Pulsed oil discharge from a mud volcano

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ABSTRACT

In this paper we document instances where change in the magnitude of natural oil seepage coincided with fluctuations of fluid temperature in a seafloor mud volcano. Oil slicks were detected floating near commercial oil fields in the northern Gulf of Mexico in a time series of six satellite synthetic aperture radar (SAR) images collected over a 10 month interval. The oil escaped naturally from a complex of fluid expulsion features at seafloor depths of about 600 m. One of these features was a 50-m-wide, mud- and brine-filled crater. Temperature in the crater fluctuated rapidly during an interval of ~1 yr (minimum 6.1 °C, maximum 48.3 °C, mean 26.1 °C, standard deviation 9.07). The areas of the oil slicks in the SAR images fluctuated repeatedly between <10 and >1000 ha. The largest oil slicks detected by SAR occurred along with the fastest increase in fluid temperature.

Keywords: hydrocarbon seep, eruption, fluid migration, diatreme, Gulf of Mexico.

INTRODUCTION

The theoretical rate for natural oil seepage into the oceans is 1.6×10^6 bbl/yr (Kvenvolden and Harbaugh, 1983), which indicates that global reserves of 1.5×10^{12} bbl (Masters et al., 1998) are sustained by a continual replenishment of oil reservoirs over geologic time (Macgregor, 1993; Miller, 1992). Newer, direct measurements of marine oil seeps, which use remote sensing (MacDonald et al., 1993; Mitchell et al., 1999) and acoustic survey (Quigley et al., 1999), suggest that previous estimates of the global seepage rate were too low. However, these investigations extrapolate from discrete measurements and might fail to detect oil that was released in brief pulses. Although many seeps are continual over observed time scales (Hornafius et al., 1999; MacDonald et al., 1993), we can now document abrupt changes in hydrocarbon seepage from a seafloor source with the analysis of satellite synthetic aperture radar (SAR) images of the sea surface and fluid temperatures from the seafloor. Episodic release of oil and gas from mud volcanoes represents a largely undetected process in the carbon cycle.

Undersea mud volcanoes are conspicuous examples of focused flow in sedimentary settings (Carson and Screaton, 1998) and have been associated with high thermal gradients (Henry et al., 1996), shallow gas hydrates (Ginsburg et al., 1999), and high-molecular-weight hydrocarbons (Roberts and Carney, 1997). However, direct data from the eruption of an undersea mud volcano are lacking. Satellite SAR readily detects layers of floating oil that form over active seeps (Espedal and Wahl, 1999), providing a means to survey the numbers of hydrocarbon seeps across oil-producing regions (Kornacki et al., 1994) and to estimate the rates at which seeps are flowing (MacDonald et al., 1993). Comparison of SAR images collected in the Gulf of Mexico (Fig. 1, left), under equivalent sea-surface conditions, shows that there can be large differences in the amount of oil seepage over short time lags (Fig. 2). These changes are too great to be attributed to weather-related phenomena. Seafloor measurements from a mud volcano explain how large, short-term differences in seepage can occur.

