Gulf of Mexico Hydrate Mapping and Interpretation Analysis

Phase-II Summary Report

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This report satisfies Deliverable/Milestone 6 (Detailed Summary Report) for the BOEM-sponsored award, Gulf of Mexico Gas Hydrate Mapping and Interpretation Analysis, Phase II.

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1 Overview

Over the Phase II project period, we analyzed publicly available seismic data within Project Areas 2.1-2.4 for natural gas hydrate prospects (Figure 1). In addition, this final report includes the analysis of a new, small project area that fills in a small gap between Project Areas 1.3 and 1.4; we refer to this as Project Area 2.5 (Figure 1). By combining the results of Phase I[1] and Phase II, a large, continuous area of 58,000 km^2 along the northern Gulf of Mexico upper continental slope was analyzed for bottom simulating reflections (BSRs). The occurrence of a BSR often indicates the presence of gas hydrate and free gas at the base of the gas hydrate stability zone.

In this final report, we summarize the results from Project Areas 2.1 to 2.5. Our work resulted in a new dataset of 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.

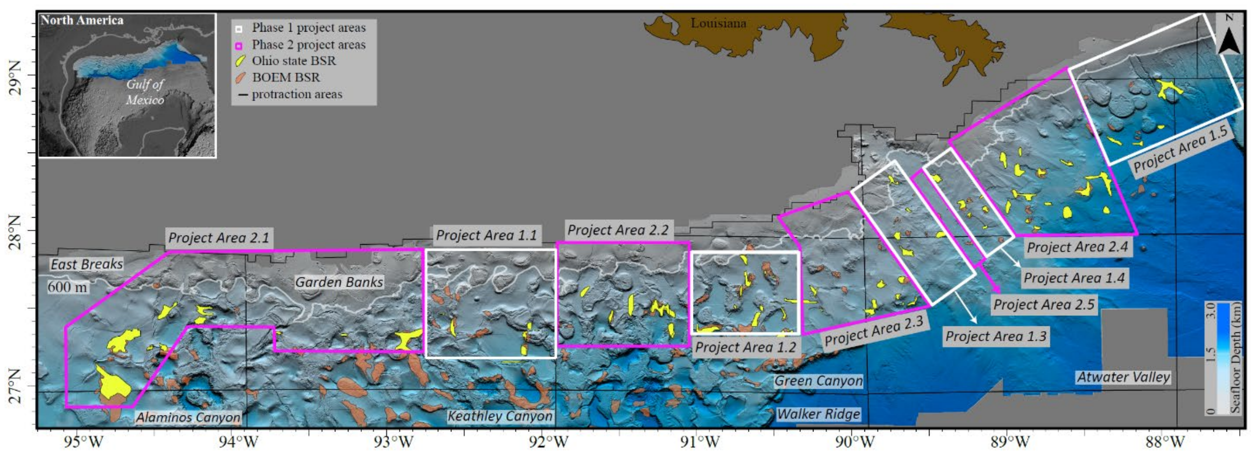

Figure 1: A map showing the regional bathymetry of the Gulf of Mexico (Kramer and Shedd, 2017), the defined Project Areas (white and pink boxes), BSRs identified by the Ohio State University (yellow areas) and BSR identified by BOEM (brown areas).

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[1] Phase I results were finalized during the period 2019 – 2021 and are available on the BOEM website: https://www.boem.gov/oil-gas-energy/resource-evaluation/ohio-state-university-methane-hydrate-prospect-analysis-gulf

2 Project Area 2.5

Project Area 2.5 fills in a very small area (only 1000 km^2) between Project Areas 1.3 and 1.4; when Phase I was proposed, seismic data were not available in this area. Project Area 2.5 is located in Mississippi Canyon and Atwater Valley (AT) and has water depths between 550 - 1500 m (Figure 2). In Project Area 2.5, we use three 3D seismic surveys from the National Archive of Marine Seismic Surveys (NAMSS; Triezenberg et al., 2016) database (Table 1), which covers all of Project Area 2.5.

We consider Project Area 2.5 to be a single zone and identify three BSR systems in Project Area 2.5, which we refer to as the northern, central and southern BSR systems (Figure 2).

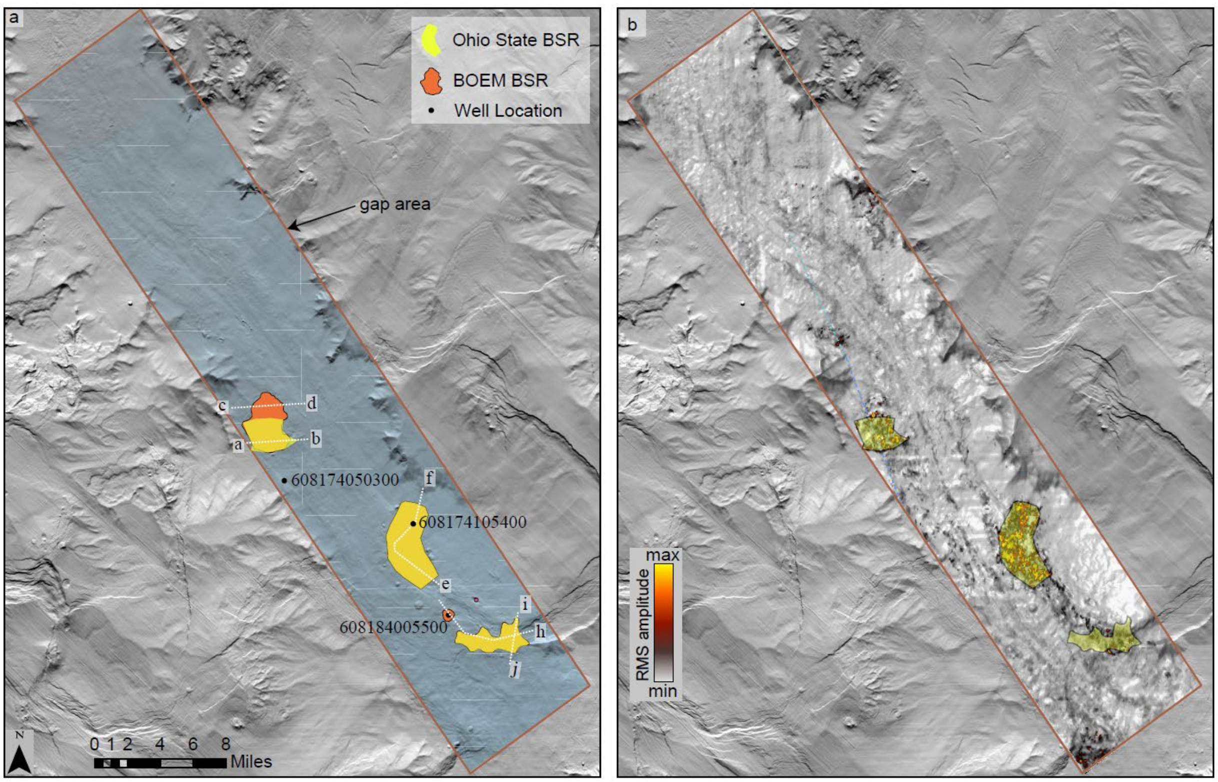

Figure 2: a) The blue shaded area overlying the regional bathymetry map from Kramer and Shedd (2017) shows the extent of Project Area 2.5. Ohio State BSRs and BOEM BSRs are shown in yellow and orange polygons, respectively. b) RMS amplitudes calculated over a window of 200-400 msec below the seafloor are shown over the regional bathymetry map. The BSR systems correlate well with high RMS amplitudes in this area.

Survey number	Survey name/BOEM identifier	Year	Area of seismic survey (km^2)	Frequency Range (Hz)	Survey quality	Bin size (m)	Projection
1	B-101-91-LA/L91-101	1991	3612	5-90	Poor	26×26	16N NAD 1927, feet
2	B-67-96-LA/L96-067	1996	3400	5-80	Fair	20×12.5	16N WGS 1984, feet
3	B-49-95-LA/L95-049	1995	2640	5-80	Fair	20×12.5	16N NAD 1927, feet

Table 1: Details on the 3D seismic surveys uploaded for initial data quality analyses within Project Area 2.5. Projected coordinate systems: NAD_1927_BLM_Zone_16N [EPSG,32066], WGS_1984_BLM_Zone_16N_ftUS [EPSG,32666].

