Gulf of Mexico Hydrate Mapping and Interpretation Analysis

Summary Report
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July 8, 2021

This report satisfies Deliverable/Milestone 7 (Detailed Summary Report) for the BOEM- sponsored award, Gulf of Mexico Gas Hydrate Mapping and Interpretation Analysis. Over the project period, we analyzed publicly available seismic data (Triezenberg et al., 2016) within Project Areas 1-5 for natural gas hydrate systems (Figure 1). Our work resulted in a new dataset of bottom simulating reflections (BSRs), new gas hydrate systems and new insights into selected gas hydrate systems based on the geological settings and data quality. This dataset may be used as a reference for further studies in selected areas as new seismic data become available.

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Table 1. List of required deliverables and figures.

	Deliverable	Figure #
1	A basemap of all newly identified gas hydrate systems	1
2	Individual prospect maps	2
3	A summary of the geological characteristics of each Project Area	3, 4, 5, 6, 7

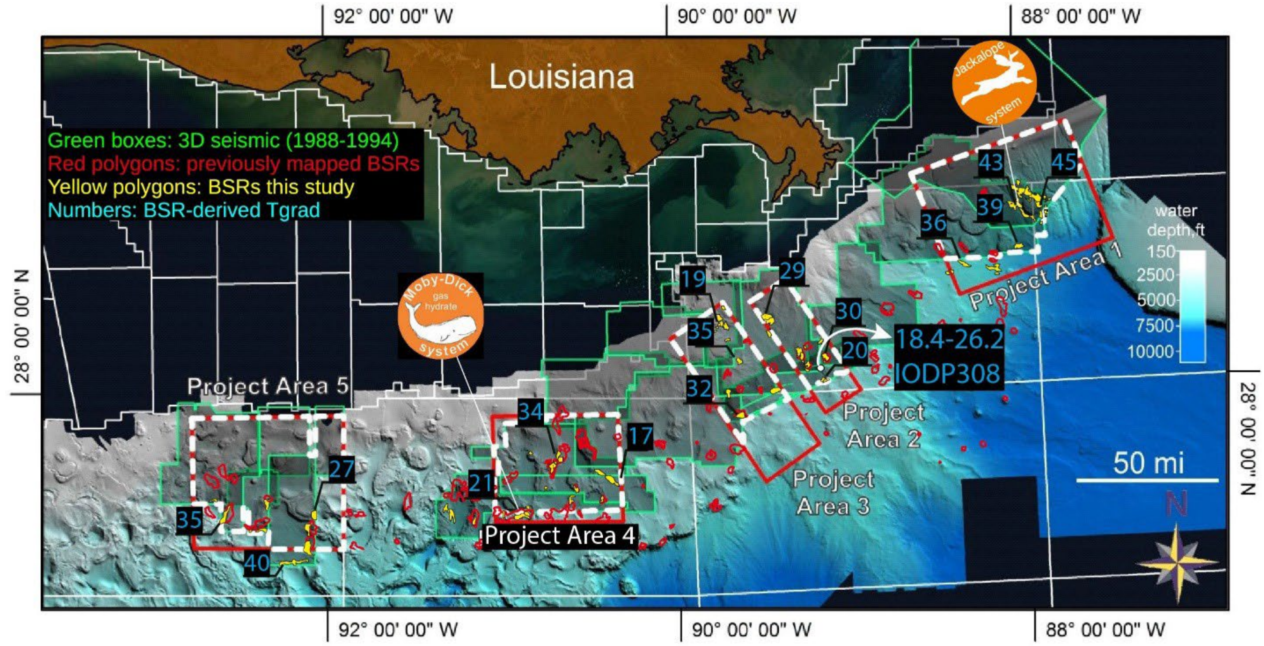


Figure 1. A map showing the seismic data used in this project (green boxes), the defined Project Areas (red boxes), BSRs identified during the current project (yellow areas) and geothermal gradients calculated from the BSR depths (black squares with blue numbers, in °C/km). Note the geothermal gradients previously measured during IODP (Integrated Ocean Drilling Program) 308 are also indicated (Flemings et al., 2006). The Jackalope gas hydrate system (orange circle with a Jackalope) that was identified in the central part of Project Area 1 at the preliminary stage of the current project is shown (Portnov et al., 2020). The Moby-Dick gas hydrate system (orange circle with a whale) was identified in the southern part of Project Area 4 during the current project (Portnov et al., 2021, accepted).

1. BSR extent and gas resources

Our project revealed new BSR systems as well as confirmed and refined previously mapped BSR systems by BOEM (Shedd et al., 2012) (Figure 1). The total area of mapped BSRs in Project Areas 1-5 is ~330 km^2 (Figure 1, Table 2). Above each BSR surface, a map of average peak-leading reflectors was constructed to qualitatively outline the potential regions with increased gas hydrate saturation (Table 2). These regions were selected for estimates of likely minimum and maximum gas resources ranging between 20.5 and 157.3 BCM at STP in total for all Project Areas (Table 2). Our resource assumptions include a minimum and maximum porosity of 30% and 40%, a minimum and maximum unit thicknesses of 10 and 50 m, and minimum and maximum gas hydrate saturations of 50 and 90%.

Table 2. The extent of BSRs and high-saturation gas hydrate resource estimates for areas of strong peak-leading amplitudes by Project Area. Resource estimates are for gas at STP.