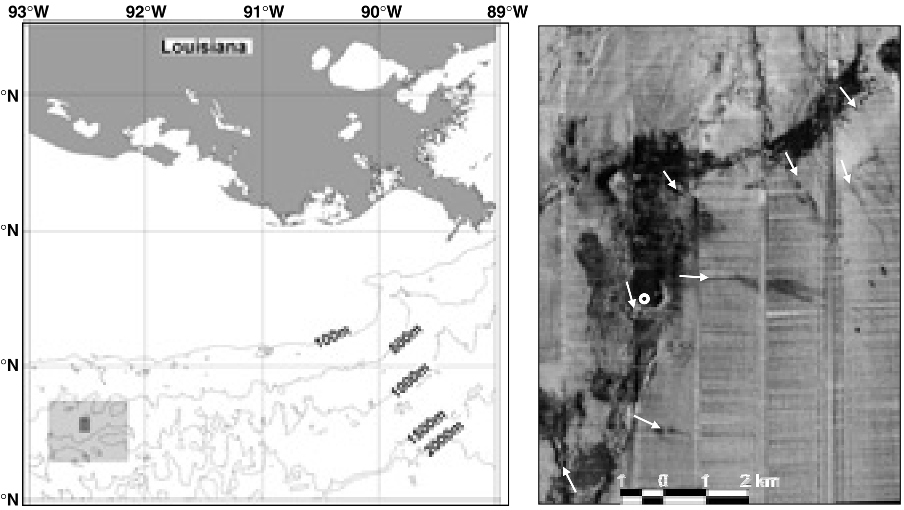
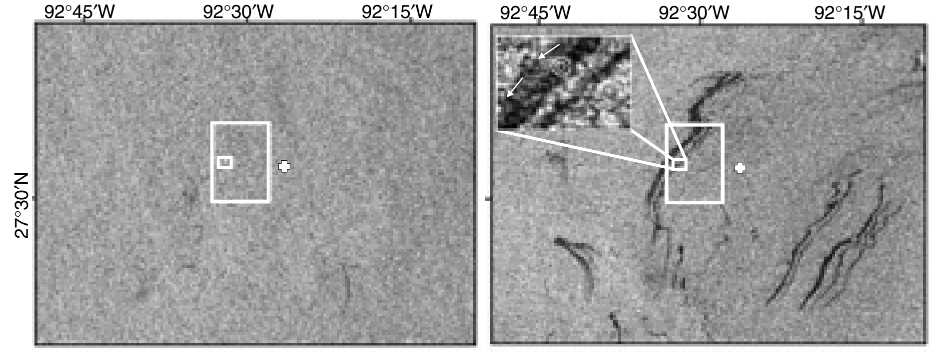


Figure 1. Study region is located on continental slope south of Louisiana, United States (left). Light gray box shows area covered in regional synthetic aperture radar (SAR) images (Fig. 2); dark gray indicates coverage of sidescan sonar mosaic and of SAR subscenes (Fig. 4). Mosaic of 75 kHz sidescan sonar tracks (left) shows acoustic texture of western Auger basin. Production facilities for Auger oil field are centered about 6 km to east. Salt wall and fault system border basin to west and northwest. Migration of fluid along flanks of this salt unit provides natural release of pressures accumulated within basin. Seafloor mounds, mud flows (arrows), and slump scars indicate dynamic material fluxes at numerous points along fault. Submarine dives were conducted at small, active diatreme on southern margin of flat-topped mound located mid-way along fault (bullseye).

Geology; October 2000; v. 28; no. 10; p. 907–910; 4 figures.



29 June 1997

6 August 1997

Figure 2. Partial synthetic aperture radar (SAR) images collected by RADARSAT compare size of natural oil slicks on July 29 (left) and August 11, 1997 (right), over oil-producing region of continental slope south of Louisiana (Fig. 1, left). Outlines in both images indicate area overlying Auger basin fault (Fig. 1, right) that was analyzed in detailed studies of slick area (Fig. 4) and show location of mud volcano. Inset shows fresh oil surfacing (arrows) close to seafloor location of mud volcano (bullseye). Plus symbol indicates location of Shell Auger Production Platform, a prominent radar target.

SETTING

The mud volcano we studied is located at the edge of Auger basin, an intraslope basin that contains economically significant hydrocarbons in the Auger, Cardamom, and Macaroni fields, Gulf of Mexico. Potential hydrocarbon traps in the Auger field are sealed against the upthrown side of faults along a paleoridge that rises to the east and northeast of the basin, thus enabling hydrocarbon accumulation and commercial production (Shew et al., 1993). In the western part of Auger basin, the potential hydrocarbon strata are pierced by downthrown faults along the flanks of tabular salt bodies (McGee et al., 1993). Geophysical records (e.g., Fig. 1, right) show that these faults have provided conduits for abundant fluid migration. Sediment samples from this zone have recovered high-molecular-weight hydrocarbons and thermogenic gas hydrate.

