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Harnessing a decade of data to inform future decisions: Insights into the ongoing hydrocarbon release at Taylor Energy's Mississippi Canyon Block 20 (MC20) site

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ABSTRACT

The release of oil and gas at Mississippi Canyon Block 20 into the Gulf of Mexico has vexed response officials since 2004 when a regional seafloor failure toppled the Taylor Energy Company platform. Despite the completion of nine intervention wells, releases continue from the seafloor, mostly captured by a recently installed containment system. Toward informing resolution, this work applies chemical forensic and statistical analyses to surface sheens, sediments, and reservoir oil samples. Our results indicate sheens are chemically heterogeneous, contain remnant synthetic hydrocarbons likely discharged from well interventions prior to 2012, and require mixing of multiple chemically-distinct oil groups to explain observed variability in diagnostic ratios. Given the respite and opportunity afforded by containment we suggest leveraging ongoing collection activities to assess release dynamics, as well as engaging the National Academies of Science, Engineering, and Medicine, to evaluate potential solutions, associated risks, and to consider policy ramifications.

1. Introduction

The response to the 2004 toppling and partial burial of Taylor Energy Company's (TEC) MC20 platform is the longest and most complex in history (see Table S1 for a timeline of select response activities). Installed in 1984 at Mississippi Canyon Block 20 in the Northern Gulf of Mexico (Fig. 1), the MC20 platform ultimately hosted 28 wells accessing 19 reservoirs with a total daily production potential (as determined by well production tests) of approximately 190 m^3 of oil, 1500 m^3 of reservoir water, and 1.7×10^8 m^3 of natural gas (normalized to STP) preceding Hurricane *Ivan* in September 2004. Of the 28 wells, 14 were producing oil in 2004, three were producing only gas, and 11 were indefinitely shut-in or otherwise plugged for lack of production (two of which were gas-only wells). Of the 14 wells actively producing oil, 13 relied on enhanced recovery through gas lift to produce at the potential rates given above, and one produced based on its own flow. Reported production reservoir temperatures and water salinities ranged from 57 to 82.2 °C and 40–93 parts per thousand, respectively. Gas and freshwater sources were also reported for strata above these production reservoirs with intrusion of gas into well casings observed during the time of drilling and active production.

In anticipation of Hurricane *Ivan*, TEC shut-in all wells and safely evacuated all personnel. On September 15, 2004 as Ivan passed (Category 4–5; 30-meter high waves) (Fig. 1), a regional seafloor-failure originating upslope of the production platform caused it to topple and become partially buried. While there were no direct observations of this event, sediment failures have been estimated to generate velocity flows of up to 20 m s^{-1} at the seafloor and deposit thick layers of sediment (Paull et al., 2013; Paull et al., 2018). During this event the platform (comprised of a jacket, deck, and 28 well conductors; Fig. 1) moved ~170 m downslope before toppling intact on/in the newly created seafloor at a water depth of approximately 140 m. Massive stresses

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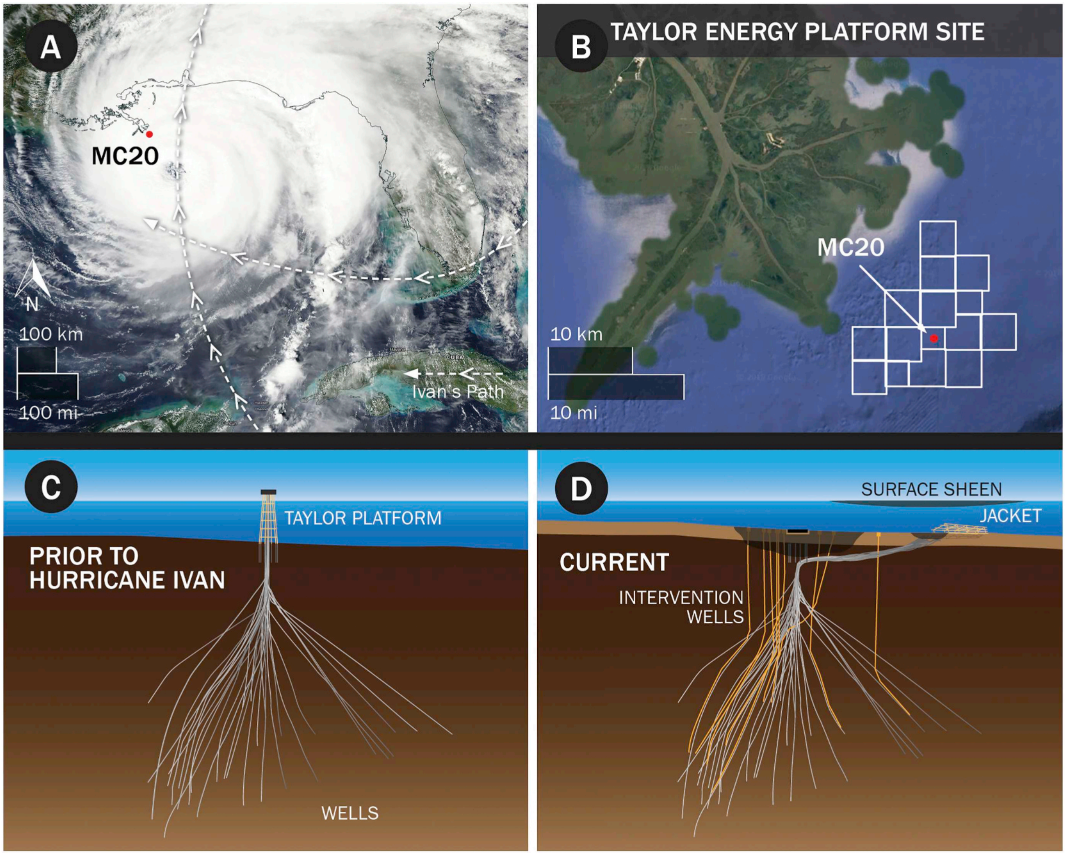

Fig. 1. (A) Satellite image of Hurricane *Ivan* and the MC20 site, showing the track of the hurricane and how it turned back into the Gulf of Mexico after making landfall. (B) Location of MC20 relative to the Mississippi River Delta and adjacent lease blocks. (C) Schematic of the TEC site preceding regional slope failure and toppling. (D) Schematic showing intervention wells, the new unconsolidated sediment in light brown (note the difference in sediments between panels C and D), and hydrocarbon-laden sediments above the bend in the conductors, along the path of damaged conductor pipes, and adjacent to the downed platform at the likely terminus of the conductors. Not shown is a containment system installed in 2019 that is attached to the jacket above the conductor termini. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

generated by the jacket's movement caused the well conductors to displace laterally at considerable depth below the original mudline while rapidly bending, deforming, and rupturing well conductors. During the toppling the tensile stresses severed the well heads, causing the conductors to detach from the deck. These conductors became buried in newly emplaced sediment, with termini believed to be near the toppled jacked (Fig. 1; herein referred to as the conductor termini area). Sediment probing indicated that the conductors were buried under sediments to a depth of ~50 m below the seafloor at the former platform area trending upwards to a depth of ~20 m near the toppled jacket (Fugro, 2005).

Major features at the MC20 site include the toppled jacket protruding above the seafloor, three large bathymetric depressions, and numerous small pockmarks (Fig. 2). The largest depression is the result of mechanical excavation created during unsuccessful attempts to access vertical sections of well conductors below the former platform for conventional plug and abandonment in 2005. A second depression at the southwest corner of the toppled jacket is due to excavation and removal of the platform deck in 2011. A third depression, located at the northeast corner of the jacket, measures ~50 m in diameter and 6-m in depth and is thought to represent the terminus of the 28 well conductors that once linked the platform to the subsurface reservoirs. Within this third depression, two areas of active gas and/or oil release from the sediments serve as the predominant source of the ongoing release (SSLWG, 2017). These two areas correspond with the locations of containment Domes C and D that were emplaced in 2009 based on hydrocarbon-survey results (Camilli, 2008). No elevated temperature or salinities associated with release of reservoir fluids (e.g., brines) have ever been reported at this location. Two multiphase plumes (gas, oil, and brine) were observed with elevated temperatures (> 43 °C) from other seafloor locations within the former platform area prior to drilling of intervention wells in 2009 (Camilli, 2008). These two plumes ceased upon completion of the first and fourth intervention wells.

Sediment within the top 1.3 m of the bathymetric depression at the conductor termini area contains oil up to 16% by mass. However, sediment borings and sub-bottom profiling of the site indicates that the former platform area potentially contains the largest volume (diameter ~150 m, depth of ≥25 m) of hydrocarbon-laden sediments, including pockets of oil to depths in excess of 30 m (Fugro, 2007). Elevated levels of hydrocarbons were also observed (Camilli, 2008) along the path of the buried conductors from the former platform area to their termini near the fallen jacket (Fig. 1D). These observations highlight the occurrence of casing failures along the conductors, which extend to at least 30 m below the seafloor, creating multiple potential flow conduits within the sediments.