	Area 1	Area 2	Area 3	Area 4	Area 5	Total
BSR Area (km^2)	81.2	75.8	31.5	70.6	70.4	329.5
Area of peak-leading (km^2)	8.1	18.9	5.0	10.5	13.2	55.7
Resources min (BCM)	2.4	11.0	1.2	2.6	3.3	20.5
Resources max (BCM)	17.3	55.0	15.0	31.0	39.0	157.3

2. Geothermal gradients

The base of the gas hydrate stability zone (GHSZ) in continental slope sediments largely depends on the geothermal gradient. In some cases, the depth of the BSR is used to estimate the geothermal gradient (i.e. Grevemeyer and Villinger, 2001; Phrampus et al., 2017). As part of this summary report geothermal gradients were calculated in zones with the most prominent BSRs. Our calculations are based on the BSR depths (using average sediment velocity of 1860 m/s to convert between TWT and depth), bottom water temperature profiles and the assumption of Structure I gas hydrate (100% CH_4 in total gas composition) using the stability equations from Sloan and Koh (2007). Geothermal gradients range between 19 °C/km estimated for the northern part of Project Area 3 to 45 °C/km in the eastern part of Project Area 1 (Figure 1, Table 3). High variability in geothermal gradients may be explained by the effects of heat-conductive salt features. Alternatively, the assumption of pure methane gas may be incorrect; if a significant concentration of higher order hydrocarbons are present in the gas hydrate system, then the calculated geothermal gradients are lower than the actual geothermal gradient.

Table 3. BSR locations and geothermal gradients estimated from BSR depths.

Project Area 1					
Zone #	Decimal Lat	Decimal Lon	Water depth (m)	BSR depth (mbsf)	Tgrad (°C/km)
1 (Jackalope)	28.87	88.02	1740	297	43
1	28.86	87.87	1850	291	45
2	28.58	88.33	1878	386	36
3	28.66	88	2181	403	39
Project Area 2					
Zone #	Decimal Lat	Decimal Lon	Water depth	BSR depth (mbsf)	Tgrad (°C/km)
1	28.33	89.46	933	306	29
4	28.13	89.14	1125	348	30
6	28.02	89.15	1220	651	20
Project Area 3					
Zone #	Decimal Lat	Decimal Lon	Water depth	BSR depth (mbsf)	Tgrad (°C/km)
1	28.32	89.72	650	227	19
2	28.13	89.63	825	187	35
4	27.86	89.62	1039	306	32
Project Area 4					
Zone #	Decimal Lat	Decimal Lon	Water depth	BSR depth (mbsf)	Tgrad (°C/km)
1 (Moby-Dick)	27.37	90.89	1350-1450	552-650	19-23
2 (over salt)	27.67	90.68	822	161	34
3	27.54	90.34	1106	739	17
Project Area 5					
Zone #	Decimal Lat	Decimal Lon	Water depth	BSR depth (mbsf)	Tgrad (°C/km)
1 (over salt)	27.15	92.21	1443	272	40
3	27.39	92.07	926	284	27
4	27.37	92.57	975	212	35

3. Promising gas hydrate systems

Continuous, discontinuous, and clustered BSRs were identified in Project Areas 1-5, as well as a BSR at the feather edge of GHSZ (see Project Area Reports). Continuous BSRs were commonly observed along channel systems and within minibasins (e.g. Project Area 1, Zone 1; Project Area 4, Zone 2; Project Area 5, Zone 4). Discontinuous BSRs were mapped where dipping coarse-grained layers intersected the base of GHSZ (e.g. Project Area 5, Zone 3). Clustered BSRs were primarily identified in salt roof closures and exhibit increased gas hydrate potential, particularly in Project Area 2, where they are associated with major channel systems (see report for Project Area 2) and gas chimneys. A prominent BSR pinching out at the seafloor along the feather edge of GHSZ was observed upslope Area 3 (Zone 1).

Strong peak-leading reflections can indicate potential hydrate bearing layer. These peak-leading horizons were often mapped in the levees of channel systems (e.g. Zone 1 in Project Area 1, Zone 1 in Project Area 3) and on the rims of gas chimneys (e.g. Zones 2,4,5 in Project Area 2; Zone 2 in Project Area 5). A primary gas hydrate prospect, named Moby-Dick, was identified in the channel-levee complex in Project Area 4.

4. Primary Prospect: the Moby-Dick gas hydrate system

The Moby-Dick gas hydrate system exhibits seismic phase reversals (a high-confidence prospecting criterion for gas hydrate) in horizons that are likely dipping sand layers of a channel-levee complex in Zone 1, Project Area 4 in OCS blocks GC592, GC593 and GC594 (Figure 1). The prospect is located under the northern slope of a salt bounded minibasin in water depths of 1350-1550 m. A well-defined BSR cuts across a package of diverging, dipping reflections at a depth of ~720 msec TWT (~550 m) below the seafloor. One of the upper dipping reflections shows a consistent phase reversal at the base of GHSZ persisting along a ~8500 m interface indicating a likely contact between hydrate-bearing and gas-bearing legs in the same layer (Figure 2). The Moby Dick hydrate system, geologically similar to Terrebonne (Boswell et al., 2012; Frye et al., 2012), is characterized in detail in the Project Area 4 report and a new paper recently accepted in Geology (Portnov et al. 2021, accepted). The minimum and maximum estimates of gas at STP from the positive reflections above the BSR in the Moby-Dick system range between 2.4 and 19.5 BCM (Table 4).