The northern BSR system was previously identified by BOEM (Shedd et al., 2012), however, the size of the BSR in this study is smaller than the BOEM BSR (Figure 2). Herein, this northern BSR system covers a smaller area of ~10 km^2 and is discontinuous in nature as shown in a seismic profile across this BSR system (Figure 3). The BSR reflections in the northern BSR system are present at 200-400 msec TWT below the seafloor, or approximately 170-340 meters below seafloor (mbsf) when using 1700 m/s as the sediment velocity. We observe high amplitude reflections in the northern side of this BSR in the area previously identified by BOEM (seismic profile c-d, Figures 2 and 4), but we do not classify these reflections as BSR, largely due to the poor seismic data on the northern side. Seismic volume B-101-91-LA covers the entire region (the northern and southern part of the BSR) but the data quality is poor (Figure 4). However, the southern part is covered by seismic volume B-49-95-LA and has fair quality data (Table 1) which allows us to identify the BSR in the southern part (Figure 5). Well API #608174050300 is the nearest to this BSR system (~2.5 km away) but does not have any data in the shallow interval.

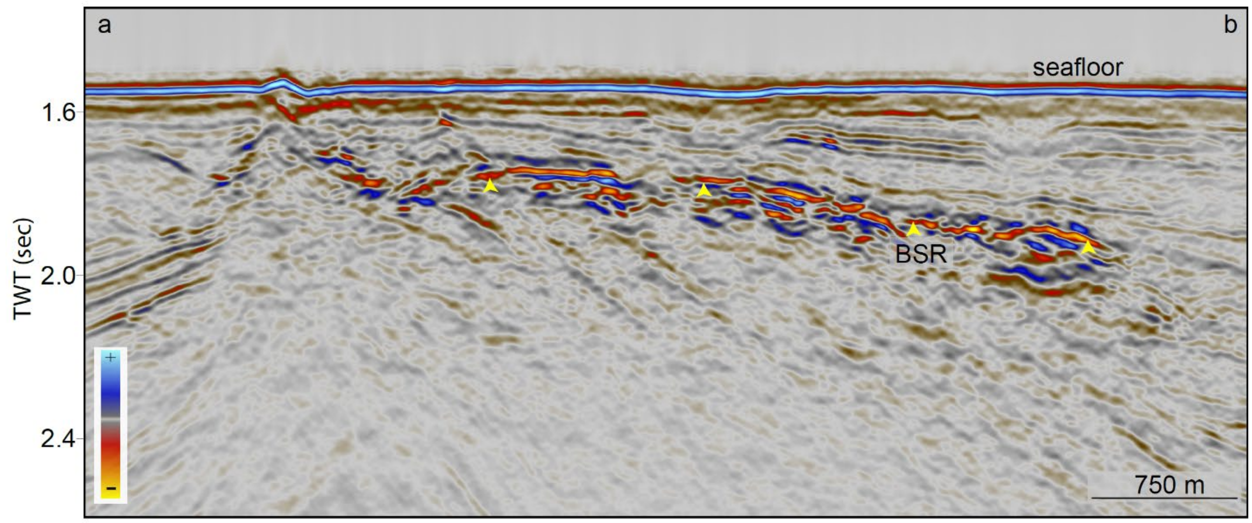

Figure 3: Seismic profile a-b showing a west-east cross-section across the northern BSR system of Project Area 2.5. The discontinuous BSR is marked with yellow arrows. The profile location is shown in Figure 2a.

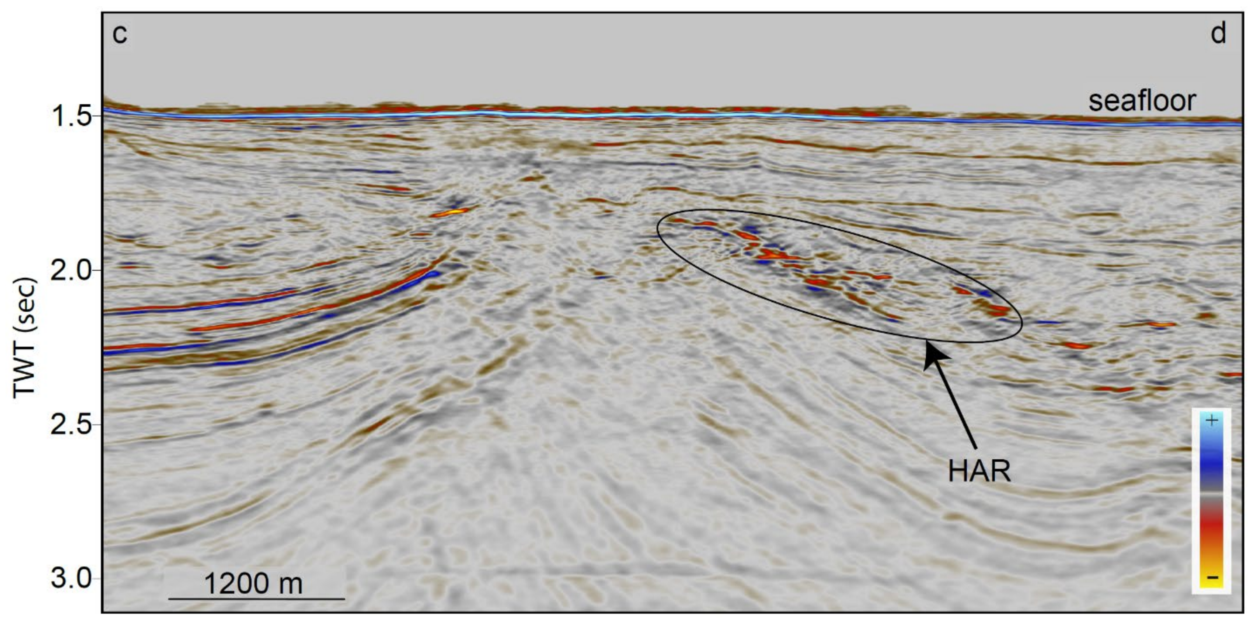

Figure 4: Seismic profile c-d showing an arbitrary west-east cross-section above the northern BSR system mapped by BOEM in Project Area 2.5. We observe high amplitude reflections in this cross-section but do not classify this as BSR. High amplitude reflections (HAR) are marked with an ellipse. The profile location is shown in Figure 2a.

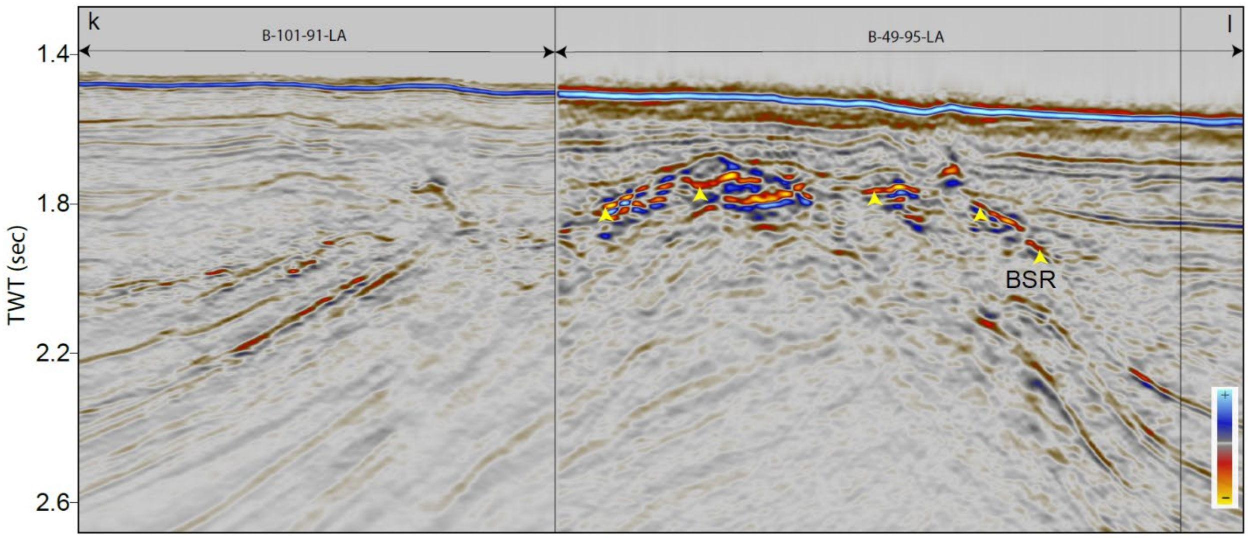

Figure 5: A seismic profile (k-l) showing a north-south cross-section in the northern BSR. We observe BSR on southern part (right side of the figure) covered by seismic volume B-49-95-LA, which has fair data quality. But we do not observe signature of the BSR in the northern part (left side of figure) which is covered by seismic volume B-101-91-LA, which has poor data quality (Table 2). Profile location shown on Figure 2a.