The day after Hurricane *Ivan* passed, TEC conducted an aerial survey and reported the MC20 platform as missing to authorities and began mitigation and decommission activities that continue to this day. Since 2007, activities have been conducted under a formal Unified Command Response structure led by the United States Coast Guard (USCG), with long-term regulatory authority for decommissioning resting with the Department of Interior's former Minerals Management Service (now the Bureau of Safety and Environmental Enforcement; BSEE). Response and decommissioning activities, although often impeded by complex site conditions (e.g. debris, buried infrastructure, chaotic current regimes, poor site visibility, unconsolidated sediments,

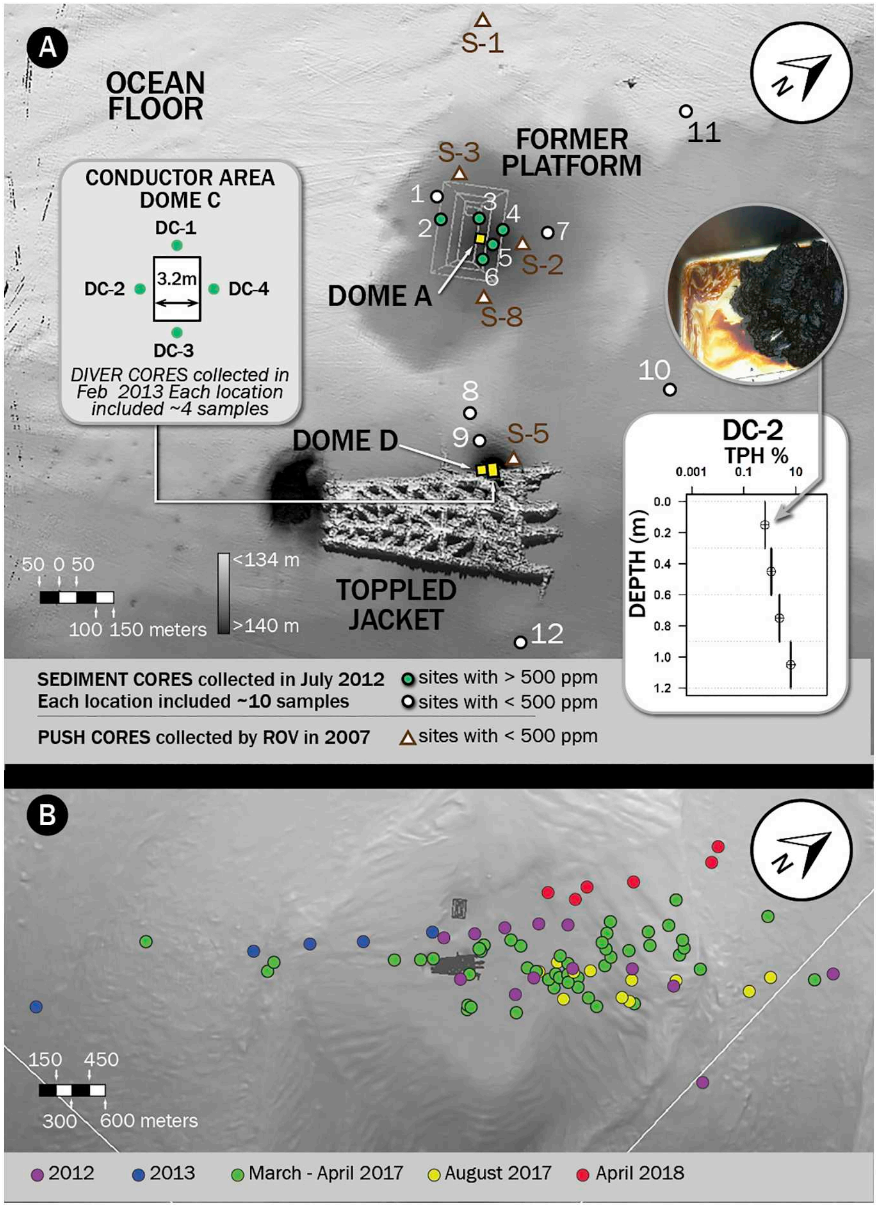

Fig. 2. (A) Bathymetric map of the MC20 study site showing the former platform area, toppled jacket, three areas of depression, three containment dome locations (Domes A, C, and D; currently buried in sediment) and relative TPH concentrations of sediment samples. Insert shows the TPH concentration profile for push core DC-2 and an image of its oiled sediment. (B) Locations of 92 out of the 97 sheen samples collected from 2012 to 2018 (five samples are located outside of the bounds of the map; see Fig. S1 for the locations of all sheen samples). The white lines denote the boundary of Mississippi Canyon Block 20.

etc.), have included dozens of surveys and assessments (Etkin, 2014; USCG, 2018)(Table S1), attempts to access conductors in the former platform area by dredging for intervention, installation of two containment systems, and the completion of nine intervention wells selected by Unified Command based on the potential to eliminate discharge versus risk of creating new discharges (including six of the 14 active oil-producing wells). The impetus for these efforts was to eliminate/reduce hydrocarbon releases from the site, with sheen frequency and estimated overflight-based volume providing the most tangible assessment metrics.

Overflight monitoring using the standard government approach (USCG, 2014; BSEE, 2015; NOAA, 2016; USCG NRC, 2019) identified a persistent surface sheen, with a median volume of ~0.08 m^3 per overflight (interquartile range = 0.03–0.26 m^3; N = 202) for data from 9/1/2016 to 9/1/2018 reported to the National Response Center. This approach, however, only provides a snapshot of oil on the surface at the time of the overflight and does not provide a flux. Several alternative approaches have been applied to estimate flux using the observed sheens. Two reports co-authored or authored by Garcia-Pineda (Pineda-Garcia, 2018; Sun et al., 2018) based on satellite remote-sensing calculated mean flux ranges between 39.6 and 111 and 7.7–274.1 m^3 per day, respectively. These estimates contributed to the USCG's decision to partially federalize the response in December 2018 (Luttrell, 2018), leading to the 2019 installation of a subsea containment system. This system overlays two of the previous containment domes (Fig. 2A, Dome C and Dome D, installed in 2009) and resides at a location initially identified in 2007 and subsequently confirmed by the Unified Command's Sheen Source Location Working Group (SSLWG, 2017). More recently reports have provided fluxes of 3.0–17 and 1.4–7.5 m^3/day, based on water-column-based visual and acoustic methods (Mason et al., 2019; MacDonald et al., 2019). Response officials have reported, only through the popular media and presentations, a capture rate of ≤3.8 m^3 oil per day averaged over ~monthly collections, by the containment system installed in 2019 (Fears, 2019; Couvillion, 2020).

While methodological concerns and variability associated with this capture have yet to be addressed by the USCG, a notable decrease in the frequency and extent of sheens has been apparent at the site.

It remains unknown whether oil currently emanating from the seafloor is from an ongoing release from a geologic reservoir and/or solely from remnant oil (released prior to well interventions) in sediments. In this work, we synthesize results from 1) petroleum-residue chemical analyses of reservoir oils, sediments, and sheens and 2) the analysis of sheen-volume estimates and benthic activities, to better characterize the ongoing release. These data derive primarily from research chartered by the Unified Command, including several cooperative studies conducted by USCG, BSEE, National Oceanic Atmospheric Administration (NOAA), Bureau of Ocean Energy Management, and TEC. We specifically test and refute the hypothesis that surface sheens originate as discharge from one or two homogeneous reservoirs, and instead find that the evidence supports release of multiple, chemically-distinct oil groups including exhumation of hydrocarbons trapped in the sediment. Ultimately the details of this work should be incorporated into the decision process prior to any further activities requiring/resulting in sediment disturbances, specifically risk-laden well interventions, especially now that releases to the environment have been reduced.

2. Methods

2.1. Sampling and chemical analysis

Four types of samples were considered in this study: (1) Two crude oils, from different production reservoirs, collected before the platform toppled; (2) Five sediment samples collected in 2007; (3) One hundred and forty-two sediment samples collected in 2012 and 2013; and (4) Ninety-seven sheen samples collected from 2012 to 2018 (Fig. 2). Field operations were entirely performed under the auspices of the Unified Command except 20 surface sheens (of the 97 total) collected in August 2017 and April 2018 on behalf of the federal government but outside of Unified Command. Analytical consistency was achieved by using a single analytical laboratory, Alpha Analytical (Mansfield, MA), that analyzed all samples by gas chromatography with flame ionization detection (GC-FID) and gas chromatography with mass spectrometry (GC–MS) (see Stout, 2016 for a detailed discussion on Alpha Analytical's methods and performance during a multi-year forensic effort for the Deepwater Horizon disaster). A three-tiered forensic analysis was used to evaluate similarity in chemical composition of all samples following the approach of the European Committee for Standardization method CEN/TR 15522-2 (CEN, 2012; Kienhuis et al., 2016). All sample information and diagnostic ratio (DR) data are listed in Tables S2 and S3 for sheen samples and sediment/crude oils, respectively.

2.1.1. Crude oil samples

Crude oils from wells A19 and A21, the two most prolific producing wells at the time of Hurricane *Ivan*, were collected prior to the platform toppling. Well A21 was the source of an emission plume of hydrocarbons, brine, and associated elevated temperatures within the former platform footprint and was successfully plugged by the first intervention well in 2009. No other crude oil samples predating the toppling of the MC20 platform were available to us for this study.

2.1.2. Sheen samples

Between July 2012 and April 2018, 97 sheen samples (as well as field blanks, lab blanks, and sheen-free reference sites) were collected using PTFE nets (USCG MSL, 2013; Aeppli et al., 2013) as part of three concerted sampling campaigns: (1) July 2012 and February 2013 (n = 20); (2) March–April 2017 (n = 57); and (3) August 2017 and April 2018 (n = 20). See Fig. S1 for collection locations of all sheen samples. A majority of samples were collected within ~1.5 km to the northeast of the site along the predominant direction of surface currents, with samples from 2/23/2013 and 3/8/2017 collected from sheens transported to the southwest of MC20 (Fig. 2B) during a reversal of the predominant current. The presence of three acoustic Doppler current velocity profilers on-site at MC20 during the March–April 2017 sampling campaign verify the anomalous current shift to the southwest on March 8th from the predominant east/northeast direction (SSLWG, 2017). Samples collected in July 2012 and February 2013 were composites collected over the course of 20–40 min along transects of sheen moving away from the site. In contrast, sampling during March 2017–April 2018 specifically focused on collecting individual droplets of oil as soon as possible following surfacing. In some cases, these samples were collected just below the water surface and did not necessarily follow the transect of a sheen, with some samples being collected only minutes and meters apart (Fig. 2B).

2.1.3. Sediment cores

Sediment cores were collected at the site in 2007, 2012, and 2013. A threshold of 500 ppm dry-weight total petroleum hydrocarbons (TPH) was established for forensic analysis (Figs. S2–S5). In December 2007, five push-cores were collected at locations selected based on real-time analysis of water-column hydrocarbons using an ROV-mounted in-situ mass spectrometer operated approximately 2 m above the seafloor (Fig. 2A). These five samples all contained < 500 ppm dry-weight TPH and hence not discussed further. In July 2012, 24 sediment cores (12 piston and 12 box core samples) were collected at 12 locations, six within the excavated footprint of the former platform area (Fig. 2A). Piston cores (~6 m in depth) were divided into 50-cm depth intervals, whereas a single bulk subsample from each box core was collected. In February 2013, four push cores (~1.3 m in depth) were collected by saturation divers (diver cores) adjacent to containment Dome C in loosely consolidated sediments (Fig. 2A). Diver cores were divided into 30-cm sections for analysis.