Previous work identified a steep-sided and flat-topped mound about 0.7 × 1.0 km, its summit at a depth of 570 m (Sager et al., 1999). It is located midway along the seep-affected region of Auger basin (Fig. 1, right). Active fluid expulsion has created a 50-m-wide, subcircular mud lake on the southwestern edge of the summit; it is one of two such expulsion features on the mound. Fine, fluidized mud emanates from a central diatreme, overflows the western margin of the lake, and moves down the southern flank of the mound. The mud is fluidized in hypersaline brine (133 practical salinity units) that is supersaturated with methane at standard temperature and pressure. Beds of the seep mussel *Bathymodiolus childressi* rim the southern edge of the diatreme. These mussels harbor methantotrophic symbionts and flourish at the edges of methane-saturated brine pools (MacDonald et al., 1990).

MATERIALS AND METHODS

The SAR images we analyzed, obtained from RADARSAT, have the following reference numbers and acquisition dates: COO115630 wide 1 (May 19, 1997), 8374-1219180 wide 1 (June 5, 1997), MO120437 wide (June 29, 1997), M0193062 SN1 (August 6, 1997), M0192826 wide 1 (November 27, 1997), C0014225 wide 1 (February 24, 1998).

Wind speeds in surface areas shown in the SAR images were in the range of 2–7 m/s (Enfotec Technical Services, 1999). Surface current speeds were in the range 0.1–0.3 m/s, as estimated from satellite altimetry (Colorado Center for Astrodynamics Research, 1999). Natural layers of floating oil—so called oil slicks—are distinguished from biogenic surfactants by having a few broad and parallel bands, which have distinct termini and many of which describe acute-angle curves as floating oil drifts with wind and current (Espedal and Wahl, 1999; MacDonald et al., 1993).

Because the SAR images covered a region much larger than Auger basin, a subscene measuring 13.1 × 18.7 km was defined by outlining the boundaries of the fault system shown in Figure 1 (right). Areas of floating oil were quantified by filtering the SAR data to the approximate decibel range of identified slicks and supervising the resulting classification to eliminate possible weather phenomena.

The thermistor array was suspended below a float anchored on a short tether. It recorded a reading every 20 min. Predeployment and postdeployment calibrations were compared to remove drift in the upper temperature range. The anchor was attached to a 75 × 75 cm plate to prevent it from sinking in the soft mud of the diatreme bottom. The well log from OCSG 7483 #1 borehole in Garden Banks 379 was accessed at the Minerals Management Service (1999) Web site.

RESULTS

The mud lake was sampled with use of submarine *Johnson Sea-Link* on July 29, 1997 and July 11, 1998. The fluid degassed violently when the sealed collection chamber was opened on the surface, indicating that gases were supersaturated with respect to sea-level temperature and pressure. The gas that evolved was >99% CH_4. Solvent extractions of sediments suspended in the brine contained high-molecular-weight hydrocarbons, as did sediments collected in short cores. Exposed deposits of gas hydrate were observed around a gas vent that was located about 200 m west of the lake.

Visual observations indicated that gas and oil discharges were minor in 1997 and the feature appeared less active than had been previously noted (Sager et al., 1999). In 1998, however, a continual stream of small gas bubbles and drops of oil emanated from the central diatreme, while bursts of larger bubbles, oil drops, and suspended sediment periodically escaped from the surrounding mud. In 1997, a thermistor was suspended 30 cm below the interface at a position about 15 m west of the apparent vent. When the thermistor was recovered in 1998, the apparent level of mud in the pool, as measured by its height on the mooring tether, had risen by 50 cm.

Changes in characteristics of pooled fluid over the ~1 yr interval demonstrate increased flow. On both occasions, a temperature profile was recorded by lowering a conductivity, temperature, and depth (CTD) measuring device into the fluid. The 1997 profile penetrated only 0.7 m into the muddy fluid (Fig. 3). In 1998, however, active venting pointed the way to a deeper part of the lake and the CTD device was lowered 3.2 m below the interface (Fig. 3). In both profiles, abrupt increases in conductivity demarcated an interface of ~1 cm between the fluid mud and overlying seawater. In 1997, convective cooling across this interface produced the monotonic 2.7 °C decrease in temperature between the pool bottom and the interface. In 1998, a subsurface maximum temperature of 26.7 °C 34 cm below the interface and the apparent rise in the level of mud in the pool provided evidence for discharge of warm mud that spread in a surficial layer and evidently flowed downslope from the mud-lake outlet.

