Lawrence Berkeley National Laboratory

Recent Work

Title

Transport and Fate of Natural Gas and Brine Escaping from a Hydrocarbon Reservoir Through a Failed Deepwater Well in the Oceanic Subsurface of the Gulf of Mexico

Permalink

<https://escholarship.org/uc/item/45h7r0wj>

Journal

Transport in Porous Media, 127(2)

ISSN

0169-3913

Authors

Reagan, MT
Moridis, GJ
Keen, ND
[et al.](#)

Publication Date

2019-03-30

DOI

10.1007/s11242-018-1207-y

Peer reviewed

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

TRANSPORT AND FATE OF NATURAL GAS AND BRINE ESCAPING FROM A
HYDROCARBON RESERVOIR THROUGH A FAILED DEEP-WATER WELL IN THE
OCEANIC SUBSURFACE OF THE GULF OF MEXICO

*M.T. Reagan,^{1,4} G.J. Moridis^{1,2}, N.D. Keen¹, Lee, K.J.²,
M. Natter³, T. Bjerstedt³, and W.W. Shedd³*

¹*Energy Geosciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720.*

²*Department of Petroleum Engineering, Texas A&M University, College Station, TX 77843.*

³*Bureau of Ocean Energy Management, New Orleans, LA 70123.*

⁴*Corresponding author: mtreagan@lbl.gov*

Acknowledgements

This work was carried out under Interagency Agreement M14PG00044 between the Bureau of Ocean Energy Management and Lawrence Berkeley National Laboratory. This research used resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

26Abstract

27The possibility of broaching, or the release of fluids at the seafloor due to a damaged or faulty
28well, is a hazard that must be assessed in the well-permitting process. This paper describes a
29numerical simulation study of a real-life scenario where a complex, permeable sandy formation,
30connected to the seafloor via known chimneys/seeps, is intersected by a damaged production
31well that drains another deeper, gas-bearing formation. The objective of the study to determine
32the transport and fate of hydrocarbon reservoir fluids (gas and brines) escaping into the sandy
33formation through the casing shoe of the failed well, and to determine the time it takes for these
34contaminants to reach the ocean floor. We conducted a detailed simulation study to represent the
35conditions, properties, and behavior of the system under such failure conditions, and we
36investigated the migration of gas and brine for a range of reservoir and chimney properties. A
37key conclusion is that, for such complex systems, modeling the three-dimensional geometry of
38the system in detail is key to describing transport and assessing the time and magnitude of
39potential releases. For the system studied here, transport times range from under two years
40(highest permeabilities) to many decades, ensuring significant time to respond to potential
41broaching hazards. Under the conditions investigated in this study, we also determine that gas-
42dominated releases associated with low rates of water flow into the sandy formation are likely to
43cause hydrate formation that can reduce permeabilities in the colder, upper regions of the
44chimneys and possibly mitigate releases.

45

46Keywords

47Broaching, Hydrate Formation, Well Failure, Hazard Assessment, Reservoir Simulation

48

491. Introduction

50

51Oil and gas production in the Gulf of Mexico often requires complex drilling technologies,
52including the use of directional drilling at great depths. Improperly constructed or damaged well
53casings could allow the escape of reservoir fluids into formations they intersect, creating the
54possibility of contaminant releases at the seafloor—a phenomenon referred to as broaching. The
55Bureau of Ocean Energy Management (BOEM) began performing broaching evaluations after
56the uncontrolled release of oil and gas from the Macondo reservoir in Mississippi Canyon Block
57252 (Oldenburg et al., 2012). The sub-seafloor segments of the Macondo well had apparently
58maintained integrity and the well was eventually capped successfully. The Macondo study
59addressed the problem of well failure at the ocean floor, and as such could not provide answers
60to the question of how long it could take for broaching to occur after a well failure deeper in the
61oceanic subsurface. For scenarios where a well failure creates connectivity between a deep, over-
62pressured hydrocarbon reservoir and overlying permeable formations, there is no methodology to
63determine the fate and transport of the released fluids and whether broaching is a possibility.
64Hazard assessments must be performed to determine whether uncontrolled releases could be
65contained and stopped in time to prevent escape of hydrocarbons into the environment. For
66example, how much time would be available to drill a relief well before broaching occurs at the
67seafloor?

68

69To answer some of these questions, BOEM completed an Interagency Agreement with the U.S.
70Department of Energy/Lawrence Berkeley National Laboratory to carry out 3D modeling of
71possible scenarios of reservoir fluid releases from compromised casing shoes in two real-life

72systems that had been qualitatively judged as either likely or possible to result in broaching. This
73paper describes the numerical simulation work for scenarios associated with the first system: a
74“supra-salt” system where a permeable formation, connected to the seafloor via known
75chimneys/seeps, is intersected by a damaged well producing from a deeper formation.

76

77The system of interest involves a roughly 6 km x 10 km (3.7 x 6.2 mi) region of permeable sand
78(the Purple Sand) intersected by a well producing from a deeper, warmer, higher-pressure
79formation (Figure 1). The Purple Sand is flanked by two chimneys (Figure 2) that are considered
80permeable to fluids escaping from deeper hydrocarbon reservoirs in the Gulf of Mexico -- at
81least one of them has been confirmed to be a prolific hydrocarbon seep (Garcia-Pineda et al.,
822010; Roberts et al., 2010). Portions of the Purple Sand formation climb updip from the potential
83casing-shoe failure point toward the two chimneys, both of which are confirmed active oil and
84gas seep sites. This suggests there are clear pathways for migration to the seafloor of fluids
85released into the Purple Sand. The seeps, seismic wipe out zones, and sea bottom seismic
86amplitude anomalies in association with them provide strong evidence for a leaky system (Figure
872).