While these sediment samples offer an opportunity to examine the contribution of remnant oil to the sheen samples, appropriate caveats must be considered to contextualize the resulting data. First, prior to collection in 2012, part of the site was dredged (in an attempt to provide access for intervention and jacket removal), disturbing seafloor sediments and homogenizing remnant oil around the former platform (see Fig. 2A). Second, although piston and push cores were sub-sectioned, the coarseness of the 30- and 50-cm intervals may have resulted in homogenization of more finely distributed oils, potentially masking the chemical signatures of distinct oils.

2.2. Sample analysis

Each sample was extracted in dichloromethane and analyzed by gas chromatography with flame ionization detection (GC-FID) and gas chromatography with mass spectrometry (GC–MS) by Alpha Analytical (see SI for discussion of quality control results). GC-FID analysis produced chromatograms used for the Tier 1 chemical fingerprinting analysis (described below) and were used to quantify TPH. GC–MS analysis produced extracted ion chromatograms used in Tier 2 chemical fingerprinting analysis (described below) and also provided data for the Tier 3 chemical fingerprinting analysis (described below). Concentrations of 37 saturated alkanes, including normal chains from C_9 to C_{40} and some branched hydrocarbons, 68 two- to six-ring polycyclic aromatic hydrocarbons (PAHs), and 56 petroleum biomarker compounds were considered in selecting the DRs used in Tier 3. Select samples were also analyzed for the presence of alkenes from drilling fluids by comprehensive two-dimensional gas chromatography (Reddy et al., 2007; Aeppli et al., 2013).

2.3. Chemical fingerprinting

Crude oils, oil sheens, and sediment samples were compared using a modified, three-tiered Nordtest approach adapted from the European

Committee for Standardization method CEN/TR 15522-2 (Kienhuis et al., 2016). Some sediment samples were excluded based on either low TPH concentrations (< 0.05%), non-detectable biomarker concentrations, or when the presence of synthetic olefins dominated the GC-FID chromatograms (see SI for more details and Figs. S2 to S7). The final dataset used for fingerprinting analysis consisted of the two neat oil samples from wells A19 and A21, 97 surface sheen samples, and 46 sediment-core samples.

2.3.1. Tier 1 and Tier 2 - visual GC-FID and GC–MS comparisons

Tier 1 and Tier 2 were visual comparisons of GC-FID chromatograms and GC–MS extracted-ion chromatograms, respectively. Although they are qualitative or semi-quantitative, both of the methods have diagnostic value. Within the CEN/TR 15522-2 methodology, Tier 1 data analysis and treatment can vary on the specific procedure and decision criteria when evaluating the degree of similarity between two samples. Criteria used in this study included carbon range, relative abundance of resolved to unresolved peaks, the size and shape of the unresolved complex mixture, and other notable features of the GC-FID chromatograms (Fig. S6). Tier 2 uses a similar approach that is a visual comparison of estimated relative distributions of peaks in GC–MS extracted ion chromatograms (Fig. S7) for saturated hydrocarbons, steranes, hopanes, triaromatic steroids, and parent and alkylated PAHs.

2.3.2. Tier 3 – quantitative diagnostic ratios

Tier 3 relies on a statistical comparison of DRs of compounds quantified by GC–MS (Table 1). The DRs were selected based on compounds known to be resistant to short-term weathering with sterane and hopane biomarkers, C_2- and C_3-dibenzothiophenes, and C_2- and C_3-phenanthrenes and anthracenes found to be conservative in transport from the seafloor to the ocean surface during the Deepwater Horizon disaster (Aeppli et al., 2014). The final set of 22 DRs included only compounds with a mean concentration for all samples > 5% compared to the 17α,21β-hopane (Hop) concentration and was further constrained to ratios reported for the sheen samples collected outside of the unified command response in August 2017 and February 2018 (Stout, 2018).

To determine the similarity of two samples, the absolute percent difference for each of the 22 DRs utilized was calculated using Eq. (1):

$$\%difference = \left| \frac{ratio_{sample\ 1} - ratio_{sample\ 2}}{mean\ ratio_{sample\ 1\ \&\ sample\ 2}} \right| \times 100 \quad (1)$$

Based on an assumed analytical uncertainty of 5% (as recommended by CEN/TR 15522-2) any percent differences less than or equal to 14%, corresponding to 2.8 times the analytical uncertainty or 0.5% type I error, were considered to be matches for a given DR. Quantized heatmaps allowing for simultaneous inspection of the 22 ratios across samples (Fig. S8) were used to visualize comparisons. Matching samples were defined as those wherein the differences in all 22 DRs were ≤14% between the two samples. As recommended by the method to provide potentially useful information in complex fingerprinting cases, we also utilized an operationally defined probable-match category, defined as comparisons for which differences in at least 18 of the 22 ratios were ≤14% and no > 2 of the 22 ratios differed by > 19%. All samples that fell outside match and probable-match criteria were defined as non-match. In the strictest comparisons, for which probable-match was not used, any sample with a single non-matching DR was considered a non-match. In the instances for which probable-match was used, non-matches were defined as any comparison for which any five ratios differed by > 14% or any three ratios differed by > 19%.

2.3.3. Mixing model

To assess the likelihood and extent to which multiple oil sources may be contributing to the observed sheen DRs, a chemical mixing-model was applied. The model considered each of the 97 sheen samples,

Table 1
Compound names and abbreviations of 22 diagnostic ratios used in this study.

Diagnostic ratio	Abbreviation
18α-22,29,30-Trisnorneohopane/17α(H),21β(H)-Hopane	Ts/Hop
17α(H)-22,29,30-Trisnorhopane/17α(H),21β(H)-Hopane	Tm/Hop
Norhopane/17α(H),21β(H)-Hopane	H29/Hop
Homohopane-22S/17α(H),21β(H)-Hopane	H31S/Hop
13β(H),17α(H)-20R-Diacholestane/13β(H),17α(H)-20S-Diacholestane	27dia R/27dia S
(14β(H),17β(H)-20R-Cholestane + 14β(H),17β(H)-20S-Cholestane)/(14β(H),17β(H)-20R-Ethylcholestane + 14β(H),17β(H)-20S-Ethylcholestane)	27bb R + S/29bb R + S
C28,20S-triaromatic steroid/(C26,20R- + C27,20S-triaromatic steroid)	28S/26R + 27S
C27,20R-triaromatic steroid/(C26,20R- + C27,20S-triaromatic steroid)	27R/26R + 27S
C28,20R-triaromatic steroid/(C26,20R- + C27,20S-triaromatic steroid)	28R/26R + 27S
C_2-dibenzothiophenes/C_2-phenanthrenes & -anthracenes	DBT2/PA2
C_3-dibenzothiophenes/C_3-phenanthrenes & -anthracenes	DBT3/PA3
(C28 Tricyclic Terpane-22R + C28 Tricyclic Terpane-22S + C29 Tricyclic Terpane-22R + C29 Tricyclic Terpane-22S)/17α(H),21β(H)-Hopane	(C28Tri R + S + C29Tri R + S)/Hop
14α(H),17α(H)-20S-Ethylcholestane/14α(H),17α(H)-20R-Ethylcholestane	29aaS/29aaR
Norhopane/18α(H)-30-Norneohopane	H29/29Ts
(Pentakishomohopane-22R + Pentakishomohopane-22S)/17α(H),21β(H)-Hopane	(H35S + H35R)/Hop
(13β(H),17α(H)-20R-Diacholestane + 13β(H),17α(H)-20S-Diacholestane)/17α(H),21β(H)-Hopane	27dia R + S/Hop
(14α(H),17α(H)-20R-Cholestane + 14α(H),17α(H)-20S-Cholestane + 13β(H),17α(H)-20R-Ethyldiacholestane + 13β(H),17α(H)-20S-Ethyldiacholestane)/17α(H),21β(H)-Hopane	(27aa R + S + 29dia R + S)/Hop
(13β(H),17α(H)-20R-Diacholestane + 13β(H),17α(H)-20S-Diacholestane)/(14α(H),17α(H)-20R-Cholestane + 14α(H),17α(H)-20S-Cholestane + 13β(H),17α(H)-20R-Ethyldiacholestane + 13β(H),17α(H)-20S-Ethyldiacholestane)	27dia R + S/(27aa R + S + 29dia R + S)
14β(H),17β(H)-20R-Cholestane/17α(H),21β(H)-Hopane	27bb R/Hop
14β(H),17β(H)-20S-Cholestane/17α(H),21β(H)-Hopane	27bb S/Hop
13β(H),17α(H)-20R-Diacholestane/17α(H),21β(H)-Hopane	27dia R/Hop
13β(H),17α(H)-20S-Diacholestane/17α(H),21β(H)-Hopane	27dia S/Hop

46 sediment core samples, and crude oil from wells A19 and A21 as potential endmembers for each remaining sample. This model further considered a mixing range of 1 to 99% (see SI for details of the calculation) for the binary chemical-mixing model using Eq. (2):

$$C_{\text{mix}} = \left(\frac{C_x}{Hop}\right)_{em\ 1} \times p_{em\ 1} + \left(\frac{C_x}{Hop}\right)_{em\ 2} \times p_{em\ 2} \quad (2)$$

where C_{mix} is the new concentration resulting from the mixture, $\left(\frac{C_x}{Hop}\right)_{em\ 1}$ is the original concentration of a compound X normalized to the concentration of 17α,21β-hopane in endmember 1, $p_{em\ 1}$ is the mixing proportion of endmember 1 in the mixture (0.01–0.99), $\left(\frac{C_x}{Hop}\right)_{em\ 2}$ is the original concentration of compound X normalized to the concentration of 17α,21β-hopane in endmember 2, and $p_{em\ 2}$ is the mixing proportion of endmember 2 in the mixture (equal to 1 - $p_{em\ 1}$). The resulting theoretical mixtures were then compared to the original data set using the Tier 3 methodology described above, resulting in 90,326,400 total comparisons.