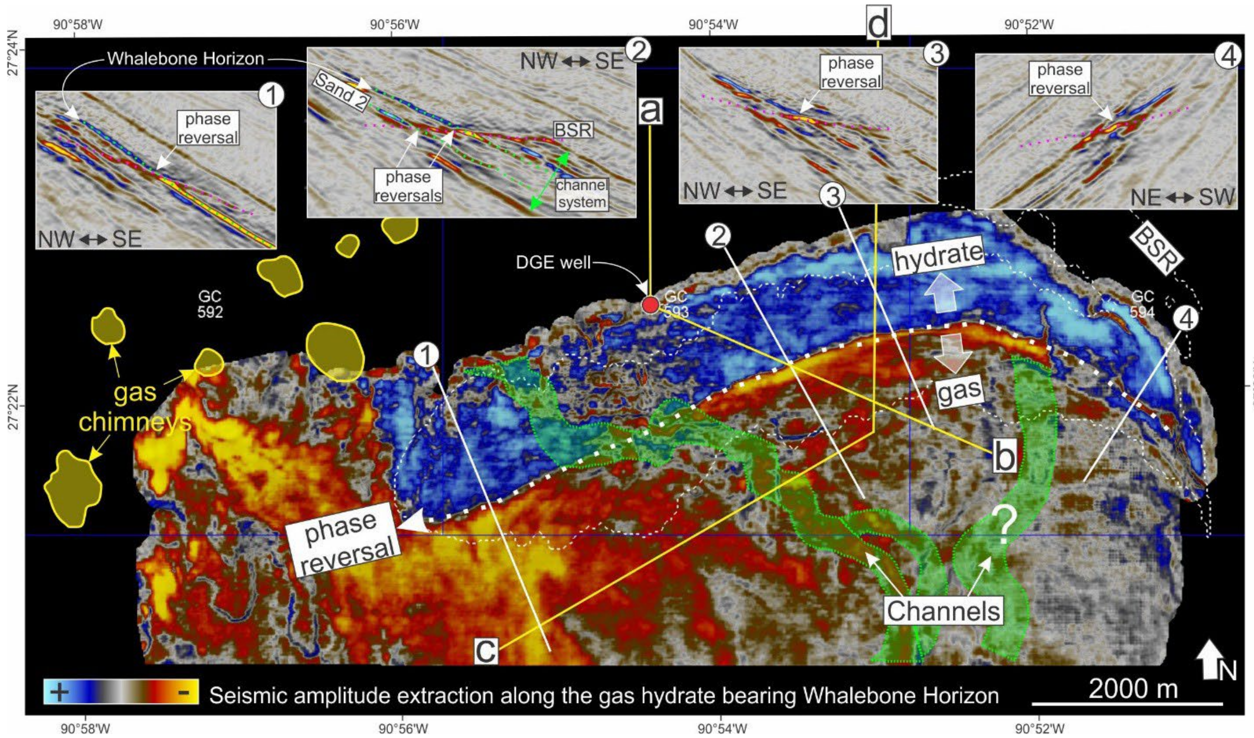


Figure 2. A map of extracted amplitudes along the hydrate-bearing Whalebone Sand in the Moby-Dick hydrate prospect. The blue color defines the extent of peak-leading amplitudes associated with gas hydrate. Insets 1-4 show phase reversals in different parts of the Moby-Dick system.

Table 4. Parameters used for total gas estimates in Moby-Dick prospect.

	Porosity (%)	Gas Hydrate Saturation (%)	Sand Thickness (m)	Hydrate/gas conversion factor	Area of peak-leading (km^2)	Total gas at STP (BCM)
min	30	50	7	164	11	2.4
max	40	90	30	164	11	19.5
Source	Kominz et al., 2011	Yun et al., 2005 Phillips et al., 2020	seismic data	Kvenvolden et al., 1999	seismic data	