88

89The goal of the overall simulation study is to assess the potential transport of reservoir fluids
90through the Purple Sand and the possibility of the emergence of reservoir fluids (gas and brine in
91this case) at the seafloor if a permeable pathway is created between the deeper reservoir and the
92Purple Sand via a failure in the intersecting well. To accomplish this, we conducted a detailed
93simulation study that faithfully represented the conditions, properties, and behavior of the system
94under such a release.

962. Methodology

972.1 Mesh Generation and System Initialization

98The effort to discretize the domain for the simulation effort included two different sets of grids.

99The first set was that of the elevation grids and included elevation data (from the dataset
100represented by Figure 2) to the top of the Purple Sand on a regular pattern (ranging in spacing
101from 150 ft x150 ft to 50 ft x50 ft). The elevation grids served as the basis for the development of
102the simulation grids, i.e., the element system used by the pTOUGH+HYDRATE simulations
103(Moridis et al., 2008; Zhang et al., 2008; Moridis, 2014). Unlike the elevation grids, the
104simulation grids (which were developed by the LBNL team) were irregular in the element size,
105providing higher definition in the vicinity of important features and a coarser discretization at
106locations that did not appear to play key roles in the fluid transport (as determined and confirmed
107by scoping simulations).

108

109BOEM provided mapped data from 3D depth migrated seismic showing the geometry of the
110geosystem over multiple Outer Continental Shelf (OCS) blocks. Mapped data was interpreted on
111a GeoFrame workstation using U.S. feet in Universal Transverse Mercator (UTM) 15 projection.
112Mapped surfaces on the top of salt and on the top of the Purple Sand and 3D seismic arbitrary
113lines provided the system geometry, and GIS shape files of sea floor features and seismic
114amplitude were available for overposting. The mechanical and formation fluid properties for the
115Purple Sand were obtained from well logs by BOEM staff using Log Evaluation System Analysis
116software.

117

118The extreme thinness of the Purple Sand carrier bed compared to the lateral dimensions of this
119formation, the very large height of the chimneys, the undulations of the sand, and the steepness
120of the elevation gradient near the base of the chimneys, coupled with the need to integrate a flow
121pathway to each seep site resulted in frequent vertical discontinuities using conventional
122TOUGH+ mesh generation methods. The MeshMaker 2.0 (MM2) gridding software (Moridis
123and Keen, 2015; Moridis, 2016) was developed specifically to address the challenges of this
124system geometry. MM2 uses the elevations of the top of the formation over its footprint (using
125data provided in tabular form) and powerful 3D interpolation algorithms to create grids that can
126conform to practically any irregular geometry. The new grids created by MM2 eliminated a
127common continuity problem in undulating surfaces by incorporating directional slopes and
128correct volumes and surface areas into elements describing those surfaces. MM2 thus allows
129irregular meshes to represent complex surfaces, while still providing the numerical stability
130afforded by meshes of pure “stacked bricks” without the distortions that such configurations
131impose on fluid flow.

132

133Several realizations of various grid refinement levels were constructed following the process
134described above, including up to 6.7M gridblocks. After comparisons of the 3D images of the
135grids (in an effort to determine which iteration captured key geometric features of the system)
136and of the corresponding execution times, a grid involving 2.65M gridblocks (Figure 3) was
137selected as the most appropriate for the simulations because it reproduced with high fidelity the
138system geometry while requiring reasonable (relatively-speaking) execution times.

139

140The final 3D system, with 2,647,145 gridblocks, was brought to a physically correct initial state
141via numerical simulation, using as fixed reference points the pressures corresponding to the
142seafloor depths at the tops of the two chimneys and temperatures at the seafloor, as well as a
143representative “average” sub-seafloor temperature gradient (see Table 1). A long-term simulation
144then calculated the hydrostatic pressure field and the equilibrium temperature profile for the
145given sediment properties. For systems that lie within the zone of hydrate stability (and thus have
146a potential for hydrate occurrence or hydrate formation if methane becomes available at the
147location under investigation), this is the only physically correct and consistent way to establish
148an initial condition. The results of this simulation provided stable initial conditions for
149subsequent fluid release modeling.

150

151The initial conditions included:

- 152 • A hydrostatic pressure distribution in the entire 3D domain (Purple Sand and chimneys,
- 153 • A specified average temperature gradient from the BOEM dataset: 2.71°C/100m, with an
154 estimated seafloor temperature of 3.9°C at the seafloor (Gallaway et al., 2001; Forrest et
155 al., 2007),
- 156 • An assumption of 1 ppm background methane in the aqueous phase. This was a
157 reasonable assumption (given the lack of information on the subject), and has no impact
158 even if it is incorrect because (a) methane solubility in water is very low and (b)
159 dissolved gas is overwhelmed when gas from the reservoir is released either as free gas.

160

161The physical parameters used were supplied by BOEM, or selected under consultation with
162BOEM, and are given in Table 2 and Table 3. Figures 3 and 4 show the mesh connectivity and
163the initial pressure distribution at the various components of this 2.6M-element system viewed

164from different angles. In Figure 3, an overall view of the system (view at an angle, from above),
165shows the extensive but thin Purple Sand, with the two chimneys, A and B, reaching upward to
166the seafloor. Note that impermeable sediments, represented as heat-transfer boundaries, are not
167shown in this or any other rendering—only permeable formations are visualized. Figure 4 shows
168a rotated view of the system, with a close-up of Chimney B and its mesh connectivity. These
169visualizations of the simulation mesh will be used later in this paper to render the water and gas
170distributions in the failure scenarios. Visualizations were performed using the tough-convert
171postprocessor (Queiruga, 2018).