To assess the possibility of additional endmember oils contributing to the 97 sheen samples, the model was extended to incorporate a third- and fourth endmember into the mixing. The DRs of the resulting theoretical mixtures were then calculated and again compared to the DRs of all 97 sheens in the original data set again using the Tier 3 methodology described above. This approach assumes that sheen samples reflect individual surfacing oil droplets representing a unique source (e.g., well A19, A21, or remnant oil in sediment). While this approach cannot guarantee that all potential endmembers are represented, it does ensure that a full range of the highest and lowest observed values for each DR and every possible combination in between is considered.

2.3.4. Additional tests for chemical heterogeneity

To statistically test for chemical heterogeneity between all 97 surface sheens the Mardia multivariate normality test was performed using all 22 DRs (Table 1). The test relies on multivariate extensions of skewness and kurtosis and, under the null hypothesis of homogeneity, predicts the dataset should follow a multivariate normal distribution (Mardia, 1970). The Mardia test was conducted using the MVN package in R (Korkmaz et al., 2014).

To further investigate the potential for a multi-endmember explanation to the chemical heterogeneity observed at the site, a k-means cluster analysis was performed using the 22 DRs simultaneously for sheen samples collected during the 2017 SSLWG sampling campaign (SSLWG, 2017). This clustering analysis was repeated for 1000 iterations to account for potential bias in initial seeding. The SSLWG samples were chosen due to their targeted sampling protocol as well as the contemporaneous operation of three acoustic Doppler current velocity profilers at the site, which provided nearly continuous measurements of current velocities for comparison.

2.4. Sheen volume and benthic disturbance

Sheen-volume estimates derived from overflight campaigns at MC20 were downloaded from the United States Coast Guard National Response Center (http://nrc.uscg.mil) and filtered to include only those events associated with "Taylor Energy". Due to clerical errors as well as name variability, up to 36 name variants were confirmed to be associated with TEC and the MC20 site from January 2008 through February 2020. The data were then collated using their associated sequence numbers (SEQNOS) and all volumetric estimates were standardized to m^3 from various units of measurement (e.g. gallons, barrels). All of the estimated volumes reported to the NRC derived from repeat overflights using standard methodology agreed upon by the Unified Command (MC20 Unified Command, 2016).

Work activity at or near mudline involving likely disturbance of the sea floor (i.e., benthic disturbance) occurred twice between 9/1/2016 and 4/16/19 at the MC20 site, providing an opportunity to assess relation to observed sheen volumes. The first was associated with data collection used to estimate flux from 9/6/18 through 9/8/18 (Mason et al., 2019). The second occurred during the emplacement of the current containment system from 2/23/19 to 4/16/19. In order to test if there is a statistically significant difference between sheen volumes observed during periods of on-site work with those without on-site activities, we used a Welch's *t*-test (Welch, 1947) and permutation tests for three distinct time comparisons. Specifically, these comparisons include: (1) all periods of work (9/6/18–9/8/18 and 2/23/19–4/16/19) versus all non-work periods; (2) spring work periods from 2019 (2/23/19–4/16/19) versus the same non-work period in 2018; and (3) spring work periods from 2019 (2/23/19–4/16/19) versus the same non-work period in 2017. A two-sided Welch's t-test was selected to test the null hypothesis that periods of on-site work and those without on-site work have means that do not differ significantly. Permutation tests were run using 100,000 replicates to test the one-sided null hypothesis that periods of on-site work and those without produced similar sheen-volume test statistics. Due to the flexibility of permutation tests, a comparison of all quantiles from 0 to 100 were compared across each dataset providing greater insight into the nature of statistical differences between sheen-volume distributions.

3. Results and discussion

Despite all efforts, permanent resolution for the MC20 site, i.e., a condition for which oil is no longer being released from the sea floor, has yet to be achieved. Impeding resolution is the disagreement as to the immediate sources of oil that may include direct flow from pressurized reservoirs (ongoing release), remnant oil emplaced in sediment prior to completion of the last intervention well in 2011, sediment oil emplaced after the last well intervention (i.e., assumes pulsed discharge from an ongoing release), and petroleum products used during well interventions (e.g. alkenes or synthetic olefins from drilling fluids). Distinguishing potential sources has direct implications for response options (e.g. top kills, drilling of intervention wells, perpetual containment, sediment capping, or sediment removal). Here we provide an analysis based on sediment- and sheen-forensic chemistry in conjunction with the relations of sheen volume and benthic disturbance to better understand release dynamics and inform ongoing response options. We specifically test the hypothesis that the release comes directly from one or two chemically distinct source oils.

3.1. Sheens are chemically heterogeneous

Chemical homogeneity of sheens collected from 2012 to 2018 was assessed using a tiered approach (CEN, 2012; Kienhuis et al., 2016) to test the underlying hypothesis that active discharge from a single, homogenous, pressurized reservoir is the sole source. The chemical composition of sheen samples under this scenario should be forensically indistinguishable especially given the conservative suite of biomarker compounds chosen in this study (Table 1).

Visual comparisons of GC-FID and GC–MS extracted ion chromatograms used in Tiers 1 and 2, respectively, revealed that the 97 sheens had subtle, informative differences (Fig. 3, Figs. S6 and S7). Select GC-FID chromatograms indicated the presence of 16-, 17-, and 18-carbon alkenes, common constituents in drilling fluids (Fig. 3; Reddy et al., 2007; Aeppli et al., 2013). Considerable variability in the relative abundance of different hopane and sterane peaks, especially in the *m/z* 218 chromatograms was observed (Fig. S7), both within sheen samples collected on different dates and, remarkably, between samples collected in sequence on the same day (see example of March 17, 2017 in Fig. S7). The variability observed in the 97 sheens collected from 2012 through 2018 is consistent with the USCG Marine Safety Lab's interpretation of sheens collected in July 2012 that found "... the spilled oil is coming from a non-homogeneous source" (USCG MSL, 2012). The

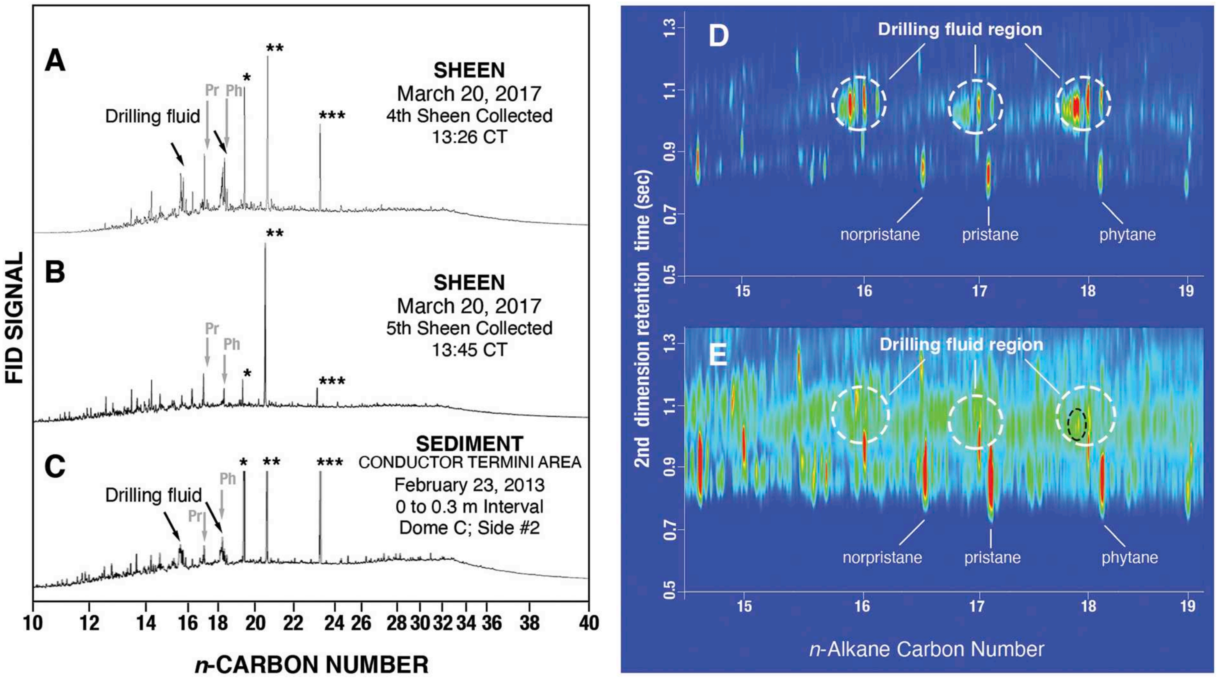

Fig. 3. Select GC-FID and GC × GC-FID chromatograms highlighting differences between two sheen samples (A and B) and similarity of one sheen sample (A) to one sediment sample (C), including the presence of alkenes (i.e., olefins) from drilling fluids. (A) Fourth surface sheen collected on March 20, 2017 with a dominant presence of hexadecenes and octadecenes. (B) Fifth surface sheen collected on March 20, 2017, 19 min after the fourth sample, approximately 50 m away, containing no observable alkenes. (C) Surface sediment collected by divers around Dome C containing an abundance of alkenes and early eluting material similar to panel A. Asterisks denote standards used in the analysis: * = *o*-terphenyl; ** = 5α-androstane; and *** = tetracosane-d_{50}. (D and E) Partial GC × GC-FID chromatograms of samples −04 and −05 from March 20, 2017 (corresponding to panels A and B, respectively). Ovals indicate the elution areas of hexadecenes, heptadecenes, and octadecenes, consistent with drilling-fluid standards (also analyzed in this study). Sample −04 contains several peaks in each oval representing an alkene content of 10%, relative to TPH. Trace levels of octadecene were present in sample −05, noted with the black oval, but not quantified.

consistent variability in sheen composition disproves the hypothesis of a single homogeneous source and implicates multiple, compositionally distinct groups of oil acting as endmembers.