The central BSR system is newly identified in this study (Figure 2) and covers an area of ~20 km^2. The central BSR system varies between 200-300 msec TWT below the seafloor equivalent to ~170-250 mbsf. An arbitrary seismic profile across the central BSR system is shown in Figure 6.

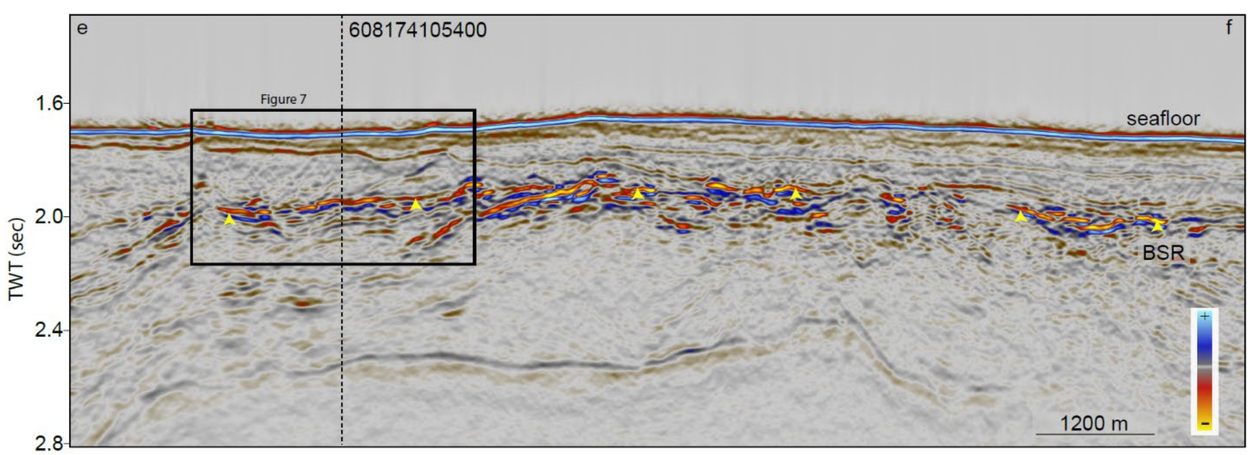

Figure 6: Seismic profile e-f showing a west-east cross-section across the central BSR system from Project Area 2.5. The discontinuous BSR is marked with yellow arrows. The profile location is shown in Figure 2a. The dotted line shows the location of API# 608174105400.

Well API# 608174105400 penetrates the central BSR as shown in Figures 2 and 6. The seafloor depth at the well location is 4181 feet below sea floor (fbsf). The gamma ray and P40H resistivity are displayed on the seismic data in Figure 7, using the velocity equation from Cook and Sawyer (2015). All available logs in the shallow interval are shown in Figure 8. The estimated BSR depth on the well log is ~4950 ft and is shown on Figure 8. A sand interval is observed with lower gamma ray values from 4650-4680 ft. Phase resistivity (P40H and P40L) increases up to 5 ohm-m in this sand interval relative to background resistivity (1 ohm-m). We interpret this layer is likely gas hydrate in sand. Notably, the attenuation resistivity curves do not show an increase in resistivity in this interval, possibly due to hole size. Interestingly, even though the well clearly penetrates the central BSR system (Figures 6 and 7), we do not observe any increase in resistivity near the estimated BSR depth (Figure 8). This is similar to the observations of Majumdar et al. (2016), that the presence of a BSR is not always linked to the presence of hydrate or free gas. It is important to note that a BSR can be caused by just a small amount of free gas (1-2%). Small saturations of gas are not easily detectable with the well logs available in this interval.

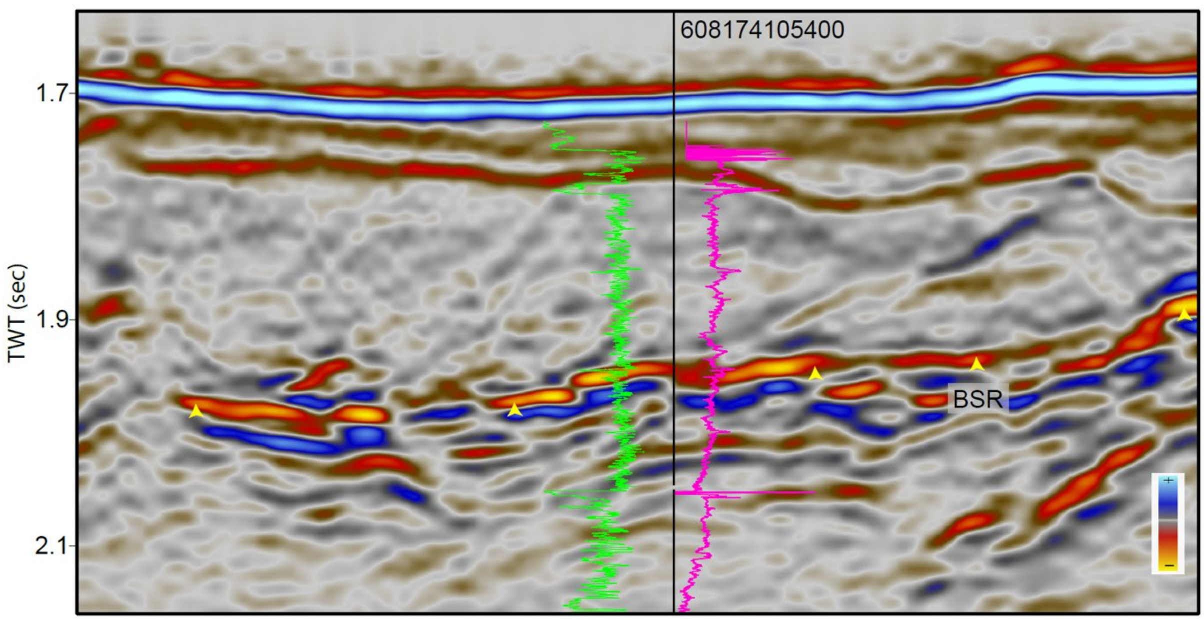

Figure 7: A zoomed-in section of the seismic profile shown in Figure 6. Gamma ray (green) and P40H resistivity (pink) logs are shown on the seismic section. The BSR is shown with yellow arrows. To see the scales for these well logs please see Figure 8.