172

1732.2 Reservoir Simulation

174Following mesh creation and system equilibration, we conducted a set of simulations describing
175several scenarios of casing-shoe failure. We varied the permeability of the sand and chimneys to
176assess the basic sensitivity to system properties. Because of lack of information on its properties
177(and a conservative approach), the fault near the base of the Chimney A was treated as a
178permeable feature, and the elevation offset was described using steeply angled but connected
179gridblocks. In the spirit of the “worst-possible scenario”, this approach allowed the fastest
180possible upward flow toward the chimney.

181

182For each release scenario, constant-pressure and temperature conditions were imposed at the
183casing shoe failure point. These were the conditions in the connecting reservoir, without any
184adjustment for the elevation differences between the reservoir and the casing shoe: $P = 51$ MPa
185and $T = 63.3^{\circ}\text{C}$. Because the pressure and temperature drops in the failed well could not be
186estimated, this conservative approach was followed. The gas saturation at the failure point was

initially $S_G = 0.99$, with an alternative case of $S_G = 0.89$ used to study the effects of water release in concert with gas release. The point of leakage was also given the properties of an open well, a pseudo-medium with $\phi = 1$, a high $k = 5 \times 10^{-9} \text{ m}^2$, a capillary pressure $P_c = 0$, a relative permeability that was a linear function of the phase saturations in the wellbore, and a low (but nonzero) irreducible gas saturation $S_{irG} = 0.005$. Simulations were run to a maximum duration of 100 years, or until a logical stopping point was reached, e.g., gas and brine broaching at one or both chimneys. During the simulations, we monitored the flow of fluids through the tops of the chimneys and monitored T and P conditions at selected points within the chimneys and in the Purple Sand.

The parametric variations used for the sensitivity study were:

Released Gas Saturation, S_G :	0.89, 0.99, with corresponding aqueous saturations
	$S_A = 0.11$ and 0.01 , respectively
Chimney Permeability, k_C :	$k_C = 541 \text{ mD}$, 100 mD , 1000 mD for $k_S = 541 \text{ mD}$
Sand Permeability, k_S :	$k_S = 541 \text{ mD}$, 100 mD , 1000 mD for $k_C = 541 \text{ mD}$

Simulation runs were performed using the pTOUGH+HYDRATE parallel code (Zhang et al., 2008), an MPI parallel version of the TOUGH+HYDRATE (T+H) code. T+H can model all the known processes involved in the system response of natural CH_4 -hydrates in complex geologic media (Moridis et al., 2014; Moridis and Pruess, 2014). T+H is a fully compositional simulator, descended directly from the TOUGH family of codes (Pruess, 2003), and it accounts for heat and up to four mass components (i.e., H_2O , CH_4 , CH_4 -hydrate, and water-soluble inhibitors such as salts) that are partitioned among four possible phases (gas, aqueous liquid, ice, and hydrate). It

can describe 15 possible thermodynamic states (phase combinations) of the CH₄+H₂O system and can handle the phase changes, state transitions, strong nonlinearities, and sharp fronts that are typical of hydrate dissociation problems. Runs were performed on NERSC Edison and Cori I, and LBNL's Lawrencium LR3 and LR4 using 384 to 4,096 processors and a total of about 1.1 million CPU-hours.

215

3. Results

3.1. All-Gas Reference Case ($k_c = k_s = 541$ mD)

Water and Gas Flows. Figure 5 shows the total upward gas and water flows at the seafloor through the top of Chimney A and Chimney B (flows through A and B were summed in pT+H to give an estimate of the total flow through both chimneys). As gas first approaches the seafloor, upward water flow increases, driven by buoyant gas rise within Chimney B. The gas first reaches the top of Chimney B, where the gas breakthrough at the seafloor begins at $t = 926$ d. Gas escapes continuously from the top of Chimney B until an abrupt cessation of gas escape at $t = 1,287$ d. Total water flows decrease during the initial period of gas release, reaching a local minimum just before the cessation of the gas release. Visualizations of the simulation results (shown in the next section) indicate that 100% of the gas release occurs at Chimney B for $t \leq 1,287$ d. Water flows increase gradually until $t = 1,959$ d, at which point gas release begins at Chimney A. The simulation was halted after 2,000 d. Water flows decrease once gas appears at the top of Chimney B.