The Tier 3 statistical comparisons of DRs confirm and extend the observations of heterogeneity from the Tier 1 and Tier 2 analyses. We applied a two-step approach to quantify and visualize sample relatedness. First, we generated quantized heat maps that used a color-coded shading to compare key DRs from each sheen sample (Fig. S8). These plots reveal which DRs differ between compared samples and to what extent, on an absolute basis. While all DRs contributed to differences between samples, nine ratios involving steranes (27bb R/Hop, 27bb S/Hop, 27dia S/Hop, 27dia R/Hop, and 29aaS/29aaR), the triphenylenes ((C28Tri R + S + C29Tri R + S)/Hop), Ts, Tm, and H35 exhibited the most variability. For example, the sheen samples collected on March 8, 2017 had consistently lower sterane ratios (especially 27bbR/Hop and 27bbS/Hop) and lower Ts/Hop, Tm/Hop, and H35/Hop ratios than other sheen samples. For all other sheen samples, the majority of the variability was still in the nine most variable DRs, but the differences were less consistent.

For the second approach to visualize sample relatedness, a pair-wise comparison of all sheen samples was conducted (Figs. S9, S10). Summarized results of this comparison are displayed as a color-coded matrix showing the percentage of matching samples for pairwise comparisons of samples collected on each day (Fig. 4). Above the diagonal in Fig. 4, we used the strict match, non-match criteria. To account for potential slight heterogeneity in oil sources and expand the utility of this approach for distinguishing between potential sources, we repeated this pair-wise comparison with reduced stringency by incorporating the probable-match criteria (Fig. 4 below the diagonal).

For the 97 sheen samples, patterns of matches suggests temporal heterogeneity of the sheen source with more (but not all) matches for samples collected on the same day than across sampling dates (Fig. 4 above the diagonal). Incorporating probable matches clearly retains the temporal heterogeneity (Fig. 4 below the diagonal). However, not all samples collected on the same day were matches or even probable matches to other samples collected on that day. In addition, it is notable that sheen samples collected during a reversal of current direction on March 8, 2017 did not match to samples from any other day.

A complementary multivariate normality test utilizing 22 DRs across all 97 sheen samples collected from 2012 to 2018 also refutes the single homogeneous source hypothesis (Mardia, 1970). Resulting *p*-values for both kurtosis and skewness of approximately 0 fall well below the 0.05 *p*-value threshold to reject the null hypothesis of homogeneity across all sheen samples.

Collectively, these results demonstrate chemical heterogeneity among sheen samples, disproving the hypothesis that the oil sheen is supported by a single, homogeneous source. Furthermore, the observed chemical complexity encompasses more distinct chemical compositions than there are production reservoirs at MC20 and indicates mixing of multiple, compositionally-distinct oil groups. However, these results do not identify the sources (e.g. multiple reservoirs, remnant oil) nor the extent to which they may be mixing.

3.2. Tier 3 comparison of reservoir oils, sediments, and sheens

To determine whether the archived reservoir oils or oiled sediments are contributing to the sheen, each sheen sample was compared to reservoir oils A19 and A21 (the two most productive wells at the time of toppling) and 46 sediment oil samples. There were no matches between either of the two archived oil samples with any of the 97 sheen samples or the 46 sediment samples (Fig. 4). Oil from well A19 had higher sterane and diasterane content and oil A21 had lower concentrations of ββ-cholestanes and ethyldiasteranes compared to the sheen samples (Tables S2 and S3). Both oils had higher 27dia/27aa ratios and lower

Sheen Samples (rows, left)	7/22/2012	7/23/2012	7/24/2012	2/23/2013	3/8/2017	3/10/2017	3/16/2017	3/17/2017	3/20/2017	3/21/2017	3/22/2017	3/28/2017	4/7/2017	4/8/2017	8/15/2017	8/16/2017	8/17/2017	4/28/2018	Former platform	Conductor area	Reservior oils	Sheen Samples (rows, right)
Number of samples	5	5	5	5	8	5	6	4	9	9	5	5	2	4	2	8	4	6	30	16	2	
	40	44	4	0	0	8	10	10	7	16	28	0	0	0	20	28	25	0	0	0	0	7/22/2012
		60	16	4	0	7	33	25	11	20	44	0	0	0	20	50	20	0	0	1	0	7/23/2012
			30	36	0	7	10	10	13	18	16	12	10	25	0	5	0	27	0	16	0	7/24/2012
7/22/2012	100			40	0	1	10	10	9	2	16	36	20	25	0	0	0	23	0	25	0	2/23/2013
7/23/2012	96	100			57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3/8/2017
7/24/2012	88	52	90			60	63	40	38	56	24	0	30	15	0	8	0	0	0	5	0	3/10/2017
2/23/2013	56	44	84	100			47	33	26	46	30	0	33	13	0	17	8	6	0	2	0	3/16/2017
3/8/2017	18	40	3	0	100			17	17	31	25	0	13	6	0	0	0	4	0	3	0	3/17/2017
3/10/2017	84	31	25	20	12	100			25	41	13	0	11	8	0	7	8	0	0	1	0	3/20/2017
3/16/2017	70	87	57	40	56	100	93			50	29	0	22	6	6	21	6	0	0	1	0	3/21/2017
3/17/2017	70	70	70	45	34	95	88	67			30	0	10	5	0	18	0	13	0	3	0	3/22/2017
3/20/2017	73	84	71	58	24	93	93	83	86			10	0	5	0	0	0	13	0	15	0	3/28/2017
3/21/2017	91	98	71	56	39	100	96	97	93	97			100	38	0	0	0	0	0	34	0	4/7/2017
3/22/2017	80	76	72	56	18	92	83	75	87	89	80			33	0	0	0	0	0	2	0	4/8/2017
3/28/2017	8	12	76	96	0	52	37	50	47	51	48	80			100	69	50	0	0	0	0	8/15/2017
4/7/2017	40	60	80	70	0	90	75	88	83	94	80	90	100			50	38	0	0	0	0	8/16/2017
4/8/2017	60	85	80	70	0	95	92	81	89	94	85	75	100	100			33	0	0	0	0	8/17/2017
8/15/2017	100	90	50	10	50	80	67	63	89	94	80	0	50	50	100			20	0	10	0	4/28/2018
8/16/2017	100	98	55	35	45	83	79	63	76	90	80	5	63	66	100	100			77	1	0	Former platform
8/17/2017	95	85	50	20	38	65	50	50	64	72	60	5	50	50	100	97	100			40	0	Conductor area
4/28/2018	37	27	73	80	0	30	14	21	24	31	50	67	50	29	0	10	13	100			0	Reservior oils
Former platform	0	3	0	0	49	1	3	0	0	2	0	0	0	0	0	0	0	0	99			
Conductor area	34	43	60	64	0	71	54	48	51	59	48	71	84	70	3	25	19	44	6	77		
Reservior oils	0	10	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	8	0	6	0	

Fig. 4. Similarity of sheen samples collected from July 2012 to April 2018 to each other; to sediment-core samples collected in July 2012 and February 2013; and to archived MC20 reservoir oils. The numbers in boxes and the extent of green shading show the percentage of sample comparisons that result in a match: above the diagonal using a strict match, non-match definition according to CEN/TR 15522-2 protocol and below the diagonal incorporating the less stringent probable-match criteria as defined in Section 2.3.2. See Figs. S9 and S10 for a more detailed pairwise sample comparison and Tables S2 and S3 for sample information. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

H35/Hop ratios than the sheen samples (Tables S2 and S3). Well A21, the source of a plume located within the footprint of the former platform area (30 m SW of Dome A), was observed to flow hot oil, gas, and brine until it was sealed by an intervention well in 2009. Given the proximity of the A21 plume to sediment samples it is perhaps surprising that there were zero matches between A21 and sediment (Fig. 4).

The differences between sediment samples are readily apparent in Fig. S10, where there were no matches or probable matches between the former platform and the conductor termini areas, the two sites with greatest oil concentrations. Most (333 matches and 99 probable matches of 435 total comparisons) of the sediment samples from the former platform area matched each other while the sediment samples from the conductor termini area were more heterogeneous (48 matches and 44 probable matches of 120 total comparisons). It is important to note within the conductor termini area, samples from different depths of the same 1.2 m-long cores and samples within ~ 3 m of each other (around Dome C; Fig. 2) did not match.

There were 0/2910 matches and 134/2910 (5%) probable matches between sheens and the former platform area sediments and 148/2320 (6%) matches and 718/2320 (31%) probable matches between sheens and the conductor termini area sediments (Fig. 4, Fig. S9). In contrast to the majority of sheen samples, those collected on March 8, 2017 showed a greater similarity to the former platform area sediments (0% match but 48% probable match) than the conductor termini area (0% match and 0% probable match; Fig. 4, Fig. S9).

Based on these differences, we consider the most likely explanation for the heterogeneity observed in sheen-sample DRs to be differential mixing of multiple chemically distinct oil groups.

3.3. Mixing two to four samples does not explain sheen heterogeneity

In order to assess the number of distinct oils, i.e., oil groups, contributing to the sheens we applied two approaches, a K-means cluster analyses of surface sheens and a quantitative mixing model of all samples. Both approaches were used to test the hypothesis that two endmember oil groups account for the observed variability in DRs.

Results of the K-means cluster analysis of 57 sheen samples collected during spring 2017 exhibit a cluster cohesion and separation maximum at k = 5, suggesting multiple chemically-distinct endmembers contributing to the sheens evaluated. The relatively low Y-axis silhouette values at this local maximum and monotonically increasing goodness of fit with increasing number of clusters, implies a relatively high level of chemical relatedness between the sheen samples (Fig. S11). Analysis of the similarity matrix for the resulting dendrogram supports a distinction between 3 or more groups (Fig. S12), with no observed matches or partial matches between the first two groups. Evaluation of bottom currents bracketing the buoyant rise of these 57 samples to the sea surface also shows a distinctive relationship between current direction and sheen composition (Figs. S12–S14). When taken together these lines of evidence highlight the existence of a complex mixing regime that results from multiple distinct endmembers including a physical separation of buoyant droplets that preferentially manifests with an eastward shift in bottom current direction.