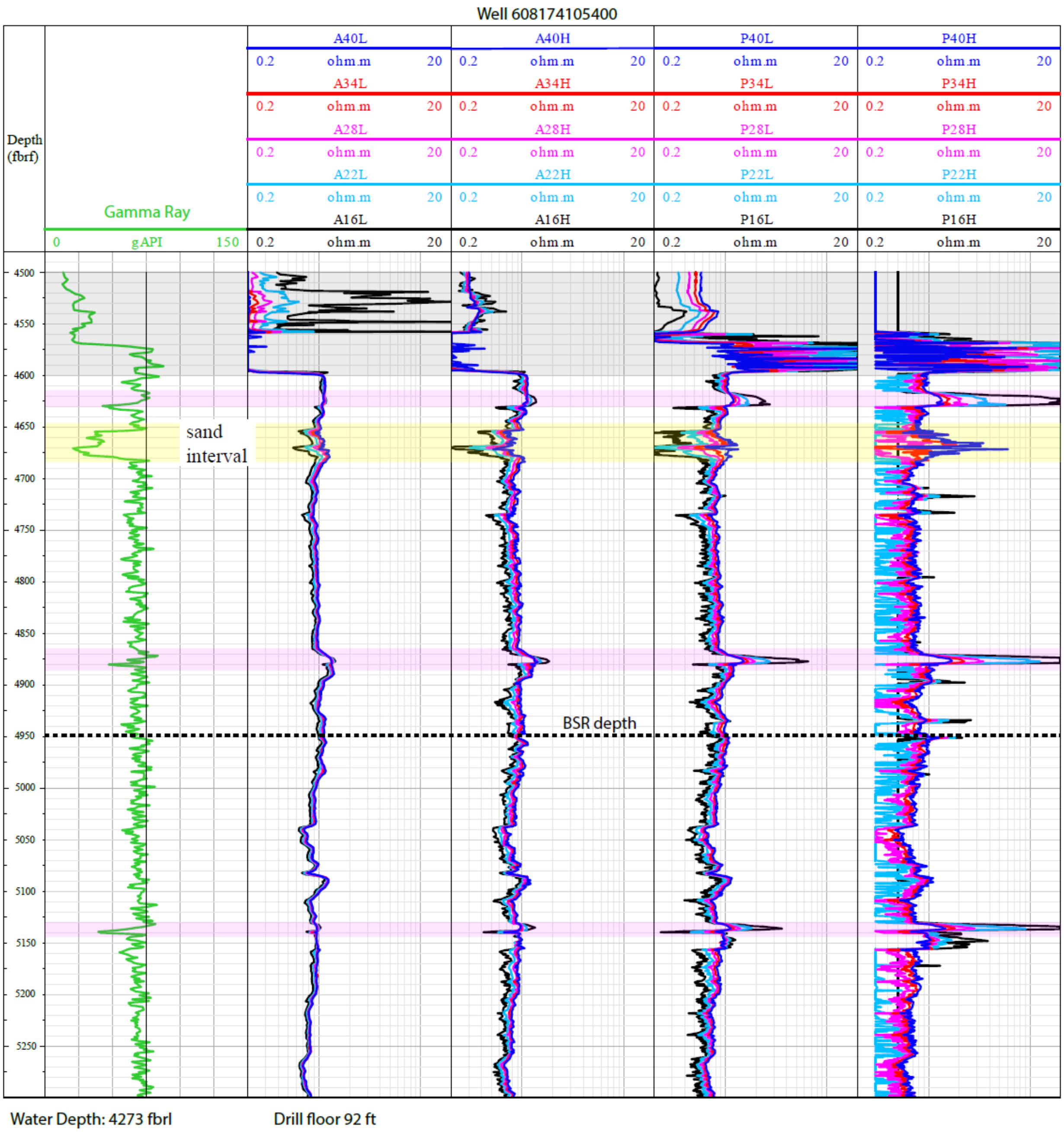

Figure 8: The gamma ray and resistivity logs from well API # 608174105400 (shown on seismic in Figure 7). Well logs in the tophole section (grey box) are erratic, poor quality and are not interpreted. Reduced gamma ray in the yellow box indicates a sand interval. Phase resistivities in this zone increase up to 5 ohm-m more than background resistivity. Attenuation resistivity curves in this interval do not show any increase in resistivity, but this may be due to hole size. Spikes in resistivity shown in the pink highlighted intervals are likely not the result of gas hydrate, as P16H should not have the highest value; these P16 spikes may be caused by mud or gel sweeps, but further confirmation is needed.

The southern BSR system completely overlaps with the BOEM-identified BSR (Figure 2) and covers an area of 10 km^2. Arbitrary seismic profiles across this BSR system are shown in Figures 9 and 10. The southern BSR is a discontinuous BSR observed over a salt structure. This BSR is present within 120-550 msec TWT below the seafloor, or nearly 100-470 mbsf. The nearest well to this BSR system is API # 608184005500 (Figures 2, 7, and 11), ~2 km away. This well is located in OCS block Atwater Valley 14 and was drilled as a part of the Gulf of Mexico Gas Hydrate JIP, Leg 1(Ruppel et al., 2008). This well does not show any significant increase in resistivity indicating presence of hydrate or free gas in the logged interval. The estimated base of GHSZ is approximately 5608 fbsf, calculated with a seafloor temperature of 4.3 °C and a geothermal gradient of 30 °C/km. This estimated base of gas hydrate stability is considerably lower than the depth of the logged interval in this well.

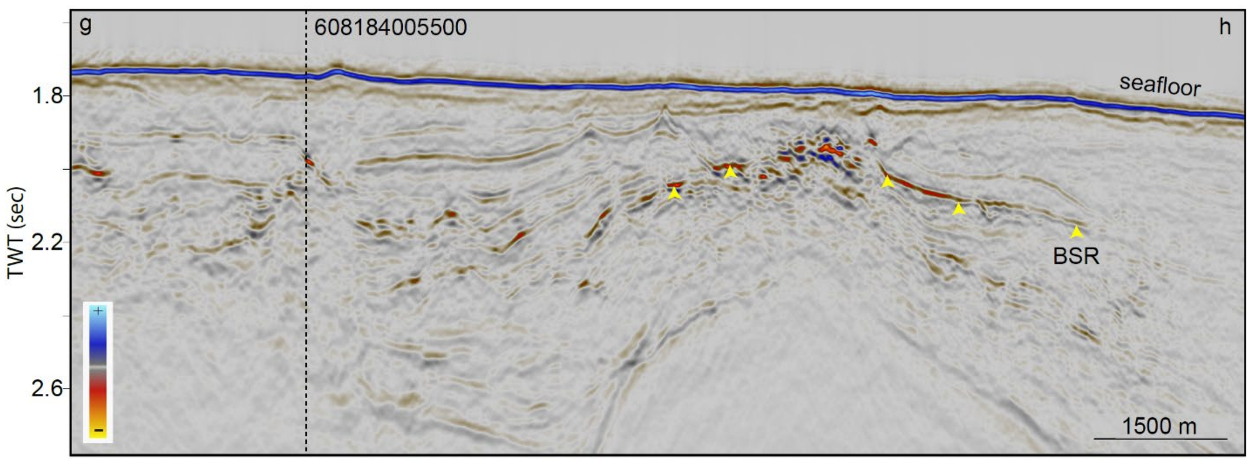

Figure 9: Seismic profile g-h showing an arbitrary cross-section across the southern BSR system of Project Area 2.5. The discontinuous BSR is marked with yellow arrows. The profile location is shown in Figure 2a. The dotted line shows the location of the nearest well, API# 608184005500.

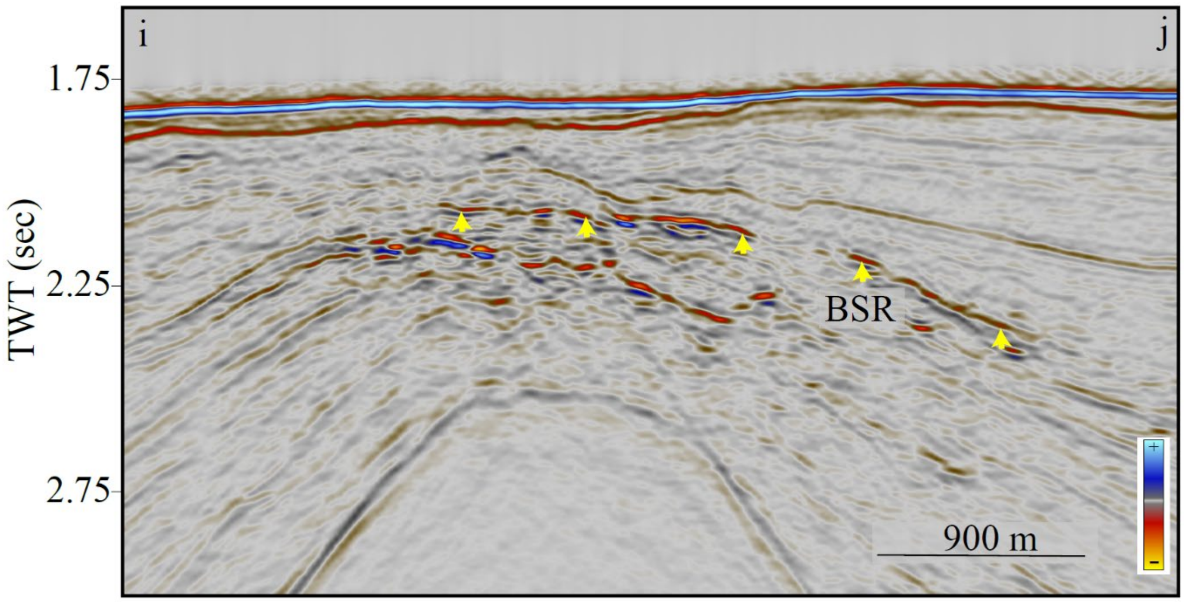

Figure 10: Seismic profile i-j showing a north-south cross-section across the southern BSR system of Project Area 2.5. The BSR is identified by yellow arrows.