230

Hydrate formation. The cessation of gas flow and the reduction of water flows are explained by the formation of hydrate near the summit of Chimney B. Figure 6 shows the total system-wide

233rate of hydrate formation vs. time for the entire simulation. Hydrate begins to form at $t = 840$ d,
234just before gas begins to escape into the ocean from the top of Chimney B. As shown by the
235visualization of the simulation results, this hydrate formation occurs entirely in Chimney B when
236the rising released gas arrives at depths with appropriately low temperatures for hydrate
237formation to occur. Hydrate formation continues as gas escapes from Chimney B at the seafloor,
238and proceeds at varying rates (as affected by changing temperature, pressure and salinity at the
239locations where hydrates form). Thus, the rate of hydrate formation Q_H reaches a first peak at
240about $t = 926$ d, and attains a maximum rate at about $t = 1,450$ d. The period from $t = 920$ d to
2411,200 d corresponds to the period of gas release at the seafloor. A column of rising gas forms a
242“tunnel” of solid, low-permeability hydrate with a permeable core, as coupled flow, thermal and
243phase behavior processes temporarily allow an open channel for gas to flow even as hydrate
244accumulates in the surrounding chimney sediments. As the hydrate saturations increase, the
245effective permeability of Chimney B decreases. Eventually, the effective permeability in the
246chimney drops to zero when hydrate saturations exceed 80%. When this occurs at about $t = 1,287$
247d, the top of Chimney B is effectively blocked, and the hydrate formation rate increases as gas
248rising in the chimney is trapped below an impermeable layer of hydrate.

249

250System-wide hydrate formation rates begin to increase again at $t = 1,900$ d, and this increase is
251associated with gas moving upward in Chimney A and encountering suitable pressures and
252temperatures for hydrate formation and stability. The decline in the corresponding water flow
253rates that are evident in Figure 5 are associated with hydrate formation in Chimney A and the
254resulting reduction in permeability. Continuation of gas flow and hydrate formation in Chimney
255A is expected to lead eventually to complete blockage to flow (as is the case in Chimney B).

256

257Figure 7 shows the cumulative hydrate mass formed within the entire simulated domain. We can
258identify the onset of hydrate formation in Chimney B at $t = 840$ d, the formation of hundreds of
259millions of kilograms of hydrate over the course of 1,200 d, and also the upward inflection in the
260cumulative curve at $t = 1,900$ d when hydrate begins forming in Chimney A.

261

262*Visualizations.* New 3-D visualization capabilities, developed in the course of the overall project,
263allow detailed tracking of gas plumes across the simulation domain. For this simulation case, the
264visualizations are renderings of mesh connectivity (each connection between elements as a line
265segment) as previously shown in Figures 3 and 4, with the gas and/or the hydrate saturations
266mapped onto the line segments via color scales. This allows some limited transparency in the
267visualization, helping to better represent the movement of gas within the thin body of the Purple
268Sand and along the sides of the chimneys.

269

270Figure 8 shows the evolution of gas saturation with a view directed toward Chimney B at
271selected simulation times. The intersection of the failed well with the Purple Sand layer is at the
272lower left corner of the domain. At $t = 180$ d and $t = 640$ d, the escaping gas expands outward
273from the point of the casing shoe failure, and is seen to preferentially move toward Chimney B
274(upper left). At $t = 870$ d, the gas has already reached Chimney B, and is seen rising (primarily
275by buoyancy, although there is some pressure differential and upward flow of water) through the
276side of the chimney facing the leak. The panel at $t = 1,000$ d depicts the phase saturation
277distributions just after gas reaches the seafloor (i.e., the boundary at the top of Chimney B). At
278this point, the permeability at the top of the chimney begins to decrease because of hydrate

279formation. The panel at $t = 1,360$ d provides a snapshot of the system just after the cessation of
280the flows of gas and water to the seafloor through the top of Chimney B, with the gas saturation
281at the top of the chimney showing evidence of uniformity—essentially the plugged chimney is
282now filling up with gas rising from below. The last frame, at $t = 2,000$ d, shows a chimney with
283the upper several hundred meters filled with gas saturations $S_G \geq 0.50$.

284

285The advance of gas toward, and release through, Chimney A is illustrated by the four frames in
286Figure 9. At $t = 60$ d and $t = 1,280$ d, the gas is seen moving in a broad front toward the chimney.
287By $t = 1,730$ d, the topographical characteristics of the Purple Sand cause the front to split into
288two plumes moving toward Chimney A, one heading upslope along the upthrown footwall of the
289fault to the chimney on the left, and one heading upslope along the downthrown hanging wall of
290the fault. By $t = 1,910$, the gas has reached Chimney A through both pathways, a lower entry
291point near the downthrown hanging wall to the right and through a more tortuous path over the
292upthrown footwall to the left. Breakthrough, or broaching, at the seafloor occurs soon after, as
293gas rises to the top of the chimney via buoyancy and pressure gradients.

294

295The evolution of hydrate saturation in Chimney B is illustrated by the four frames in Figure 10.
296At $t = 910$ d, hydrate appears along the side of the chimney as the rising gas deposits the first
297layers of solid hydrate. By $t = 1,090$ d, hydrate formation has reached the seafloor, and
298saturations increase rapidly near the top of the chimney, with a corresponding reduction in
299permeability. The frame for $t = 1,280$ d depicts the hydrate saturation distribution just as water
300and gas flows out of the chimney have ceased. At that time and beyond, gas accumulating in the
301chimney leads to hydrate formation at successively lower elevations within the chimney (in

parallel with the accumulation of gas in those regions, see Figure 8). At $t = 2,000$ d, hydrate deposits at saturations of $S_H \geq 0.50$ are extensive throughout Chimney B even at elevations hundreds of meters below the seafloor, creating permeability barriers to upward flow.