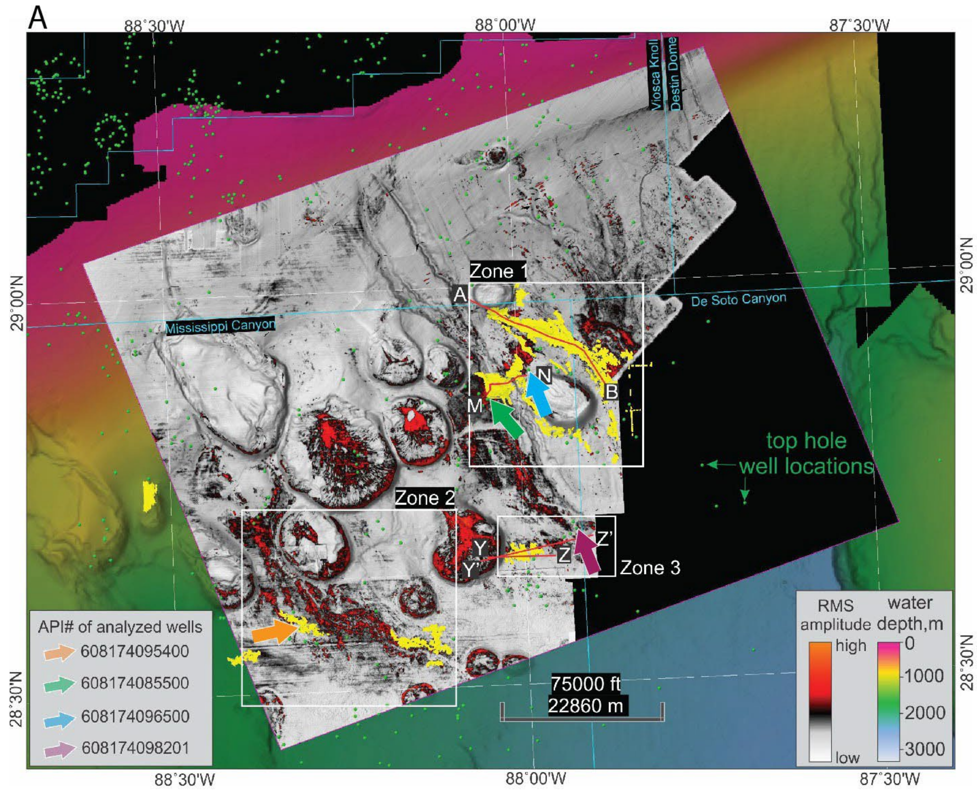
5. Brief Overview of the Project Areas

5.1 Project Area 1

Project Area 1 is located in the northeastern Gulf of Mexico south of the Mississippi-Alabama continental slope in ~300-2400 meters of water (Figure 1, 3). The area is characterized by multiple salt bodies outcropping at the seafloor, and several canyon systems transporting coarse-grained sediments from the shelf delta seaward across the slope. Potential gas hydrate systems in Project Area 1 occur in three Zones associated with several modern and buried channel systems and widespread salt tectonics (Figure 3A, B).

Zone 1 features the highest gas hydrate potential. It is associated with the Jackalope gas hydrate system previously characterized in Portnov et al. (2020) as well as several newly discovered scattered accumulations in the outer levees of a paleochannel. Zone 2 features a complex paleochannel system with significant levee build-ups and several BSR clusters. Insufficient data quality did not allow for a more precise interpretation of seismic facies at the reservoir level in Zone 2, yet this area definitely warrants additional attention when new seismic and borehole datasets may become available. Zone 3 features a discontinuous BSR likely associated with paleochannel facies, and slight resistivity increase in a well outside of a mapped BSR, yet poor seismic data quality precludes a more accurate interpretation in this region.

Please refer to the Project Area 1 report for a full description of methods, data, wells, and prospects. A complete description of the Jackalope gas hydrate system is available in Portnov et al. (2020).



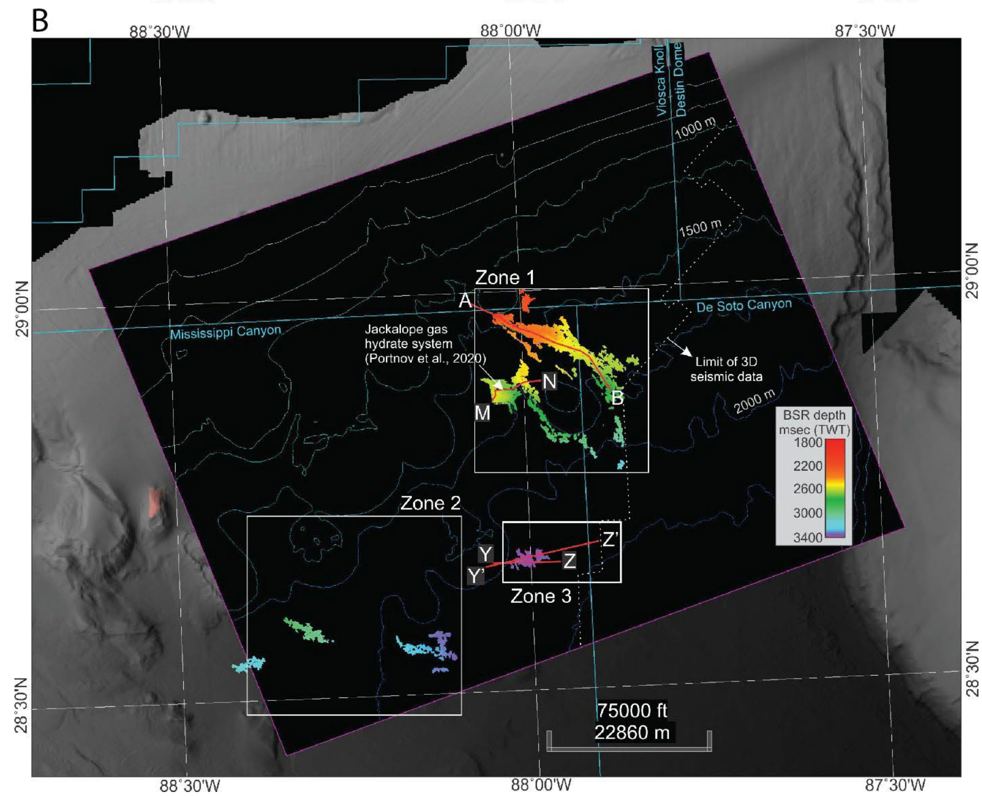


Figure 3. (A) The BSR distribution (yellow areas) within Project Area 1 based on semi-automated mapping. Arrows mark four wells selected for more detailed analyses (see the Project Area 1 report for details); (B) Depth of the BSR (msec TWT) combined with seafloor bathymetry contours.