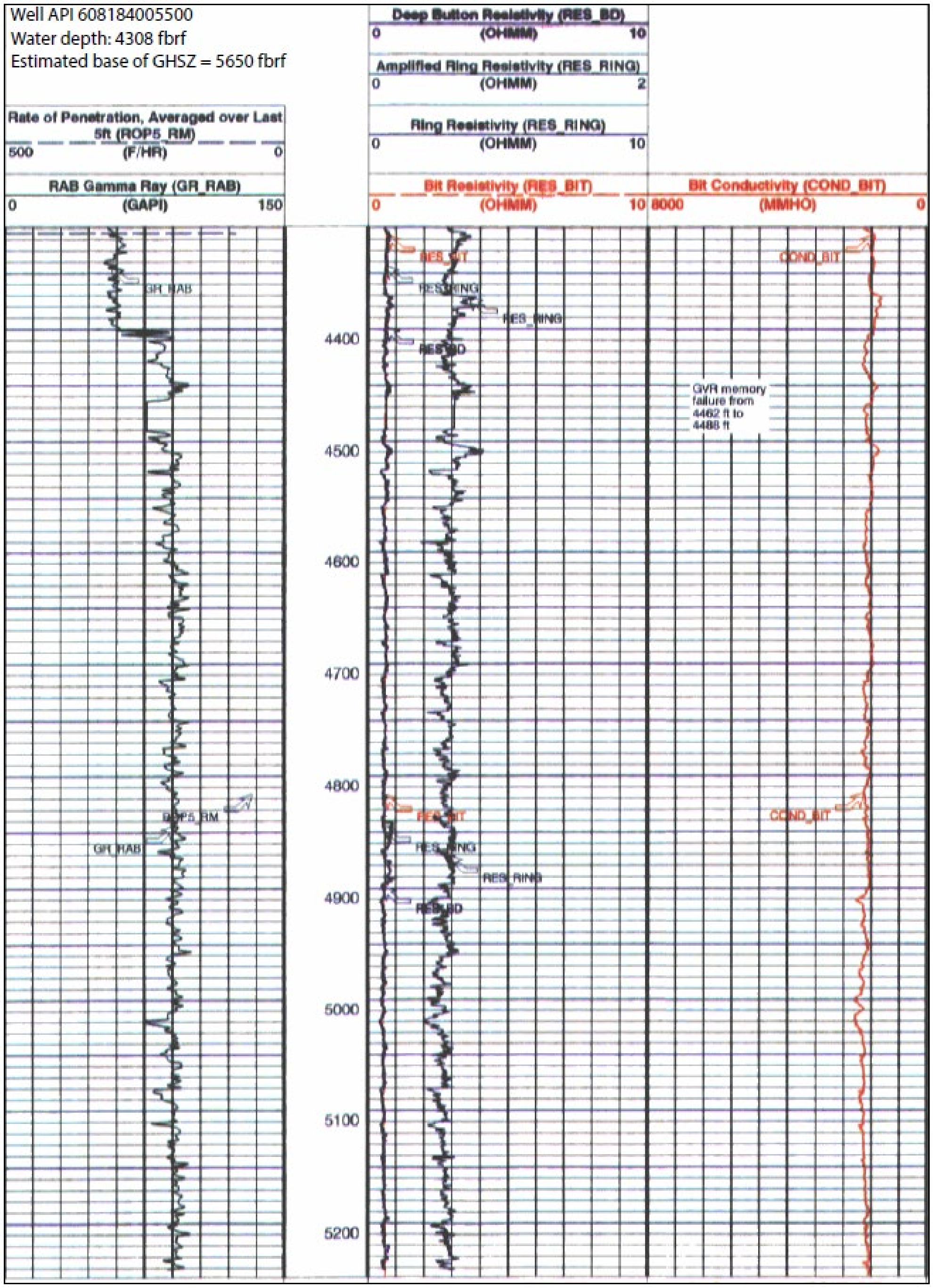

Figure 11: The gamma ray, resistivity, and conductivity logs from API #608184005500, drilled in AT 14 as part of the Gulf of Mexico Gas Hydrate JIP, Leg 1. The location of this well is shown on Figures 2 and 9. We do not observe any increase in resistivity in this log indicating the presence of hydrate or natural gas. The estimated base of GHSZ is at 5608 fbsf, calculated with a seafloor temperature of 4.3 °C and a geothermal gradient of 30 °C/km, which is below the interval logged in this well.

We derive geothermal gradients from the BSR assuming an equilibrium model: 1) heat flow is constant, one-dimensional (vertical) and occurs only through conduction; 2) pore pressure is hydrostatic; 3) pore fluid salinity is 3.5 %; and 4) gas composition is pure methane. We estimate the geothermal gradient in Project Area 2.5 between 25°- 95° C/km. The highest estimated geothermal gradient occurs just above the salt on the southern BSR system.

3 Phase II Summary

Phase II 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 Phase II is 1364 km^2 (Figure 1, Table 2). When peak-leading reflections were present above a BSR, the area of peak-leading reflections was interpreted to identify potential regions with high gas hydrate saturation (Table 2). Then, potential gas resources were calculated from peak-leading reflections. The same assumptions were used in each estimate, including, a minimum and maximum porosity of 30% and 40%, a minimum and maximum unit thicknesses of 10 and 30 m, and minimum and maximum gas hydrate saturations of 50% and 90%. Details about these assumptions are described in the Project Area 2.4 report.

These peak-leading reflections resulted in minimum and maximum gas resources ranging between 82.99 and 575.63 billion cubic feet (2.35 and 16.3 billion cubic meters (BCM)) at standard temperature and pressure (STP) for Phase II (Table 2). The resource estimate is conditional upon success and does not account for the geologic risk of not finding gas hydrate at any one particular prospect.

	Area 2.1	Area 2.2	Area 2.3	Area 2.4	Area 2.5	Total
BSR Area (km^2)	706	203	80	335	40	1364
Area of peak-leading (km^2)	-	3.5	0.35	5.5[2]	-	9.35
Resources min (BCM)	-	0.9	0.1	1.35[1]	-	2.35
Resources max (BCM)	-	6	0.6	9.7[1]	-	16.3

Table 2. The extent of BSRs and gas hydrate resource estimates for areas with strong peak-leading amplitudes distribution by Project Area in Phase II. Resource estimates are for gas at STP in billion cubic meters of natural gas (BCM). There were no peak-leading reflections identified in Project Areas 2.1 and 2.5.

4 Geothermal Gradients

Geothermal gradients were estimated from all BSRs using the assumption that the BSR represents the base of gas hydrate stability. The calculated GTG values are derived from the BSR subseafloor depths, bottom water temperature profiles and the assumption of Structure I gas hydrate (100% CH_4) using the stability equations from Sloan and Koh (2007). The water depth is calculated assuming a water velocity 1500 m/s and the BSR depth is approximated assuming that the sediment velocity is 1700 m/s. We find that geothermal gradients largely range between 20°C/km to 70°C/km in the Phase-II Project Areas (Figure 1, Table 3), with local exceptions where GTG is calculated to be as high as 200°C/km. High variability in geothermal gradients may be explained by the effects of the heat-conductive salt features that are widespread across the GOM. 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.

[2] This includes a prospect update detailed in Section 5.1 for Project Area 2.4.

Project Area	Zone #	Water depth (m)	BSR depth (mbsf)	GTG (°C/km)
2.1	1	1200-1700	200-500	30-55
2.1	2	900-1350	110-260	35-75
2.1	3	650-1400	100-400	25-65
2.1	4	850-1000	140-270	30-40
2.1	5	700-1200	75-475	20-65
2.1	6	750-1300	170-450	20-55
2.2	1	750-1000	380-420	20-25
2.2	2	850-1300	125-450	30-60
2.2	3	850-1900	200-600	25-53
2.3	1	950-1300	150-350	30-50
2.3	2	1200-1475	15-300	40-52
2.3	3	950-1200	130-680	20-60
2.3	4	1050-1400	42-255	40-200
2.4	1	800-1100	300-400	25-30
2.4	2	1300-1500	200-450	40-60
2.4	3	1500-1900	210-300	40-70
2.4	4	1200-1750	250-450	35-55
2.4	5	1750-2100	225-350	50-70
2.5	1	550-1500	100-340	25-95

Table 3. BSR depths and geothermal gradients in BSR zones of each Phase II Project Area. Water depth is calculated assuming water velocity 1500 m/s and BSR depth is approximated assuming sediment velocity is 1700 m/s.

5 Primary Prospects

Below, we describe two hydrate prospects from Phase II. These two prospects were selected as they have peak-leading reflections or seismic phase reversal at the BGHS, which are strong seismic indicators of natural gas hydrate in sand reservoirs.