305

3063.2. Sensitivity to Permeabilities.

To assess the complex variation in breakthrough times (at the seafloor), multiple full simulations of the broached system were conducted using identical initial conditions, but higher or lower permeabilities for the Purple Sand and for the chimney media. The range of permeabilities included:

311

Chimney Permeability, k_c : $k_c = 100$ mD, $k_c = 541$ mD, $k_c = 1000$ mD for $k_s = 541$ mD

Sand Permeability, k_s : $k_s = 100$ mD, $k_s = 541$ mD, $k_s = 1000$ mD for $k_c = 541$ mD

314

For the sensitivity simulations, simulation length was limited to the point of gas breakthrough at the seafloor, as dictated by the need to efficiently utilize limited supercomputer CPU time. For these sensitivity simulations, we did not conduct a full analysis of hydrate formation and permeability reduction because we expected similar behavior for all cases that exhibit breakthroughs. The breakthrough curves for the permeability cases listed above are found in Figure 11.

321

As would be expected, lower-permeability features result in longer times until release at the ocean floor. Decreasing the chimney permeability by a factor of five results in a 60% longer breakthrough time (625 days) for gas to appear at the seafloor. Doubling the chimney

permeability, however, results in only a slightly faster appearance of gas at the seafloor (by 64 days only, probably because of the rapid rise of the buoyant gas in the limited vertical dimension of the chimney). Decreasing permeability of the Purple Sand to 100 mD, however, has, unsurprisingly, a large effect—gas takes 3.5X longer (3,858 days) to emerge at the ocean floor. Doubling the sand permeability, conversely, only shifts the gas breakthrough forward by 309 days (617 days).

331

Plots of the arrival times at the seafloor (solid lines) and of the arrival times at the base of chimney B (dotted line) are presented in Figure 12, which shows the significantly non-linear dependence of these times on the permeabilities of the various components of the system. The red curve gives arrival times at the seafloor for $k_s = 541$ mD and k_c values of 100, 541 (base), and 1000 mD. The blue curve shows arrival times at the seafloor for $k_c = 541$ mD, and k_s values of 100, 541 (base), and 1000 mD. Figure 12 also shows arrival times at the base of chimney B (first gas exiting the Purple Sand) for k_{sand} values of 100, 541, and 1000 mD with $k_{chimney} = 541$ mD (arrival times at the chimney did not vary significantly with $k_{chimney}$).

340

To help with hazard assessment, parametric expressions were created to estimate arrival time for a range of permeabilities. A series of curve fits was used in an attempt to represent the limited data points as a larger response surface. Various functional forms (polynomial, power laws) were tested, and the resulting curves were selected for convenience and ease-of-use. Although the system is very complex (and strongly dependent on the specific geometry of the sand in particular), it is reasonable to expect the arrival times to vary smoothly and gradually with

respect to permeabilities. Thus, the curves generated through fits to an exponential form gave the only smoothly varying representation.

After fitting the data within Igor Pro (our data analysis and plotting environment), we generated the following equations:

Equation (1) estimates the arrival time at chimney B for varying Purple Sand permeabilities.

$$t_{chimney} = 418.62 + 4814.5 \exp\left(-5.2184 \times 10^{-3} k_s\right) \dots\dots\dots(1)$$

Equation (2) estimates the arrival time at the seafloor for varying chimney permeabilities when $k_s = 541$ mD.

$$t_{seafloor} = 855.51 + 1171.9 \exp\left(-5.1974 \times 10^{-3} k_c\right) \dots\dots\dots(2)$$

Equation (3) estimates the arrival time at the seafloor for varying Purple Sand permeabilities when $k_c = 541$ mD.

$$t_{seafloor} = 584.77 + 5506.6 \exp\left(-5.1407 \times 10^{-3} k_s\right) \dots\dots\dots(3)$$

These single-parameter variations can be expanded to a multiparameter surface. However, one additional detail that must be included is that the transit times through the chimneys, while largely a function of chimney permeability, will also vary slightly due to Purple Sand

permeability. Differences in permeability may cause a different quantity of gas to arrive, or to arrive at a slightly different location. Additionally, attenuation via hydrate formation may change transit times. Consequently, a general equation for estimating breakthrough must include time-to-chimney, $t_{chimney}(k_s)$ and both $t_{chimney-seafloor}(k_c)$, and $t_{chimney-seafloor}(k_s)$. Calculated chimney transit times and the variation in transit times due to the effect of k_s are shown in Figure 13.

375

Now we can construct a parameterization of broaching time as:

377

$$t_{seafloor}(k_s, k_c) = t_{chimney}(k_s) + t_{chimney-seafloor}(k_c) + t_{difference}(k_s) \dots\dots\dots(4)$$

379where

$$t_{difference}(k_s) = t_{chimney-seafloor}(k_s) - t_{chimney-seafloor}(k_c = 541 \text{ mD}) \dots\dots\dots(5)$$

381

Fitting each of the three terms to exponentials results in the following parametric expression:

383

$$t_{seafloor}(k_s, k_c) = 513.95 \dots\dots\dots(6)$$

$$+ 4814.5 \exp(-5.2184 \times 10^{-3} k_s)$$

$$+ 1172.9 \exp(-5.1974 \times 10^{-3} k_c)$$

$$+ 696.78 \exp(-4.6773 \times 10^{-3} k_s)$$

388

A visualization of the 3D surface associated with Equation (6) is given in Figure 14.

390

Note that these estimates are entirely a function of the specific (complex) geometry of the Purple Sand (and, to a lesser extent, of the chimneys), as represented in the model. For a system of this

complexity, the gas arrival times at various locations of interest in the domain are strongly dependent on the accuracy of the 3D model. Heuristics that attempt to generalize to other (even similar) systems are not likely to be accurate. Note that the potential for hydrate formation and permeability reduction must be considered in any analysis of similar systems.