To further explore the potential for mixing, a binary chemical mixing model was used to assess whether multiple sources could explain the variability in the observed sheen DRs. The maximum number of matches for any combination of two samples was 69 out of 97 (~71%). This resulted from a mixture of one sheen collected on March 21, 2017 (170321-1) and one collected on April 28, 2018 (WM005). Although this combination resulted in the greatest number of matches, a total of 118 combinations of endmembers produced 60 or more matches (Fig. S15). Of these 118 combinations, 74 involved either a sheen sample from March 8, 2017 or a piston core sample, which is notable because the March 8, 2017 samples and the 2012 piston core samples were chemically distinct from the rest of the dataset in that they had higher sterane content. Furthermore, the currents on March 8, 2017 resulted in transport of the sheen to the southwest of MC20 (Fig. 2B) and may have caused isolated surfacing of oil from sediments at a location distinct from those that resulted in the majority of the other sheen samples (Figs. S12–S14). The percentage of each endmember in the optimal mixture fluctuated, however, indicating spatial or temporal variability in the contribution from each endmember (Fig. 5). Notably, mixtures of archived reservoir oils A19 and A21 resulted in zero matches to sheen samples and only eight probable matches. The failure of two-endmember mixing to explain all of the variability in observed sheen DRs precludes the possibility of only two oil groups acting as compositional endmembers. Furthermore, the variability in the optimal mixing proportion is difficult to reconcile with a constant release rate of each endmember as could be expected for pressurized wells.

To assess the possibility that additional endmember oil groups explain the observed chemical heterogeneity among sheen samples, a third- and fourth-endmember were incorporated into the mixing model. The optimal third endmember identified was a sheen collected on March 8, 2017 (170308-01), while the fourth was a sheen sample collected on August 17, 2017 (Slick Oil #11). Ternary and quaternary mixtures yielded a maximum of 82 matches (85%) and 88 matches (91%) to the 97 sheens, respectively (Fig. 5). As with the binary mixing model, the optimal mixing proportions for each endmember were not constant suggesting temporal or spatial variability in the contribution of each oil group. Whereas the four endmember model does explain much of the variability in the sheen sample DRs, nine samples could not be matched to any 2-, 3-, or 4-endmember mixture indicating more than four chemically distinct sources provide the best explanation of variability in DRs observed in sheen samples at MC20 (Fig. 5).

Collectively, the K-means cluster analysis and the results of the mixing model refute the hypothesis that two chemically distinct oil groups account for the observed variability in DRs. In terms of geological sources the results demonstrate that more than two reservoirs must have contributed to the sheens evaluated, assuming homogeneity within each reservoir. Further, these two analyses are consistent (but not definitive) with > 4 oil groups contributing to the sheen samples but are agnostic as to whether there is active flow from a former production reservoir and/or release from remnant oil pooled in the sediment.

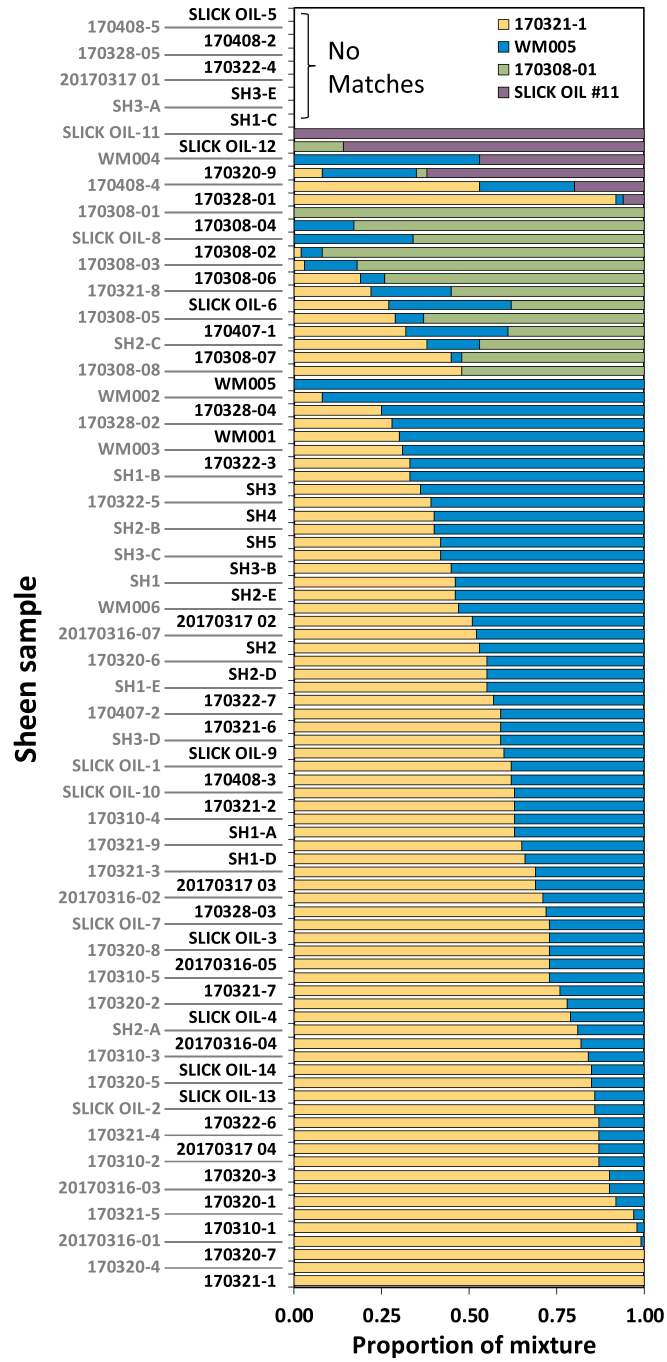

Fig. 5. Mixing proportions for the top four endmembers identified by the mixing model. Results are shown for each sample that matched to a mix of two to four endmembers. Using this optimal set of endmembers, nine sheen samples did not match any mixture (shown at the top of the figure). Rows alternate between black and gray samples along the vertical axis.

3.4. Alkenes/olefins from drilling fluid as a source constraint

The extent to which sediments may serve as an oil repository/capacitor is a key factor to understanding oil and gas release at MC20. Sediment oil content is highly variable (Figs. S2–S5, S16, S17), with cores at MC20 containing up to 16% oil by dry mass similar to other study sites where remnant oils in sediment cause surface sheening (McLinn and Stolzenburg, 2010; Erten et al., 2011; USEPA, 2019). Notably, the sediments collected around Dome C in February 2013 (Fig. S17), which were most similar to the surface sheens, had varying amounts of hydrocarbons even within the same sediment core. These observations point to a need for extensive sediment sampling to capture variability and to understand sediment release potential as interpretations drawn from small numbers of samples would fail to capture the diversity in concentrations and compositions.

As mentioned for sheens, some GC-FID chromatograms revealed putative alkene mixtures (C_{14} to C_{20} alkenes; Fig. 3, Figs. S18–S20), and numerous sediment samples with low oil concentration collected in 2012 also exhibited notable alkene abundance (Fig. S16). The occurrence of alkenes in sheens comprising as much as 10% of TPH was confirmed by comprehensive two-dimensional gas chromatography and high-resolution time of flight mass spectrometry for sheen sample L1708654-04 (collected on 3/20/17; Fig. 3A and D. Figs. S18–S20). Such alkenes do not occur in native crude oils (Hunt, 1996) but are commonly used as a fluid phase in olefin-based fluids (or muds) used for drilling (Reddy et al., 2007; Aeppli et al., 2013). However, drilling muds are typically recovered prior to well completion and are expected to be rapidly flushed from a well once production begins, and thus their occurrence in sediments and sheens is likely related to drilling of the intervention wells. Notably, intervention well IW21 lost $> 4.8 \times 10^4$ l of drilling mud preceding plugging of well A21 in 2009 and is a potential source of the observed olefins. Our present interpretation of these observations is that drilling fluids were lost to the newly deposited (resulting from regional slope failure) sediments during intervention well drilling in 2009–2011, and remained a component of the release through at least 2017. Because drilling fluids are unlikely to originate within a reservoir, these observations indicate that hydrocarbons once entombed in the sediment were later exhumed and contributed to surface sheens. We interpret these results to indicate that hydrocarbons pooled in the sediment during the 2009–2011 well interventions and contributed to the release ≥6 years later, providing compelling evidence that sediments act as a hydrocarbon capacitor at MC20 and that remnant hydrocarbons are a component of the release at MC20.

3.5. Estimated sheen volume related to seafloor disturbance

Based on the observed chemical heterogeneity, we asked whether the release rate might also manifest heterogeneity. Data are yet to be made publicly available associated with the contemporary containment, but an internally-consistent time series of reports made to the USCG's National Response Center was available for analysis. Importantly, comparisons of sheen volume estimates for the time period from 9/1/2016 to 4/16/2019 show a statistically significant difference between periods of on-site benthic response activity (research in September 2018 and containment system installation in spring 2019) and those without. Results from the Welch's *t*-test produced t-statistics > 3 across all temporal comparisons with p-values < 0.005. Permutation tests run for each of the temporal comparisons produced statistically significant deviations of oil volumes in the upper 60–75% of the quantile range between periods of response activity and inactivity (Fig. 6; Fig. S21). Note the higher sheen volume on May 7, 2019 when the new containment system was operational coincides with a reported "mishap" involving a remotely operated vehicle that disturbed the seafloor sediments hours before the overflight (Fig. 6; ~100× the post containment median), and the higher volumes for February 2020 correspond to apparent repair work for the containment system. The implication of this analysis is that benthic disturbance releases hydrocarbons from sediments, which in-turn provides additional evidence that sediments act as a capacitor. This must be considered when interpreting data acquired during periods of benthic disturbance such as oil to gas ratios and flux estimates as presented in Mason et al., 2019. The sensitivity of hydrocarbon releases to benthic response activity has further implications for determining the source(s) of ongoing releases and for evaluating response actions.