5.2 Project Area 2

Project Area 2 is located in the northeastern Gulf of Mexico at the eastern margin of Mississippi Canyon in ~300-1500 meters of water (Figure 1, 4). In the north, Project Area 2 is characterized by several cross-slope ridges with gentle slopes (0.5-2.5 deg) and seafloor escarpments related to mass movement events with up to 9 degrees steep head scarps. In the south, normal faulting caused by salt movement dominates the bathymetry. In contrast to Project Area 1, there are no salt diapirs outcropping at the seafloor. BSRs in Project Area 2 concentrate within six distinct zones (Figure 4). In the northern part of the area, we mapped a classical continuous BSR at 1500-1600 msec TWT (~400 msec below the seafloor). Downslope, where channels merge and become more organized, we mapped high-amplitude clustered BSRs.

Potential gas hydrate systems in Project Area 2 are associated with several buried channel-levee systems that deposited sand-bearing sediments at the approximate base of the GHSZ. In the southern part of Project Area 2, underlying salt bodies create an anticlinal framework favorable for entrapment of gas at the BHSZ and formation of clustered BSRs that are good indicators of high-saturation gas hydrate reservoirs in turbidites (Portnov et al., 2019). We see robust evidence of vertical fluid flow and gas migration through the salt roof towards the seafloor. These large gas migration systems may feed overlying gas hydrate reservoirs distributed in close proximity to the gas chimneys. Based on the distribution of strong peak-leading amplitudes, Zones 2, 3 and 6 may be considered as higher-priority. Resource estimates in Project Area 2 are significantly higher compared to Project Area 1 (Table 2) due to large BSR area and thicker sand units as evidenced by the seismic data and existing literature (Sawyer et al., 2007, 2009).

Please refer to the Project Area 2 report for a full description of methods, data, wells and prospects.

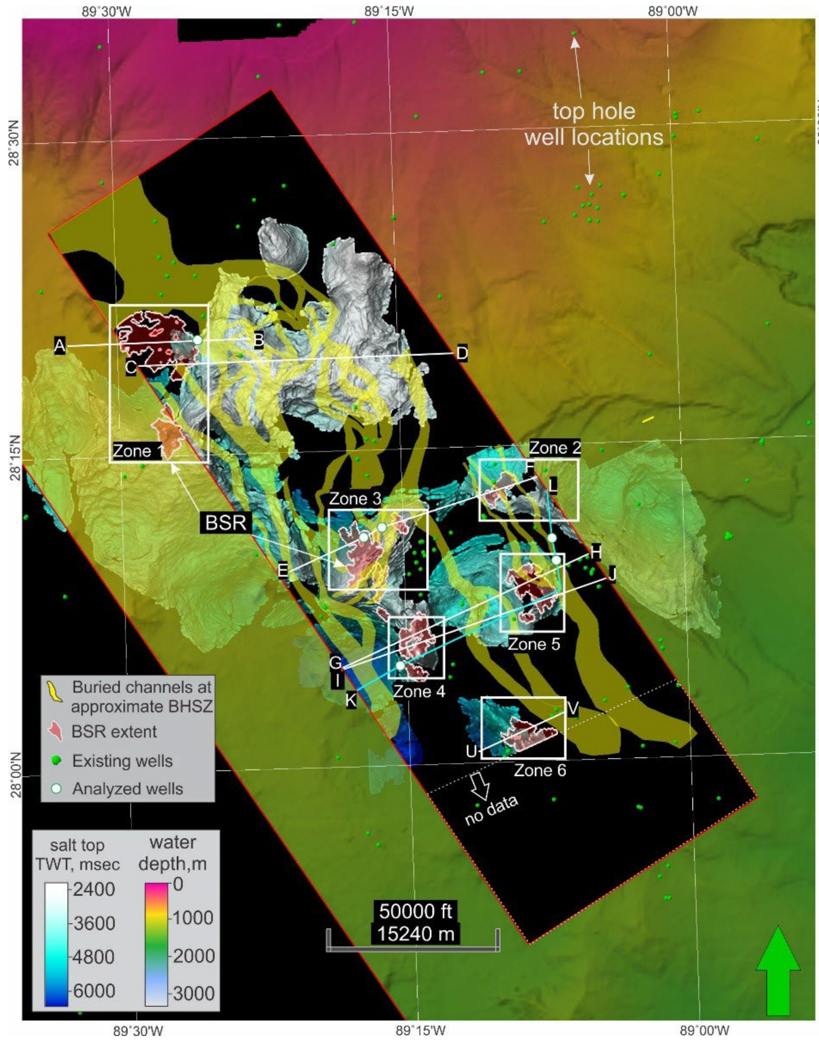


Figure 4. The top of salt (blue-green white), paleo-channels and BSR distribution interpreted from RMS attribute maps in Project Area 2. White and blue lines are seismic sections crossing major high-amplitude systems that potentially contain gas hydrate (see the Project Area 2 report for further details).

5.3 Project Area 3

Project Area 3 is located in the northeastern Gulf of Mexico at the western margin of Mississippi Canyon in ~250-1500 meters of water (Figure 1, 5). Project Area 3 extends from the continental shelf over the slope to the head of the uppermost Mississippi fan lobe. In the northeast, Project Area 3 is characterized by canyon re-entrants and cross-slope ridges with gentle slopes (0.5-2.7 deg), multiple seafloor escarpments and residual knolls indicating active mass wasting at the canyon western sidewall. The northern part of Project Area 3 is characterized by a complex stratigraphic sequence from Mississippi Canyon incision and development, slope processes and cyclic prodeltaic sedimentation (Goodwin and Prior, 1989). Zones 1 and 2 are located at the margin of the canyon fill, which onlaps onto the underlying bedded shelf deposits (Figure 5). Potential gas hydrate systems in Project Area 3 are associated with several buried channel-levee systems that deposited sand-bearing sediments at the approximate modern base of the GHSZ. Gas hydrate may also occur in mass transport deposits and prodeltaic canyon sediments delivered from the Mississippi river delta.