397

3.3. Water and Gas Release

Water and Gas Flows. Preliminary data provided by BOEM suggested a water saturation of approximately 11% within the underlying reservoir. As this is somewhat larger than the irreducible saturation of the Purple Sand, we considered an additional gas-release case where the released fluids included 11% water (likely an upper limit for water release). All other initial conditions were equal to the previous case.

404

The water-gas case exhibits drastically lower release rates at the shoe failure point, and much longer timeframes for gas migration. Figure 15 gives water and gas flow rates and cumulative release at the point of the leak vs. time. After an initial surge for $t < 1$ d, the release rates drop rapidly and eventually settle at a low rate of $0.03 \text{ m}^3/\text{s}$ of gas and 19 kg/s for water. This is because of relative permeability effects, limited pressure gradients and weak buoyancy (as the density difference between the released brine and the native water is small).

411

Monitoring points within the Purple Sand (a point opposite the broach) and points in the center of each chimney tracked evolving conditions during the course of the release (Figure 16). We observe sharp increases in temperature within the chimneys after a few hundred days of leakage. This is caused by the constant flow of the warmer water into the system, and the temperature

416increases are attributed to both the temperature of the leaking water (63.3 °C) and the fact that
417warmer water from deeper parts of the Purple Sand is swept upward toward the seafloor. As a
418results, the simulation was run for an additional 30 yr, to $t = 100$ yr, and yet no hydrate formation
419occurs anywhere in the system.

420

421*Visualizations.* Visualizations of the evolving system are shown in Figure 17. At $t = 4$ yr, the
422expanding plume of gas moves away from the failure point, but much slower than in the all-gas
423case (Figures 8 and 9). By $t = 25$ yr, the plume has separated into two lobes, each heading toward
424each of the chimneys via the local high point (saddle) in the Purple Sand that connects the bases
425of the chimneys. Gas reaches the base of the chimneys at $t = 41$ yr, and reaches the seafloor at
426both chimneys at $t = 70$ yr. Careful examination of the visualizations shows the appearance of
427gas throughout and Purple Sand, and in areas away from the main plume as well, after $t = 41$ yr.
428This is caused by exsolution of dissolved gas from the aqueous phase due to the temperature
429increases as warmer water moves outward and upward from the release point at the casing shoe.

430

431To track the movement of the water front, Figure 18 visualizes the salinity of the pore water over
432the same time intervals as seen in Figure 17. To create a natural tracer, the reservoir water
433entering at the failed casing shoe was given a concentration of 3.6wt% vs. 3.5wt% for water in
434the Purple Sand at the initial condition. This allows clear visualization of the water front.
435Compared to the narrow plumes of gas seen moving along the high points of the Purple Sand
436topography, the water front expands outward uniformly (because of favorable relative
437permeability conditions and very small density differences with the native water), initially
438outpacing the released gas at $t = 4$ yr and 25 yr. The more saline water enters the chimneys

roughly at the same time as the gas at $t = 41$ yr, and reaches the seafloor at $t = 70$ yr. However, by this time the reservoir brine has largely displaced most of the water in the Purple Sand.

The most important conclusion from this alternative scenario is that the release of water with the gas shifts the timeframe for potential broaching from a few years to several decades. Release of water also adds heat (and, if the reservoir fluids are even more saline, an inhibitor) and prevents the formation of hydrate at the tops of the chimneys. Release rates are thus much smaller, broaching is delayed significantly, but the mitigating effects of hydrate formation will not be a factor.

4. Conclusions

The key conclusion from this investigation is that, for a system as complex as the Purple Sand/Chimney system, the three-dimensional geometry of the system is key to assessing the time and magnitude of releases. Any release pathway will have a length determined by a potentially tortuous gas or water pathway dependent on the topography of the sand body. The volume of this pathway will be dependent on the thickness of the sand. Changes in the geometry or topography, changes in connectivity between features, and any known heterogeneity must be included in a detailed and realistic model. Multiple release pathways between the shoe failure point and the chimneys may form depending on the contours of the permeability zone or zones. The multiphase flow regime (proportion of gas/water released) will also affect release rate, release travel time, and also alter the shape and length of the release pathway. All of these factors must be considered in hazard assessments. For this particular scenario, we expect timeframes from

462two years to many decades between casing shoe failure and potential broaching, depending on
463system permeabilities and the composition of the release. It is thus likely that there would be
464sufficient time to drill a relief well and control fluid releases before broaching of hydrocarbons at
465the sea floor could occur.

466

467Once the geometries are established, parametric variations within those geometries result in
468fairly straightforward changes in expected travel times, with the unsurprising conclusion that the
469permeability of the pathway will greatly control the release timeline. Relative permeability
470effects related to the composition of the release would have even greater consequences, reducing
471leakage rates at the well and delaying releases at the seafloor. Alterations of the estimated
472thickness of the Purple Sand would likely have similarly large effects.

473

474For systems with gas release and low rates of water injection into the system (water flow limited
475to displacement by the gas phase) it is likely that hydrate formation will reduce permeabilities in
476the colder, upper regions of the system and possibly mitigate release under the conditions seen in
477the simulations. One question that we cannot address at this point is how a system with all outlets
478blocked by hydrate would eventually behave if releases continued for longer periods of time.