3.6. Reservoir source constraints

Limited chemical composition data dating to MC20 exploration activities in the 1980s, and subsequent production activities, provide additional insight as to the release. Some reservoirs at MC20 exhibited relative *n*-alkane content substantially greater than in samples analyzed for this study, inconsistent with biodegradation within the reservoir, and consistent with high API gravity from regular production reports. Given the paucity of *n*-alkanes in any of the 97 sheen samples, we can reasonably exclude active and unimpeded flow from these un-biodegraded reservoirs as sources of the contemporary release. Chemical characterization is not available for each reservoir, but a review of API gravity for each well provides a possible proxy to exclude specific reservoirs as active contributors. To our knowledge this approach is not being considered by the responsible federal agencies, despite its potential to further reduce the complexity through reservoir exclusion. The elevated temperature and salinity of the reservoir fluids also provides potential constraint, insomuch as any active flow from a reservoir is expected to retain some of its reservoir characteristics, as was observed at two emission locations that were halted by intervention wells. The lack of elevated temperature or salinity anomalies reported for the ongoing release is informative and warrants investigation.

4. A path forward for MC20

The observations and analysis presented in this work reveal a complex release including multiple oil groups, a sediment repository, and no definitive evidence of hydrocarbon discharge directly from a reservoir. Currently a containment tent is suspended from the partially buried platform jacket and is collecting a majority of the emissions of hydrocarbons from underlying sediments. The USCG has stated that the system has a useful lifetime of approximately a decade, although presumed design flaws have prevented the complete elimination of surface sheens. Higher sheen volumes have been observed on some days post containment than were observed pre-containment (i.e. February 2020; Fig. 6). Nonetheless, since April 2019 this system has resulted in a substantial reduction in the frequency and extent of surface sheens. The final resolution for MC20 is uncertain but will be bounded by safety, environmental, engineering, liability and regulatory considerations, and is the focus of this section. Here we synthesize our findings in the context of other available information to address key questions that remain for MC20.

4.1. Why not complete conventional plug and abandonment?

Conventional plugging and abandonment is not considered a viable option due to safety and environmental risk. Conventional plugging and abandonment involves reentering the well vertically from the surface. The first attempt to dredge overburden to access well bores for conventional plugging and abandonment was in 2005. After multiple efforts, dredging was halted in 2007 because the unconsolidated sediments infilled the nascent excavation from the side and the bottom. Seafloor sediment instability makes large-scale excavation technically infeasible and unsafe (Fugro, 2006; Roberts and Bea, 2008). In addition, the exact failure condition of the buried pipes (e.g., bent, breached) is uncertain, as is the extent to which excavation would release hydrocarbons from the sediment. In September 2008, the former MMS (now BSEE) agreed that TEC was not expected to perform conventional plugging and abandonment activities on the wells.

4.2. Why not just plug all the remaining wells by drilling intervention wells?

In April 2008, MMS granted TEC approval for alternative procedures using intervention wells. The first intervention well was completed in March 2009 and the last (ninth) was completed in March 2011 (Table S1). In 2012, a Unified Command chartered workgroup

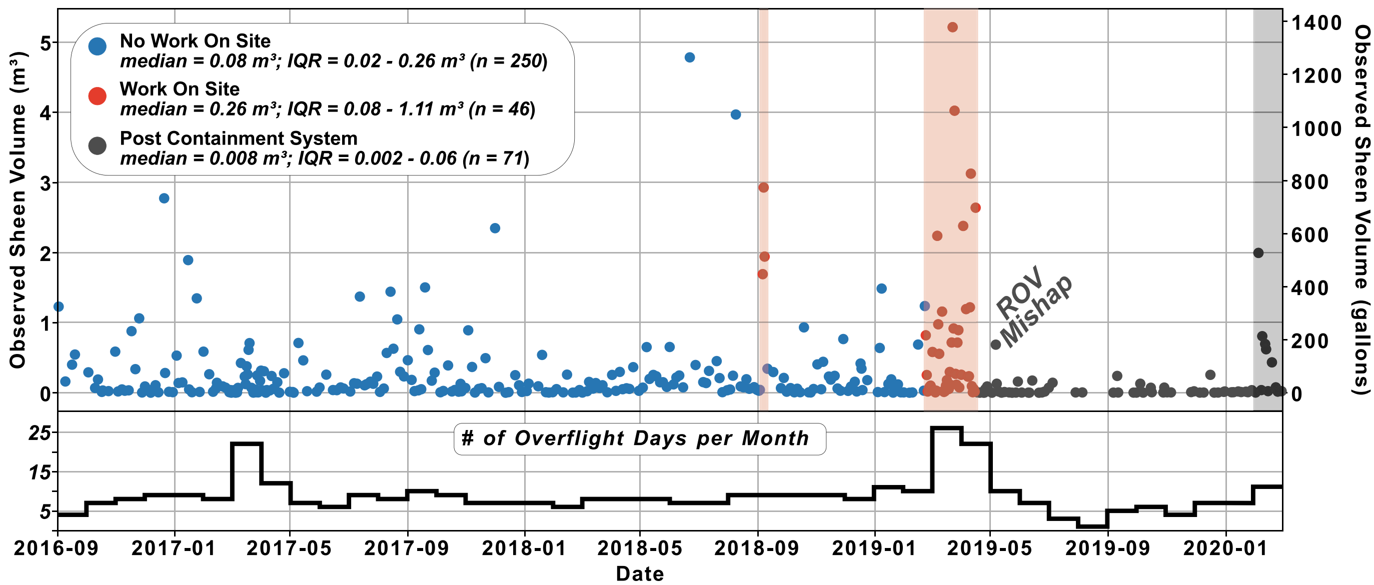

Fig. 6. USCG National Response Center overflight sheen volume estimates from 9/1/2016 to 3/1/2020. Periods of on-site work, specifically benthic activity, are shown in red with blue points denoting periods without benthic work. Gray points denote sheen volumes recorded following emplacement of the containment system completed in April 2019 with a recorded ROV "mishap" on 5/7/19 associated with elevated sheen volume observed on this date. The gray shading in February 2020 corresponds with an apparent failure and repair of the containment system. The lower histogram shows the number of sheen observation days for each month across the NRC dataset shown above. Note that the two periods of elevated observation frequency correspond to increased monitoring during the Sheen Source Location Work Group activities (March–April 2017; only ocean surface activity) and the preparation and installation of a containment system from 2/23/19 to 4/16/19 (denoted by the most recent red band and points). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

composed of representatives from USCG, BSEE, BOEM, and TEC determined the probability of success for the sixteen remaining interventions ranged from 6 to 42%. Because further intervention activity poses significant risk of negative environmental consequences and the probability of a loss of well integrity increases with each additional intervention well, no additional interventions have been planned. The risks with intervention wells include well collisions, inadequately plugged perforations that are in communication with higher-pressured reservoirs, cross-flow, breaches of near-surface seals, and other threats to well integrity. The benefit and risk associated with additional unconventional well interventions has been and remains at the forefront of the MC20 response and consideration of their utility should incorporate the observations from this research.

4.3. What are the major scientific uncertainties remaining at the site?

There remain key uncertainties at MC20: (1) shallow gas sources separate from deeper production reservoirs may contribute to or fully comprise ongoing gas releases; (2) there is potential for recharge to the release location from residual oils in sediments including along/within the bent conductors from the former platform area; and most importantly, (3) the evidence presently available suggesting an ongoing release of reservoir oils is not conclusive (contrary to recent claims - https://coastalscience.noaa.gov/project/mc20report/). This latter uncertainty should be resolved prior to taking actions that could worsen the release. In order to help address this uncertainty we have provided chemical constraints on the heterogeneity of hydrocarbon sources contributing to the sheens and sediments as well as documented specific instances of increased discharge associated with known benthic activity at the site.

4.4. Can data from the present containment system inform response?

The collection system at MC20 contains tanks that are pumped off on ~monthly basis. Collection of ≤3.8 $m^3\ d^{-1}$ has been reported, though it is important to note that the methodology has not been independently verified or validated, and reporting of capture rate to-date has appeared only through the media (Fears, 2019) and verbal presentations (Couvillion, 2020). The ongoing collection provides an opportunity to gather data that would inform the release, but requires modifications to the collection system and protocols. Presently, oil volume is measured only at the ~monthly pump-off, which we view as a lost opportunity to inform release dynamics. We suggest that the collection system be outfitted to measure the capture rate at higher temporal resolution, and to further measure gas release (note that gas is presently separated and vented subsea), temperature, and salinity. Furthermore, time-series of samples should be collected during pump-offs (or in-situ if possible) and made available for chemical analysis. The combination of capture rate, chemical composition, temperature, and salinity data could be invaluable for interpreting the dynamic behavior of oil and gas subseafloor, and inform possible and appropriate long-term solutions. Samples and data from the collection system should also be made available to parties outside the response, which is not present USCG practice.

4.5. What is a path forward for MC20?

The scope and complexity of actions taken during this response is unprecedented, yet after 15 years, no consensus has emerged as to the release mechanism or the path to a permanent resolution. Given the challenging scientific and technical nature of this problem and the stalled progress, we call on the responsible federal agencies to capitalize on the respite and opportunity afforded by active containment and initiate a fast-track study by the National Academies of Science, Engineering, and Medicine to develop response options. Through this established mechanism, independent experts can evaluate scientific uncertainties and advanced engineering solutions and potentially develop a path forward based on sound scientific and engineering principles. This mechanism further allows for a consideration of the policy ramifications for both protracted response operations and for the role of catastrophic events in the federal oil and gas leasing program. Nonetheless, major logistical hurdles must be overcome. First, a subset of the > 400 million dollars that remain held in trust for decommissioning at MC20 should be made available toward developing solutions, as presently these monies may only be used for implementation. A second major hurdle for any path forward is managing the liability associated with a failed outcome that results in the release of more oil, damage to property, or worse, causes harm to responders. These are genuine concerns given the challenging and complex environment at MC20.

Author contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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All survey operations described herein were conducted in coordination with cognizant regulatory agencies and approved by the MC20 Unified Incident Command; associated costs of survey and analyses were paid or reimbursed by Taylor Energy Company.

CRediT authorship contribution statement

Wade L. Bryant:Conceptualization, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Supervision, Project administration.**Richard Camilli**:Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration.**G. Burch Fisher**:Software, Formal analysis, Data curation, Writing - review & editing, Visualization.**Edward B. Overton**:Conceptualization, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing, Supervision.**Christopher M. Reddy**: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration.**Danny Reible**:Writing - original draft, Writing - review & editing.**Robert F. Swarthout**:Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization.**David L. Valentine**:Conceptualization, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision.