In the central part of Project Area 3, underlying salt bodies create anticlinal structures favorable for entrapment of gas at the base of the GHSZ and formation of clustered BSRs. The best prospects are in Zones 1 and 2. Zone 1 is located at the feather edge of the GHSZ, which is, to our knowledge, the only BSR identified at the feather edge of hydrate stability zone in the Gulf of Mexico. This region may be of interest for future investigation because gas hydrate formation and recycling at the feather edge of hydrate stability zone are important for slope stability and seafloor-ocean carbon exchange. Zone 2 shows an amplitude phase reversal at the base of the GHSZ that is evident even in the poor-quality seismic data. A strong peak-leading reflection above the phase reversal is mapped over the area of ~1.2 km^2. Yet, defining the exact extent of the peak-leading reflection requires better quality seismic data. In the deeper part of Project Area 3 (Zones 3-5), gas hydrates likely occur above clustered BSRs associated with uplifting salt. However, given poor seismic data quality and absence of wells, hydrate accumulations in Zones 3-5 are low confidence. Please refer to the Project Area 3 report for a full description of methods, data, wells and prospects.

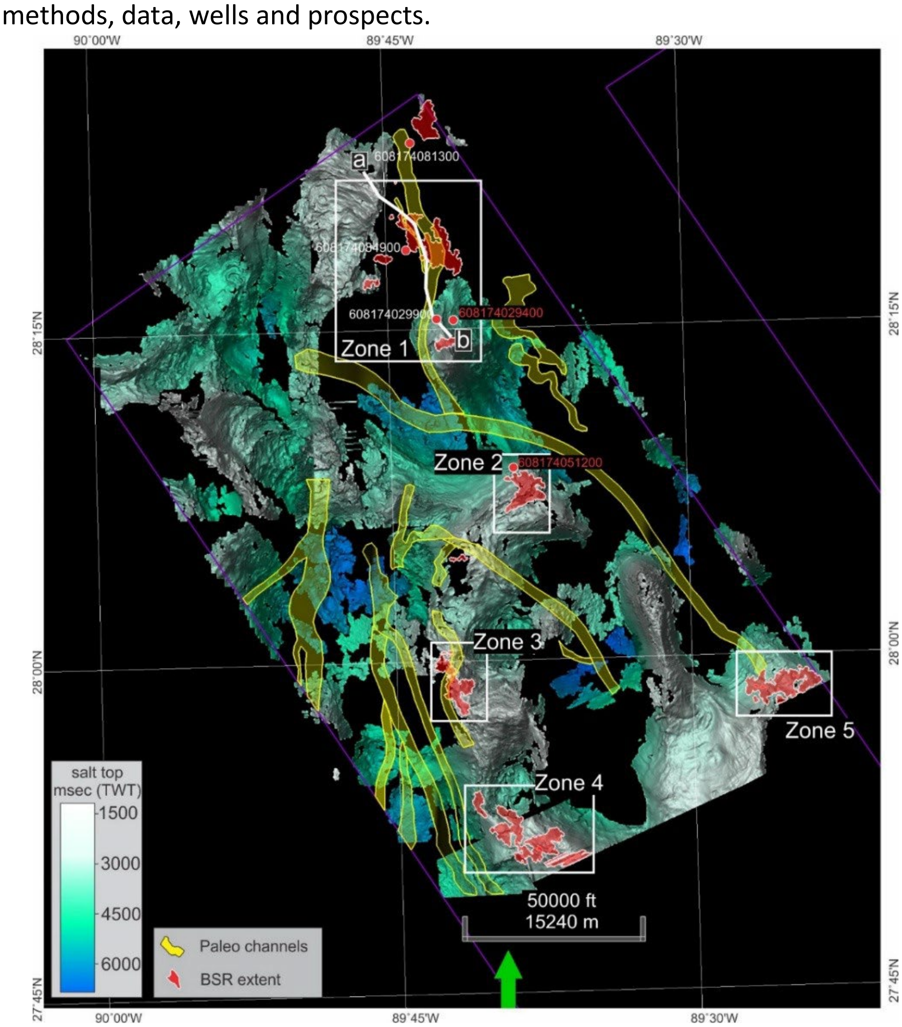


Figure 5. The top of salt (blue-green white) in two-way time, paleo-channels (yellow) and BSR distribution (red) interpreted from RMS amplitude maps in Project Area 3.

5.4 Project Area 4

Project Area 4 occupies the northern and northeastern sectors of the Green Canyon protraction area in the northern Gulf of Mexico, in water depths ranging from 400-1600 m (Figure 1, 6). Project Area 4 includes several allochthonous salt ridges and sedimentary minibasins, including the Thibodaux, Stewart, and Ship minibasins. The area is characterized by persistent sediment mass transport deposits as evidenced by multiple escarpments in the modern bathymetry data as well as from paleo mass transport complexes observed in the seismic data. There is no evidence of modern channels in the seafloor bathymetry. We do observe several buried channel systems in the seismic data, however, they are less developed and less organized than in Project Areas 1, 2 and 3. In the southwestern part of Project Area 4, seismic data show multiple gas chimneys that have not been previously identified.