Available time-series data from the 1997–1998 period comprised six SAR images and the records from the thermistor (Fig. 4). Three of the SAR images were collected in May and June 1997, prior to deployment of the thermistor; three were concurrent with the deployment. The area of oil slicks overlying the fault zone repeatedly underwent order of magnitude changes between the May 1997 and February 1998 observations (Fig 4, middle). During the 349 day thermistor deployment, fluid temperatures varied between 6.1 and 48.3 °C with a mean of 26.1 °C and standard deviation of 9.07 (Fig. 4, lower).

Some fresh oil can be seen in SAR images near the location of the diatreme (Fig. 2, inset). Lateral offsets of ~1000 m are typically seen between a seafloor vent and the location where rising oil reaches the sea surface (MacDonald et al., 1996).

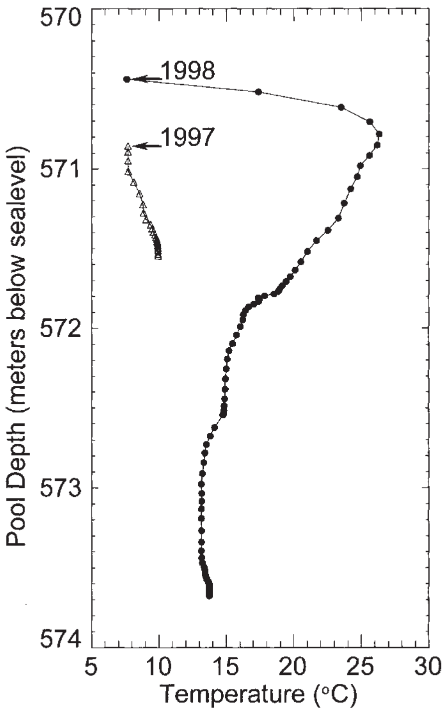


Figure 3. Temperature profiles from points where oil and gas venting was most evident on July 27, 1997 (triangles), and July 11, 1998 (solid circles), respectively. Depths of interface (arrows) were determined from conductivity response of conductivity, temperature, and depth (CTD) measuring device and comparison of pictures that showed change in height of mud on thermistor mooring tether.