Declaration of competing interest

All authors have served or currently serve as consultants to the Taylor Energy Company, a company that exists solely to manage the response to the MC20 Incident, holds no assets, and produces no oil or gas.

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Appendix A. Supplementary data

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References

Aeppli, C., Reddy, C.M., Nelson, R.K., Kellermann, M., Valentine, D.L., 2013. Recurrent oil sheens at the Deepwater Horizon disaster site fingerprinted with synthetic hydrocarbon drilling fluids. Environ. Sci. Technol. 47, 8211–8219. https://doi.org/10.1021/es4024139.

Aeppli, C., Nelson, R.K., Radović, J.R., Carmichael, C.A., Valentine, D.L., Reddy, C.M., 2014. Recalcitrance and degradation of petroleum biomarkers upon abiotic and biotic natural weathering of Deepwater Horizon oil. Environ. Sci. Technol. 48, 6726–6734. https://doi.org/10.1021/es500825q.

Bureau of Safety and Environmental Enforcement, 2015. Incident archive - Taylor energy (Mississippi canyon) oil spill - U.S. coast guard fact sheet. Retrieved May 13, 2015 from. https://www.bsee.gov/newsroom/library/incident-archive/taylor-energy-mississippi-canyon/fact-sheet.

Camilli, R., 2008. Mississippi Canyon 20 Plume and Soil Contamination Survey Project Using the TETHYS Mass Spectrometer. Come Monday Inc, pp. 21 January 30, 2008.

Center for European Norms, 2012. Oil Spill Identification – Waterborne Petroleum and Petroleum Products – Part 2: Analytical Methodology and Interpretation of Results Based Upon GC-FID and GC-MS Low Resolution Analysis; Technical Report 15522–2. (Brussels, Belgium, Oct. 3, 2012).

Couvillion, T., 2020. A Rapid Response Solution Designed and Deployed at MC20 in the Gulf of Mexico to Successfully Contain the Longest Active Oil Spill in U.S. History. Gulf of Mexico Oil Spill and Ecosystem Science Conference, February 2020, Tampa, Florida.

Erten, M.B., Gilbert, R., El Mohtar, C.S., Reible, D.D., 2011. Development of a laboratory procedure to evaluate the consolidation potential of soft contaminated sediments. Geotech. Test. Journal 34, 467–475. https://doi.org/10.1520/GTJ103689.

Etkin, D.S., 2014. MC20 Final Risk Assessment and Cost Estimate (FRACE): Executive Summary. Report to Unified Command, March 26, 2014. Retrieved on December 20, 2019 from. https://mc20response.com/wp-content/uploads/2019/01/FRACE-Executive-Summary.pdf.

Fears, D., 2019. A massive gulf oil spill is finally being contained after more than 14 years. The Washington Post, May 16, 2019. Retrieved December 15, 2019 from. https://www.washingtonpost.com.

Fugro-McClelland Marine Geosciences, 2005. Fugro Conductor Probing Report, March 2005.

Fugro-McClelland Marine Geosciences, 2006. Seafloor Failure Analyses MC20-A Platform Block 20, Mississippi Canyon Area Gulf of Mexico. (Report No. 0201-5381-7).

Fugro-McClelland Marine Geosciences, 2007. Excavation Project Block 20, Mississippi Canyon Area, Gulf of Mexico. Geology and Engineering Analyses, Report No. 0201-6235-1, December 14, 2007.

Hunt, J.M., 1996. Petroleum Geochemistry and Geology, 2nd edition. W.H. Freeman, San Francisco.

Kienhuis, P.G.M., Hansen, A.B., Faksness, L., Stout, S., Dahlmann, G., 2016. CEN methodology for oil spill identification. In: Stout, S., Wang, Z. (Eds.), Standard Handbook Oil Spill Environmental Forensics. Academic Press, Boston, MA, USA, pp. 685–728. https://doi.org/10.1016/B978-0-12-803832-1.00014-3.

Korkmaz, S., Goksuluk, D., Zararsiz, G., 2014. MVN: an R package for assessing multivariate normality. The R Journal 6, 151–162.

Luttrell, K.M., 2018. United States Coast Guard: New Orleans, LA. (Notice of Federal Assumption, November 16, 2018).

MacDonald, I.R., Taylor, J.C., Roa, C., O'Reilly, C., 2019. Chapter 8. Estimates of oil flux to the ocean at MC20 using optical and acoustical methods. In: Mason, A.L., Taylor, J.C., MacDonald, I.R. (Eds.), An Integrated Assessment of Oil and Gas Release into the Marine Environment at the Former Taylor Energy MC20 Site. NOAA National Ocean Service, National Centers for Coastal Ocean Science. NOAA Technical Memorandum 260. Silver Spring, MD., June 2019, pp. 107–118. https://doi.org/10.25923/kykm-sn39.

Mardia, K.V., 1970. Measures of multivariate skewness and kurtosis with applications. Biometrika 57, 519–530. https://doi.org/10.2307/2334770.

Mason, A.L., Taylor, J.C., MacDonald, I.R. (Eds.), 2019. An Integrated Assessment of Oil and Gas Release into the Marine Environment at the Former Taylor Energy MC20 Site. NOAA National Ocean Service, National Centers for Coastal Ocean Science. NOAA Technical Memorandum 260, Silver Spring, MD. https://doi.org/10.25923/kykm-sn39. June 2019.

MC20 Unified Command, 2016. Standard operating procedures: aerial Overflight oil sheen observations. Retrieved from. https://mc20response.com/wp-content/uploads/2019/01/MC-20-Aerial-Observation-SOP_28SEP16_Update_Signed.pdf.

McLinn, E.L., Stolzenburg, T.R., 2010. Ebullition-facilitated transport of manufactured gas plant tar from contaminated sediment. Environ. Toxicol. Chem. 28, 2298–2306. https://doi.org/10.1897/08-603.1.

National Oceanic and Atmospheric Administration, 2016. Open water oil identification job aid for aerial observation. In: With Standardized Oil Slick Appearance and Structure Nomenclature and Codes. NOAA Office of Response and Restoration, Emergency Response Division, Seattle, Washington, pp. 1–51. Retrieved from. https://response.restoration.noaa.gov/sites/default/files/OWJA_2016.pdf.

Paull, C.K., Talling, P.J., Piper, D.J.W., 2013. How are subaqueous sediment density flows triggered, what is their internal structure and how does it evolve? Direct observations from monitoring of active flows. Earth-Sci. Rev. 125, 244–287. https://doi.org/10.1016/j.earscirev.2013.07. 005.

Paull, C.K., Talling, P.J., Maier, K.L., Parsons, D., Xu, J., Caress, D.W., Gwiazda, R., et al., 2018. Powerful turbidity currents driven by dense basal layers. Nat. Commun. 9, 4114. https://doi.org/10.1038/s41467-018-06254-6.

Pineda-Garcia, O., 2018. Expert Report of Oscar Pineda-Garcia, Ph.D. Rec Doc 81-03 Exhibit 3. Taylor Energy Company LLC v. The United States (No. 16-12C, United States Court of Federal Claims, September 14, 2018).

Reddy, C.M., Nelson, R.K., Sylva, S.P., Xu, L., Peacock, E.A., Raghuraman, B., Mullins, O.C., 2007. Identification and quantification of alkene-based drilling fluids in crude oils by comprehensive two-dimensional gas chromatography with flame ionization detection. J. Chromatogr. A 1148, 100–107. https://doi.org/10.1016/j.chroma.2007.03.001.

Roberts, H.H., Bea, R., 2008. Stability Analyses of Excavation on Submarine Apron of Mississippi River Delta Block 20, Mississippi Canyon Area Gulf of Mexico. Taylor Energy Company, New Orleans, LA (39 pages).

Sheen Source Location Work Group, 2017. MC20 Unified Command Sheen Source Location Workgroup Final Report 11.17.2017. Retrieved September 20, 2019 from. https://mc20response.com/wp-content/uploads/2019/01/SSLWG-Final-Report-including-individual-scientific-rpts.pdf.

Stout, S.A., 2016. Oil spill fingerprinting method for oily matrices used in the Deepwater Horizon NRDA. Environ. Forensic 17, 218–243. https://doi.org/10.1080/15275922.2016. 1177759.

Stout, S.A., 2018. Expert Report of Scott A. Stout, Ph.D., P.G. Rec Doc 81-4 Exhibit 4. Taylor Energy Company LLC v. The United States, No. 16-12C, United States Court of Federal Claims September 11, 2018.

Sun, S., Hu, C., Garcia-Pineda, O., Kourafalou, V., Le Hénaff, M., Androulidakis, Y., 2018. Remote sensing assessment of oil spills near a damaged platform in the Gulf of Mexico. Mar. Pollut. Bull. 136, 141–151. https://doi.org/10.1016/j.marpolbul.2018.09.004.

United States Coast Guard, 2014. Chapter 20: Oil Spill. In: U.S. Coast Guard Incident Management Handbook. Commandant Publication P3120.17B, Washington, DC (May 2014).

United States Coast Guard, 2018. MC20 Records Index Unified Command Response. Unified Command, New Orleans, LA August 27, 2018. Retrieved on December 20, 2019 from. https://mc20response.com/wp-content/uploads/2019/01/Record-Index-Aug-2018.pdf.

United States Coast Guard Marine Safety Laboratory, 2012. Oil Sample Analysis Report, MSL Case Number 12–204; Unit Case/Activity Number 3253625. (Coast Guard Sector New Orleans, August 2012).

United States Coast Guard Marine Safety Laboratory, 2013. Oil Sample Handling and Transmittal Guide, 8th edition. (New London, CT, January 2013).

United States Coast Guard National Response Center, 2019. Retrieved December 20, 2019 from. http://www.nrc.uscg.mil.

United States Environmental Protection Agency, 2019. Superfund National Priorities List (NPL) Sites – By State. Retrieved on December 1, 2019 from. https://www.epa.gov/superfund/national-priorities-list-npl-sites-state.

Welch, B.L., 1947. The generalization of "Student's" problem when several different population variances are involved. Biometrika 34, 28–35. https://doi.org/10.1093/biomet/34.1-2.28.