5.1 Southwestern BSR, Zone 2, Project Area 2.4

Zone 2 of Project Area 2.4 is present in Mississippi Canyon (Figures 1 and 2 of Project Area 2.4 report). The southwestern BSR system in Zone 2 covers 16 km^2 and is associated with a salt diapir and in close proximity to the Chandeleur Landslide (Figure 12). The southwestern BSR is a discontinuous BSR and is adjacent to a paleochannel feature on the eastern side (Figure 13). The BSR depth varies between 250-450 mbsf. As shown in Figure 13, the BSR follows the seafloor topography, which is altered due to the landslide. This indicates that the BSR has moved downward due to the change in temperature and pressure from the landslide. This downward shift may have resulted in the capture of free gas beneath the old BSR into the hydrate stability zone, potentially leading to concentrated hydrate deposits at the site. Prominent, peak-leading reflections are observed above the BSRs in this system, also suggesting the presence of hydrate above the BSR (Figure 13). The average positive seismic amplitude map shows the extent of the peak-leading reflection within this system (Figure 14).

We likely underestimated the area covered by peak-leading reflections in our last report of Project Area 2.4. Herein, we map the peak leading reflections manually to calculate their areal extent (Figure 14). We estimate that peak leading reflections cover an area of ~5 km^2. Based on refined peak-leading map, we re-estimate the gas resources for this BSR. Our new estimate for natural gas for this gas hydrate prospect is between 1.2 BCM to 8.9 BCM for this BSR, which is included in Table 2.

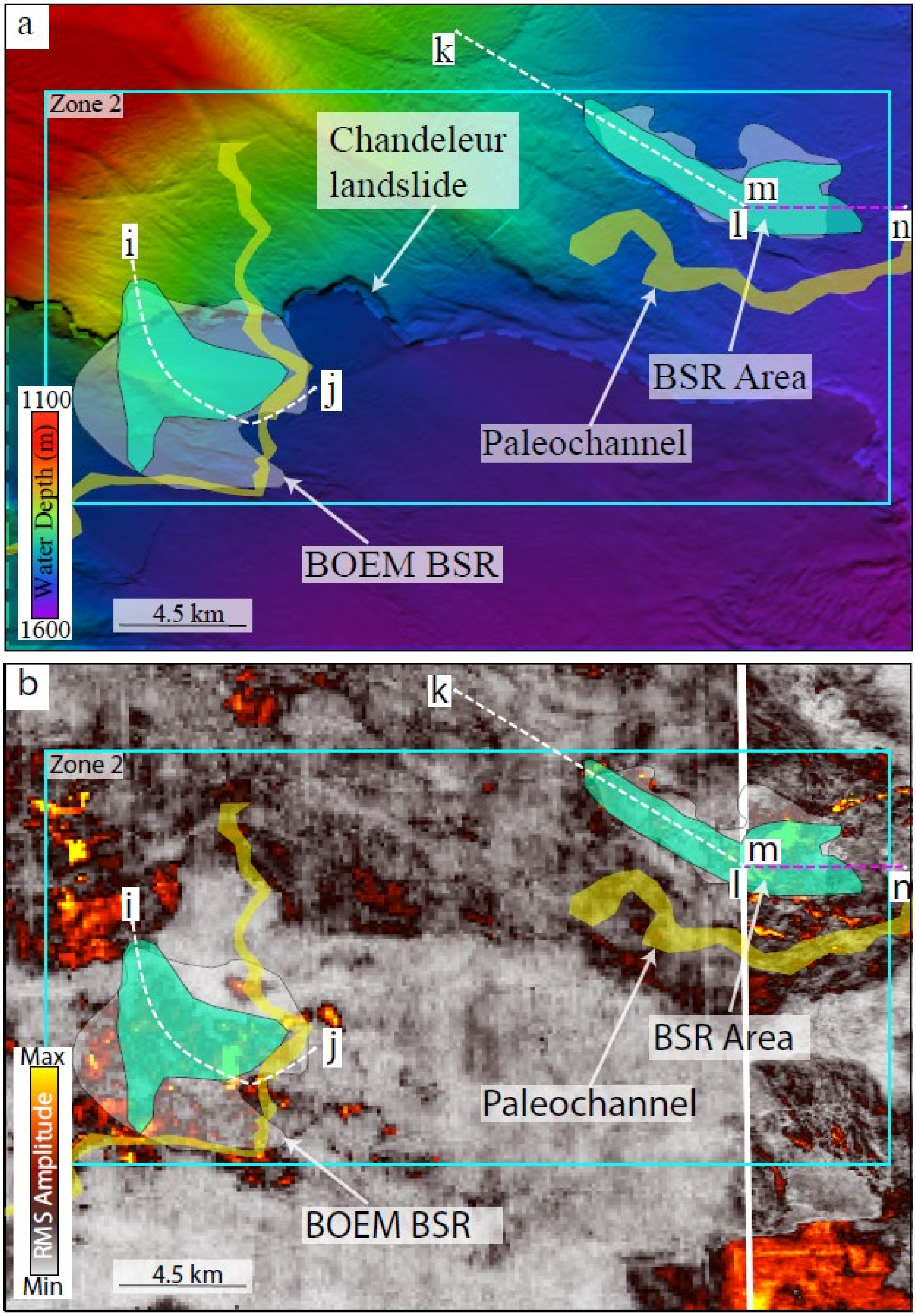

Figure 12: a) A bathymetry map showing the BSR extent within Zone-2 of Project Area 2.4. Ohio State BSRs and BOEM BSRs are shown in green and white polygons, respectively. b) RMS amplitudes calculated over a window of 350-450 msec below the seafloor. The BSR systems correlate well with high RMS amplitudes in this area.

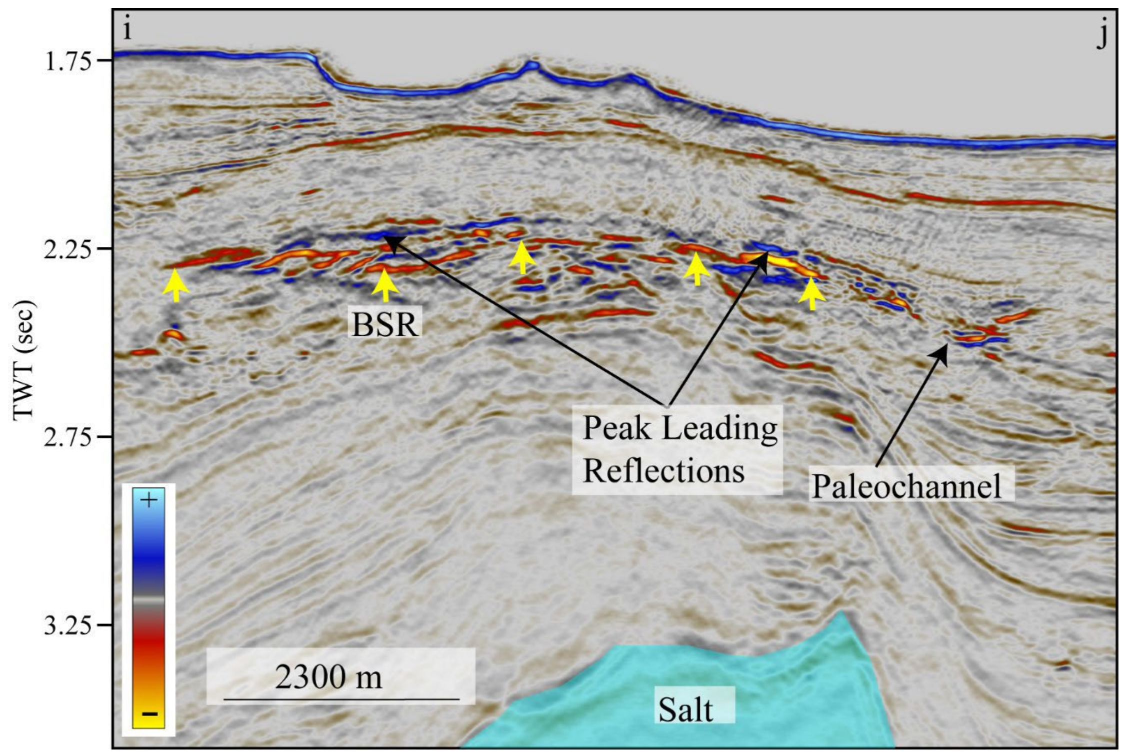

Figure 13: A seismic profile (i-j) showing a discontinuous BSR below the landslide across southwestern BSR system of Zone-2. A few peak-leading reflections are observed above the interpreted BSR. The salt diapir and paleochannel features are also shown in the profile. The profile location is shown in Figure 12.