The best gas hydrate prospect in Project Area 4 is in Zone 1 and was named Moby-Dick (Figures 2, 6). It is located in the southwestern part of Project Area 4 in OCS lease blocks GC592, GC593, and GC594. Moby-Dick is characterized by extensive amplitude phase reversals at the BSR with two sand reservoirs occupying 10.5 km^2. For more details, see Section 4 of this report.

Additional low-confidence gas hydrate accumulations were interpreted based on the BSR distribution in Zones 2 and 3 (Figure 6). The seismic data in Zone 3 does show the presence of paleo-channels associated with the BSR, however in Zone 2 the presence of channel deposits is not evident. No well data were available to confirm the seismic interpretation in Zones 2 and 3. Please refer to the Project Area 4 report for a full description of methods, data, wells and prospects.

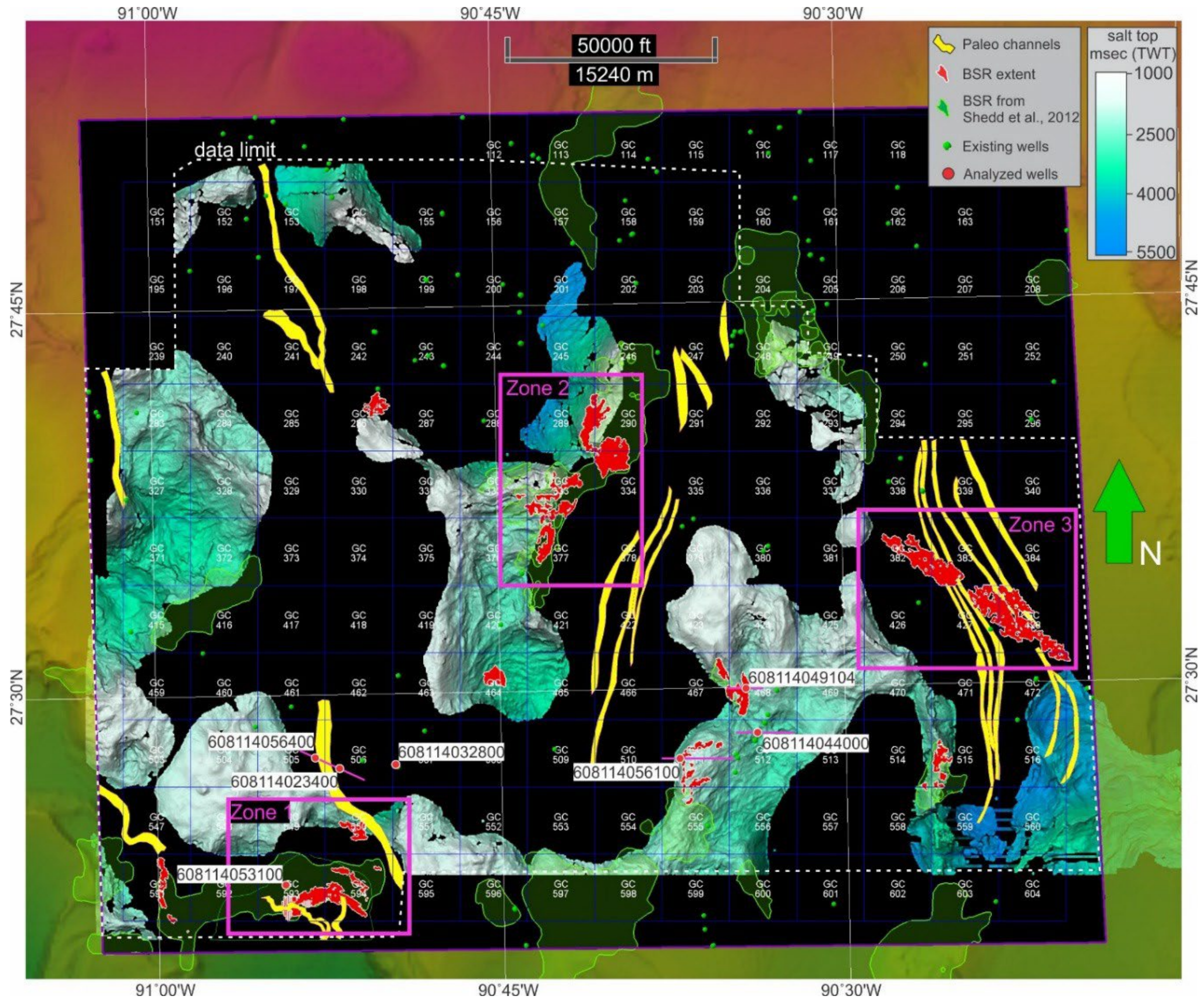


Figure 6. The top of the allochthonous salt surface in TWT within Project Area 4. The black background areas indicate sediment basins with no shallow salt present. The extent of the BSRs identified in Project Area 4 is shown in red. Paleo-channel systems are indicated with yellow polygons.