479

4805. References

481Forrest, J., E. Marcucci and P. Scott, Geothermal Gradients and Subsurface Temperatures in the
482 Northern Gulf of Mexico, Search and Discovery Article #30048, 2007, adapted from paper
483 published in GCAGS Transactions, 55, 233-248, 2005

484Gallaway, B.J., J.G. Cole and L.R. Martin, The Deep Sea Gulf of Mexico : An Overview and
 485 Guide, OCS Study MMS 2001-065, U.S. Department of the Interior, Minerals Management
 486 Service, Gulf of Mexico OCS Region, 2001
 487Garcia-Pineda, O., MacDonald, I., Zimmer, B., Shedd, B., Roberts, H., Remote-sensing
 488 evaluation of geophysical anomaly sites in the outer continental slope, northern Gulf of
 489 Mexico. Deep Sea Research Part II: Topical Studies in Oceanography 57, 1859-1869, 2010
 490Moridis, G.J., User's Manual for the HYDRATE V1.5 Option of TOUGH+ V1.5: A Code for the
 491 Simulation of System Behavior in Hydrate-Bearing Geologic Media, Report LBNL-6869E,
 492 Lawrence Berkeley National Laboratory, Berkeley, CA, 2014,
 493 <https://pubarchive.lbl.gov/islandora/object/ir%3A1005569>
 494Moridis, G.J., and Reagan, M.T. Gas Production From Oceanic Class 2 Hydrate Accumulations,
 495 OTC 18866, 2007 Offshore Technology Conference, Houston, Texas, U.S.A., 30 April–3
 496 May 2007.
 497Moridis, G.J., User's Manual of the MeshMaker V1.5 Code: A Mesh Generator for Domain
 498 Discretization in Simulations of the TOUGH+ and TOUGH2 Families of Codes, Report
 499 LBNL-1005134, Lawrence Berkeley National Laboratory, Berkeley, CA, 2016
 500Moridis, G.J. and K. Pruess, User's Manual of the TOUGH+ v1.5 Core Code: A General Purpose
 501 Simulator of Non-Isothermal Flow and Transport Through Porous and Fractured Media,
 502 Lawrence Berkeley National Laboratory Report LBNL-6869E, August 2014,
 503 <https://pubarchive.lbl.gov/islandora/object/ir%3A1005566>.
 504Moridis, G.J. and N. Keen, MeshMaker V2.0S And V2.0P: New Grid Generators For Complex
 505 Heterogeneous Domains in TOUGH2/TOUGH+ Simulations, Proceedings, TOUGH

506 Symposium 2015, Lawrence Berkeley National Laboratory, Berkeley, California, September
 507 28-30, 2015
 508 Moridis, G.J., Kowalsky, M.B., Pruess, K., TOUGH+HYDRATE v1.0 User's Manual: A Code
 509 for the Simulation of System Behavior in Hydrate-Bearing Geologic Media, Report LBNL-
 510 0149E, Lawrence Berkeley National Laboratory, Berkeley, CA, 2008.
 511 Lawrence Livermore National Laboratory (LLNL), VisIt User's Manual, Version 1.5, Report
 512 UCRL-SM-220449, 2005.
 513 Oldenburg, C.M., Freifeld, B.M., Pruess, K., Pan, L., Finsterle, S., Moridis, G.J., Numerical
 514 simulations of the Macondo well blowout reveal strong control of oil flow by reservoir
 515 permeability and exsolution of gas, PNAS, 109 (50), 20254-20259, 2012.
 516 Pruess, K., 2003. The TOUGH Codes – A Family of Simulation Tools for Multiphase Flow and
 517 Transport Processes in Permeable Media, LBNL Report 53630,
 518 <https://pubarchive.lbl.gov/islandora/object/ir%3A121930>.
 519 Queiruga, A.F. and M.T. Reagan. (2018, February 2). tough_convert: Version 1.0. Zenodo.
 520 <http://doi.org/10.5281/zenodo.1164418>
 521 Roberts, H.H., Feng, D., and Joye, S.B. Cold-seep carbonates of the middle and lower
 522 continental slope, northern Gulf of Mexico. Deep sea research part II: Topical Studies in
 523 Oceanography, 57(21), 2040-2054, 2010.
 524 van Genuchten, M.Th., A Closed-Form Equation for Predicting the Hydraulic Conductivity of
 525 Unsaturated Soils, Soil Sci. Soc., **44**, 892 - 898, 1980
 526 Zhang, K., G.J. Moridis, Y.S. Wu and K. Pruess, A Domain Decomposition Approach For Large-
 527 Scale Simulations Of Flow Processes In Hydrate-Bearing Geologic Media. Proceedings of

the 6th International Conference on Gas Hydrates (ICGH 2008), Vancouver, British Columbia, Canada, July 6-10, 2008

Table 1: Reservoir Properties Summary

Properties of Sand Layer and Chimneys			
Location	Parameters	Value	Unit
General	Geothermal gradient	0.0271	°C/m
	Temperature at ocean floor	3.9(*)	°C
	Porosity:		
	Average	0.25	fraction
	Low	0.1	fraction
Purple Sand	High	0.33	fraction
	Permeability:		
	Average	541/5.3E-13	mD/m ²
	Low	0.7/7.0E-16	mD/m ²
	High	1416/1.41E-12	mD/m ²
	Thickness	10/3	Ft/m
	Temperature (3,020 m)	127/52.8	°F/°C
	Well (x,y,z) at Purple Sand		
	x	9659.42	m
	y	4050.77	m
	z	-3136.39	m
Chimneys	Porosity	Same as Purple Sand	
	Permeability	Same as Purple Sand	
	Depth at ocean floor:		
	Chimney A	-1,135.38	m
Casing shoe	Chimney B	-1,181.10	m
	(x,y,z) of casing shoe		
	x	9799.3	m
	y	3810.0	m
Escaping Fluids	z	-2915.1	m
	P	7385	Psi
	T	146/63.3	°F/°C
	X _{CH4}	100	%

(*) Gallaway et al., 2001; Forrest et al., 2007

535
536
537

Table 2. Reservoir parameters

Region	k (mD)	ϕ	S_H	S_W
0. Boundary Layers	0	0.0	0.0	1.0
1. Chimney A	541	0.25	0.0	1.0
2. Chimney B	541	0.25	0.0	1.0
3. Purple Sand	541	0.25	0.0	0.0
4. Failed Well Casing	500-5000	1.0	0.0	varies

538
539
540
541
542
543
544
545

Table 3. Other simulation parameters.