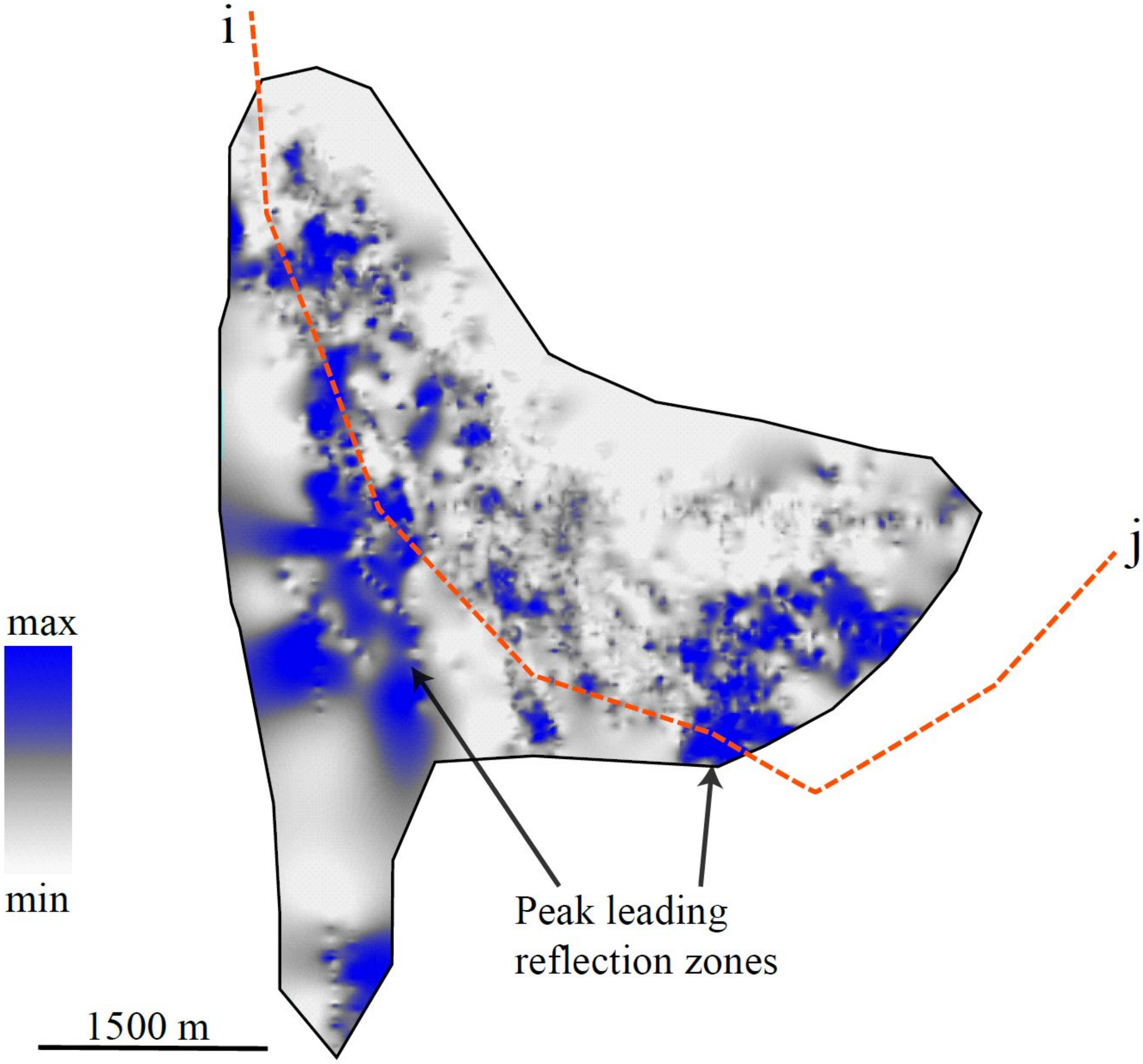

Figure 14: A map of average positive amplitude calculated within a 60 msec window above the BSRs in the southwestern BSR system of Zone-2. The yellow line shows the track of seismic profile i-j shown in Figure 13.

5.2 Southern BSR, Zone 3, Project Area 2.2:

Zone 3 of Project Area 2.2 is located in the Green Canyon protraction area in the GOM (Figures 1 and 2 of Project Area 2.2 report). The southern BSR in Zone 3 covers 30 km^2 and is associated with a north-south trending salt ridge (Figure 15). A discontinuous BSR is observed on seismic data (Figures 16-18), with a depth that varies between 250-500 mbsf. We observe a possible seismic phase reversal at the BSR (Figure 16-18). We manually track this phase reversal horizon, and show the instantaneous amplitude along the phase reversal horizon in Figure 19. The positive part of the horizon covers an area of ~ 2.5 km^2. However, it should be noted that this phase reversed amplitude is not a strong positive amplitude. Also, as shown in Figure 19, the interpreted free gas phase associated with the negative amplitude does not express any downdip concurrence with structure that could be interpreted as a gas-water contact.

The nearest well (API# 608114022900) is ~ 2 km away from the interpreted BSR (Figure 20). A seismic profile across the BSR zone and the well is shown in Figure 20b. The well log interval from ~5100-6900 ft is mapped to the BSR (Figure 20b). The resistivity at some intervals in the well increases slightly above background (~1 Ωm) but remains less than 2 Ωm (Figure 20b and c). Because these variations are not significant, it is difficult to determine whether these variations are related to gas, gas hydrate, or change in lithology and/or porosity. We observe low gamma and low resistivities in the well at a depth of ~6400 ft (Figure 20c); this interval maps to the approximate depth of BSR (Figure 20b), suggesting this may be a sand-rich interval.