5.5 Project Area 5

Project Area 5 is located in the Garden Banks protraction area at the edge of the Louisiana continental shelf and it is the most western Project Area (Figures 1, 7). In general, Project Area 5 is characterized by widespread salt diapiarism in both the subsurface and outcropping at the seafloor. Salt-induced normal faulting is common in this area, especially in the western portion of the study area. These faults likely serve as a fluid migration pathway through the subsurface and up to the seafloor. Faults occur near mapped BSRs in multiple locations. Areas with active fluid flow, including mud volcanoes previously identified by BOEM, are also present near zones of interest. In the southern portion of Project Area 5, there are numerous narrow channel features, and some that coincide with BSRs.

Potential gas hydrate systems in Project Area 5 are associated with widespread salt tectonics and active fluid flow. In the southeastern part of the study area, where Zones 1, 2, and 3 are located, salt bodies create an anticlinal framework that traps gas at the base of GHSZ. Numerous buried channels identified in this Project Area suggest that sands are present near the base of GHSZ. In Zone 2, we see evidence of vertical fluid flow to the seafloor. The areas near these gas chimneys could supply gas to overlying hydrate systems. This makes Zone 2 a high-confidence gas hydrate prospect. In Zone 4, a phase reversal was observed with strong trough-leading reflections below the (base of gas hydrate stability)BGHS and strong peak-leading reflections above. There is evidence of vertical fluid flow in Zone 4 with BSRs occurring adjacent to a mud volcano. Zone 4 represents a second high-confidence gas hydrate prospect. A lack of well data in Garden Banks prevented further in-depth analysis for the BSR systems identified. As more well data becomes available, a second look at this study area could be warranted. Please refer to the Project Area 5 report for a full description of methods, data, wells and prospects.

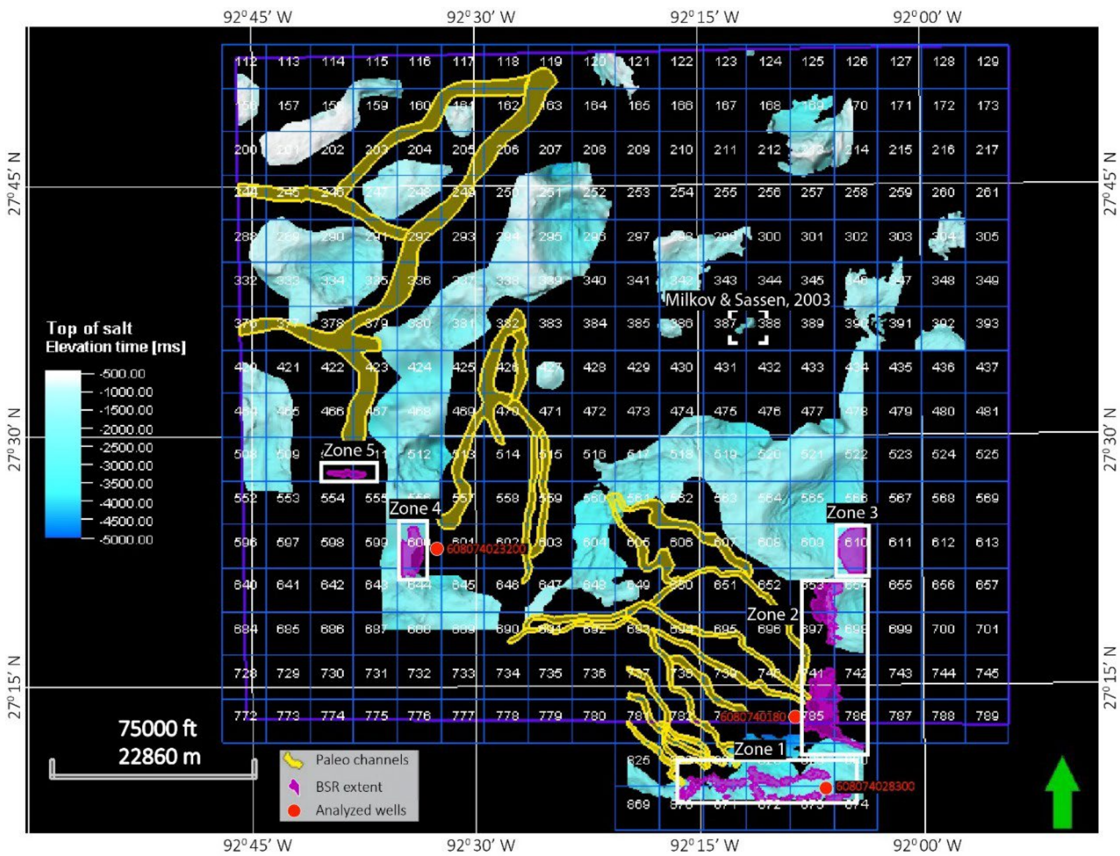


Figure 7. The top of salt (blue-teal-white), paleo-channels (yellow) near base of GHSZ and the BSR distribution (pink) in Project Area 5. Features were interpreted from RMS amplitude maps and manual interpretation. Garden Banks blocks are outlined in blue and labeled with the block number. Please refer to the Project Area 5 report for details.

6. Summary

Over five Project Areas on the northern Gulf of Mexico slope, we identified 22 new BSRs systems covering a total of ~330 km^2. As higher-quality seismic data becomes publicly available, further promising gas hydrate accumulations may be identified in deep-water minibasins and salt-roof systems of the northern Gulf of Mexico.

7. Acknowledgements

We thank BOEM for supporting this project and Matt Frye and Stephen Palmes for their feedback and encouragement.

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