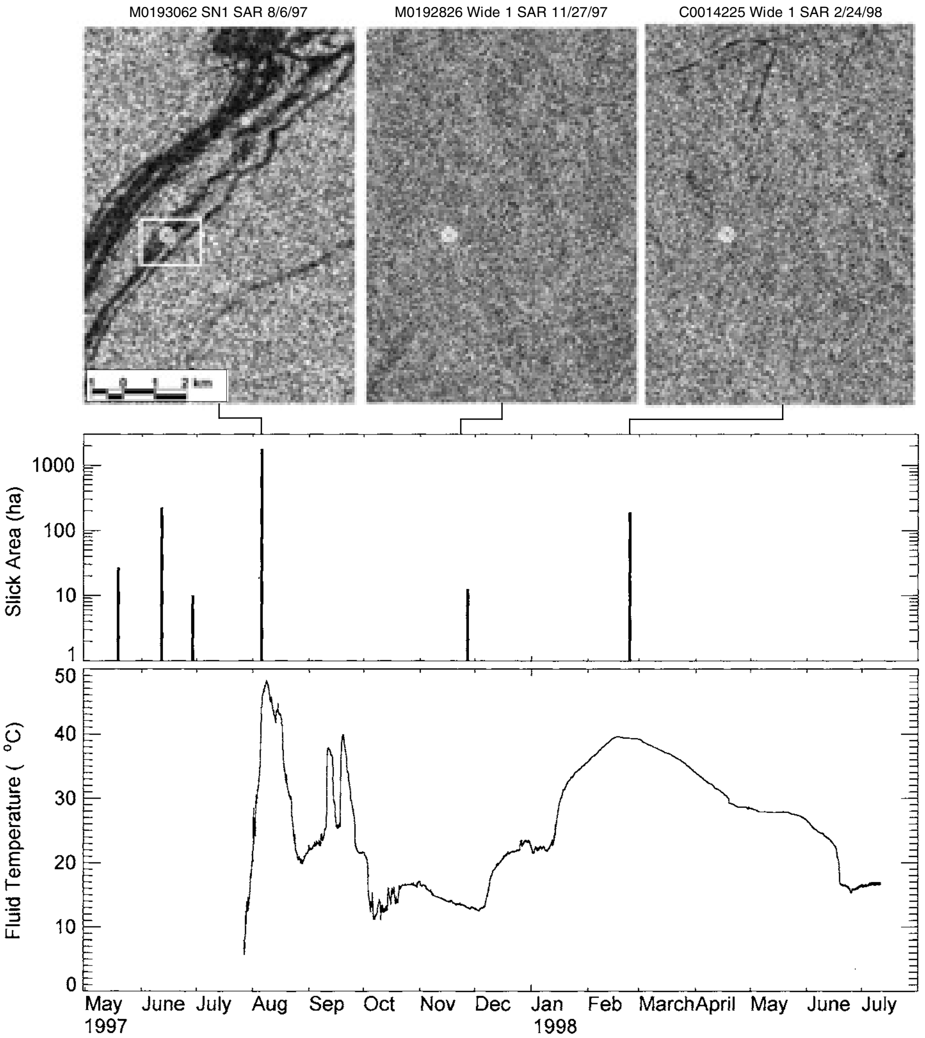


Figure 4. Three subscenes of synthetic aperture radar (SAR) data reproduced to show, from left to right, large-, small-, and medium-size oil slicks (upper). Time series of areas covered by oil slicks are detected in available SAR data (middle). Slick areas were compiled for 18.7 by 13.1 km region overlying Auger basin fault zone (Fig. 1). Temperature time series from fluid in diatreme was recorded between July 27, 1997, and July 11, 1998 (lower).

In addition, because the analyzed portions of the SAR images covered a much wider area than the vent, only a portion of the oil slicks that were detected could have originated from this specific source. Acoustic anomalies on the seafloor indicate active mud volcanism in a zone along the basin-bounding normal faults. We believe that additional surface oil slicks came from other seepage points along this zone. Temperature data confirm pulsed flow at a point source within the zone. SAR data indicate that these flows were part of a regional pattern of discharge.

DISCUSSION

Previous studies of mud volcano systems have identified pulsed flow in sealed boreholes based on temperature increases of at most 4 °C over periods of months (Carson and Screaton, 1998). The extreme, rapidly fluctuating temperatures of pooled fluids reported here and the coincidence of large oil slicks demonstrate energetic flow from considerable subbottom depth. Vertical transfer of geothermal heat is intensified in the presence of subbottom halite (McBride et al., 1998), so the rate of increase in subbottom temperature is likely to be greater in the vicinity of the salt unit bounding the Auger basin. The temperature in a bore hole, located ~8 km northwest of the mound over shallow salt, reached 48 °C at 2309 m subbottom. This suggests that fluids we recorded with temperatures of 48 °C would have leaked from at least this depth in the diatreme.

There are at least two published mechanisms of pulsed fluid flow, but neither is supported by the present data. Seafloor temperature anomalies recorded in diatremes have been ascribed to shallow convection within mud-filled chambers, perhaps driven by dissociation of gas hydrates (Henry et al., 1996). Gas hydrate cannot act as a forcing mechanism in this diatreme because, at pressures of ~5–20 MPa, the high temperature and salinity of the fluid would prevent gas hydrate from forming. Some evidence suggests that earthquakes stimulate the activity of hydrocarbon seeps (Macgregor, 1993); however, there is no record of seismic activity in this region during 1997–1998. We speculate that pulsed flows in this setting result when ongoing filling of hydrocarbon traps in the western Auger basin induces the failure of the permeable seals in the fault zone, thereby injecting gas, oil, brine, and mud into surface strata and the ocean.

Previous remote sensing surveys have depended on repeated detection of floating oil to confirm flowing seeps (Kornacki et al., 1994; MacDonald et al., 1993, 1996; Mitchell et al., 1999). This criterion would have overlooked seeps like the one described here. Our results suggest that the time dependence of seepage rates should be considered when remote sensing results are used for evaluating the hydrocarbon potential of a new basin or extrapolating to estimate a regional seepage rate. Such studies are needed to constrain the balance of hydrocarbon generation, entrapment, and natural seepage into the biosphere.

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