and oil content, (**E** – **F**). Bubbles are counted and sub-sampled in the counting region (60 pixels in this example). Bubble count for each pixel line (1-60) is summed across every frame in a clip, and then total line counts are averaged to generate three values of bubble release at each threshold (high, medium, low) for one clip. This sequence is repeated for each clip to create a time series of bubble release for the entire deployment time.

Fig. 4: Frame grabs of individual vents investigated in this study. **A** Birthday Candles 1 at GC600. Frame grab from the camera where dark oily bubbles escape from a gas hydrate out crop. **B** Birthday Candles 2 at GC600. Frame grab from the VTLC showing release of dark oily bubbles escaping from a gas hydrate out crop at the edge of a hydrate mound. Pink ice worms (*Hesiocaeca methanicola*) can be seen nestled in the brown gas hydrate. **C** Mega Plume 1 at GC600, VTLC frame grab. Bubbles escaping from gas hydrate out crop. **D** Mega Plume 2 at GC600. Oil stained gas hydrate is visible around the vent, and white mats on surrounding sediments expanded and retracted during deployment. White oval indicates an area where acute, episodic gas explosions would occur, lasting approximately 2 h. Bubble stream in the foreground was used for analysis. **E** Rudyville at MC118. Frame grab from this deployment shows bubbles are clear and gaseous escaping from small tubes of gas hydrate. Fish in the foreground was observed grazing on the bacteria mats that surround the vent.

Fig. 5: Vent classifications. Close up of bubbles depicting the difference between gaseous, mixed, and oily vent type.

Fig. 6: Bubble size distribution. Individual bubble size distribution of the three different classes of vents (oily, mixed, and gaseous). Smooth kernel distribution was used to fit the histogram, where n is the number of bubbles measured. Inset depicts a visual of the bubble size distribution in line with the measuring stick. Measuring stick shows ticks every 1 cm.

Fig. 7: Bubble size average plotted with standard deviation and compared to results from Wang et al. (2016) at the same sites.

Fig. 8: Average bubble release rates and standard error for each site considering the different thresholds (strict, medium, loose) and manual cross check count. **A:** Birthday Candles 1, **B:** Birthday Candles 2, **C:** Mega Plume 1, **D:** Mega Plume 2, **E:** Rudyville.

Fig. 9: Time series of bubble release rates compared to pressure changes. Time series of bubble release plots the variation based on the medium threshold in Fig. 8. **A** Birthday Candles 2, **B** Mega Plume 1, **C** Mega Plume 2, **D** Rudyville.