Water salinity (mass fraction)	0.035
Grain density ρ_R (all formations)	2600 kg/m ³
Dry thermal conductivity k_{QRD} (all formations)	0.5 W/m/K*
Wet thermal conductivity k_{QRW} (all formations)	3.1 W/m/K*
Composite thermal conductivity model (Moridis et al., 2008)	$k_C = k_D + (S_A^{1/2} + S_H^{1/2}) (k_W - k_D) + \phi S_I k_I$
Capillary pressure model (van-Genuchten, 1980; Moridis et al., 2008)	$P_{cap} = -P_0 \left[(S^*)^{-1/\lambda} - 1 \right]^{1-\lambda} S^* = \frac{(S_A - S_{irA})}{(S_{mA} - S_{irA})}$
S_{irA}	0.24
	0.6
$1/P_0$	$5.3 \times 10^{-5} \text{ Pa}^{-1}$
3-Phase (Aqueous-Gas-Hydrate) Relative Permeability Model (Moridis et al., 2008)	$k_{rA} = (S_A^*)^n$ $k_{rG} = (S_G^*)^n$ $S_A^* = (S_A - S_{irA}) / (1 - S_{irA})$ $S_G^* = (S_G - S_{irG}) / (1 - S_{irA})$ OPM model (Moridis et al., 2008)
n	3.0
S_{irG}	0.02
S_{irA}	0.25

546(*) Moridis and Reagan, 2007.
547

548

549
 550 Figure 1. Structure map on the purple sand showing relative depth subsurface) in grey-shade,
 551 gas chimney locations, and seismic traverse A-A'. The well surface location is designated by a
 552 square and the bottom-hole location is designated by a circle (proprietary data courtesy of
 553 Western Geco/Schlumberger).
 554

555
 51
 52

556Figure 2. Purple sand seismic traverse A-A' that shows well path, 11.75-in casing shoe, purple
557sand, broaching pathways, adjacent salt structures, natural seeps, and gas chimneys
558(proprietary seismic courtesy of WesternGeco, LLC).
559

560
561

562
563

564Figure 3. Grid connectivity and initial pressure distribution in the entire domain. "Well zone"
565points toward the region of the sand intersected by the well, and thus the point at which fluids
566from a failed casing shoe would emerge into the formation. Impermeable sediments overlying
567the sands are not visualized.
568

569

570

571 Figure 4. Connectivity and initial pressure distribution in the vicinity of Chimney B. Impermeable
 572 sediments overlying the sands are not visualized.

573

574

575

576

577

578

579Figure 5: Gas and water flow rates at the seafloor (Chimney A + Chimney B) for the all-gas
580release case. Arrows indicate gas arrival times for Chimneys A and B.

581

582

583

584

585 Figure 6: Total hydrate formation rate, Q_H , for the overall system for the all-gas release case.

586

587
 588
 589 Figure 7: Cumulative hydrate formation, M_H , for the overall system in the all-gas release case.
 590
 591

592
593

594
595
596

t = 180 d

t = 640 d

597
598
599

t = 870 d

t = 1,000 d

600
601
602

t = 1,370 d

t = 2,000 d

603Figure 8: Visualizations of S_G , showing gas approach to, and release through, Chimney B.

604
605
606
607

t = 60 d

t = 1,280 d

t = 1,730 d

t = 1,910 d

Figure 9: Visualizations of S_G , showing gas approach and release through Chimney A.

617

618

619

620

621

622

623

624 Figure 10: Visualizations of S_H , showing hydrate formation in Chimney B.

625

626

627

628

629

630Figure 11: Variations in breakthrough curves, Q_G vs. t , as a function of permeabilities.

631

632

633

634

635Figure 12: Gas arrival times at Chimney B and the seafloor as a function of permeabilities.

636

637

638

639

640
641Figure 13: Gas arrival times at Chimney B and the seafloor, transit times through the chimney
642and k_s/k_c adjustment as a function of permeabilities.

643

644

645

646

647

648Figure 14: Gas arrival time surface as a function of k_s and k_c .

649

650

651

652 a)

653

654 Figure 15: Rates of water and gas released at the leak (a) and cumulative volume/mass (b).

655

656

657

658

659

660Figure 16: Change in temperature at monitoring points within the chimneys and in the Purple

661Sand

662

663

664

665

666

t = 4 yr

t = 25 yr

667

668

t = 41 yr

t = 70 yr

669 Figure 17: Visualizations of S_G , showing gas transport and escape through the chimneys for a
670 mixture of water and gas.

671

672

673

674

675

676

677

678

679 Figure 18: Visualizations of X_{NaCl} , showing brine transport and escape through the chimneys for
 680 a mixture of water and gas.

681

682