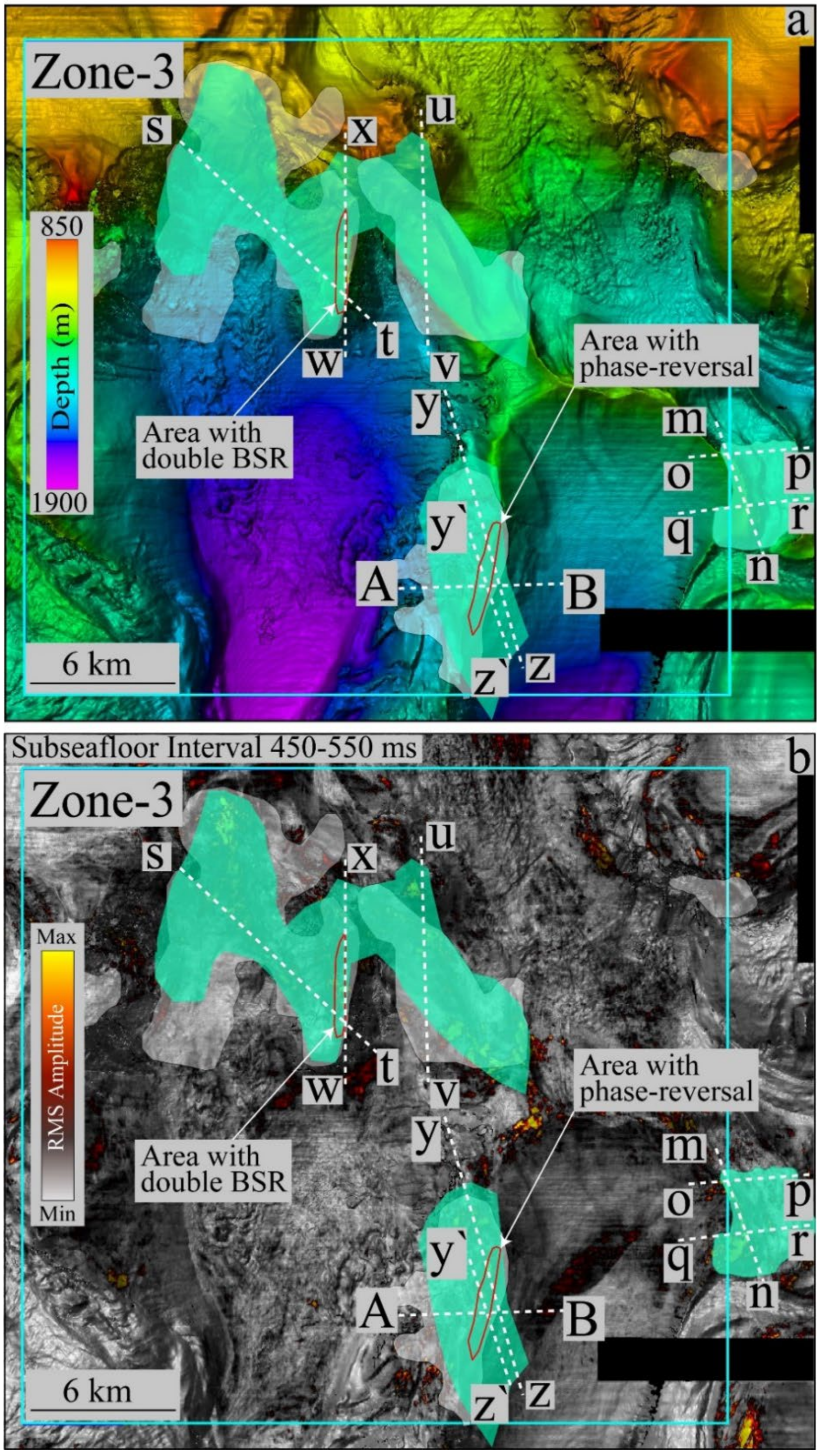

Figure 15: a) A bathymetry map showing the BSR extent within Zone-3 of Project Area 2.2. Ohio State BSRs and BOEM BSRs are shown in green and white polygons, respectively. b) RMS amplitudes calculated over a window of 450-600 msec below the seafloor. The BSR systems correlate well with high RMS amplitudes in this area.

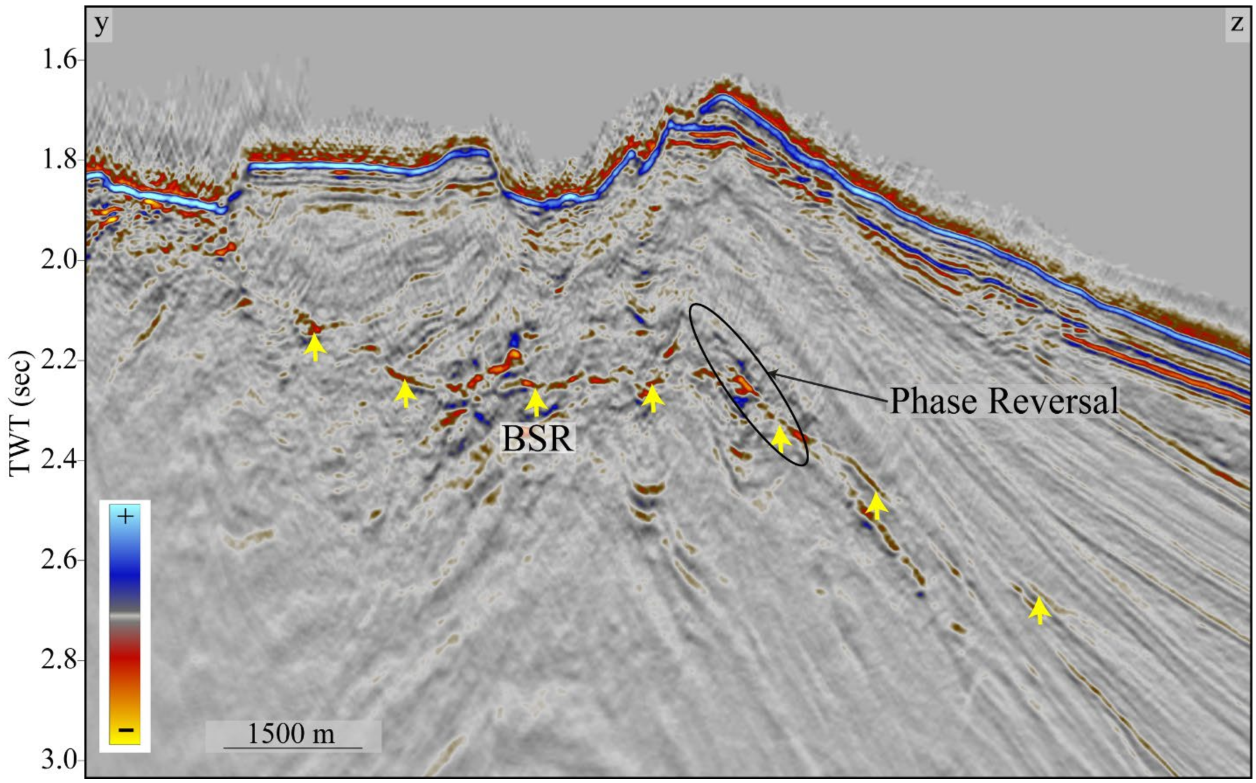

Figure 16: A seismic profile (y-z) showing a north-south cross-section across the southern BSR system of Zone 3. A discontinuous BSR is marked with yellow arrows. The profile location is shown in Figure 15.

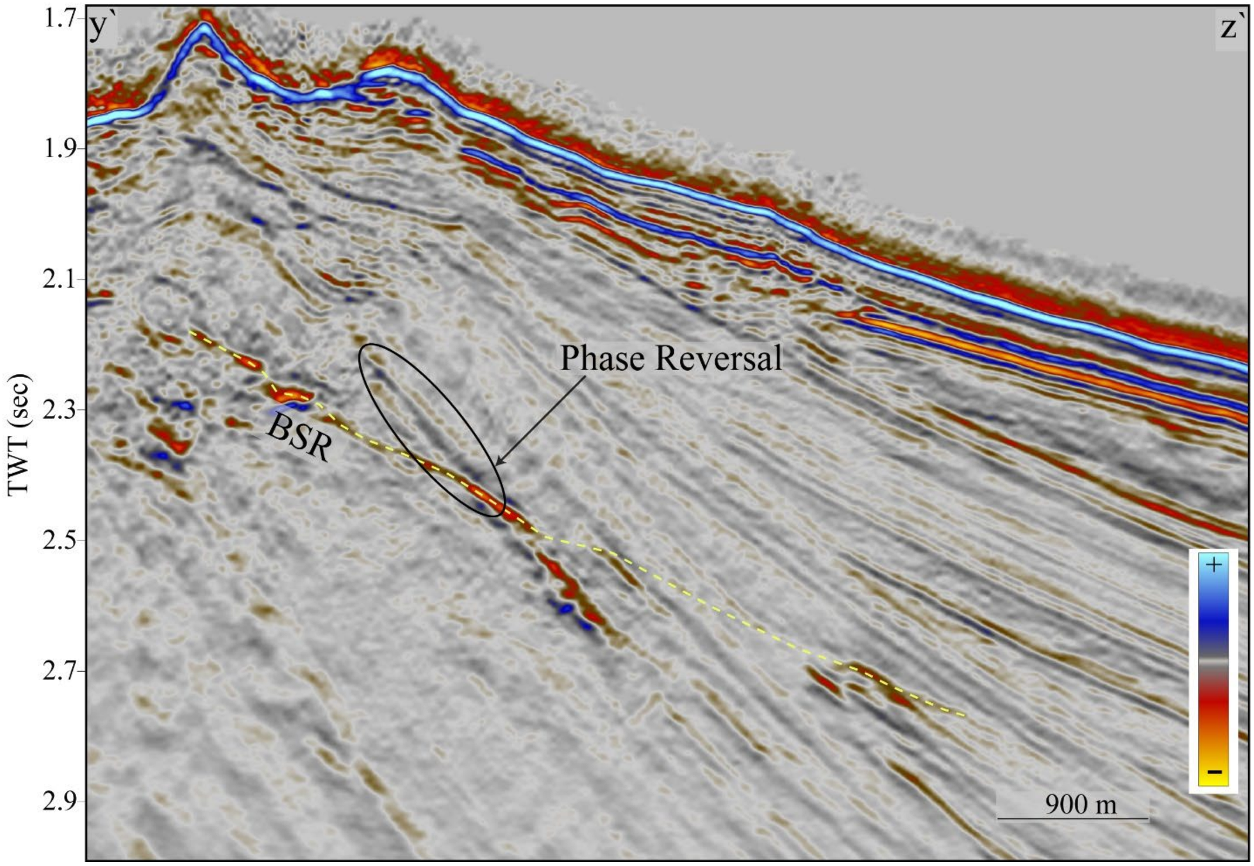

Figure 17: A seismic profile (y'-z') showing a north-south cross-section across the southern BSR system of Zone 3. A discontinuous BSR is marked with a yellow line. The profile location is shown in Figure 15. The interpreted phase reversal event is noted on the image, where a peak-leading event reverses to a trough-leading event at the BGHS.

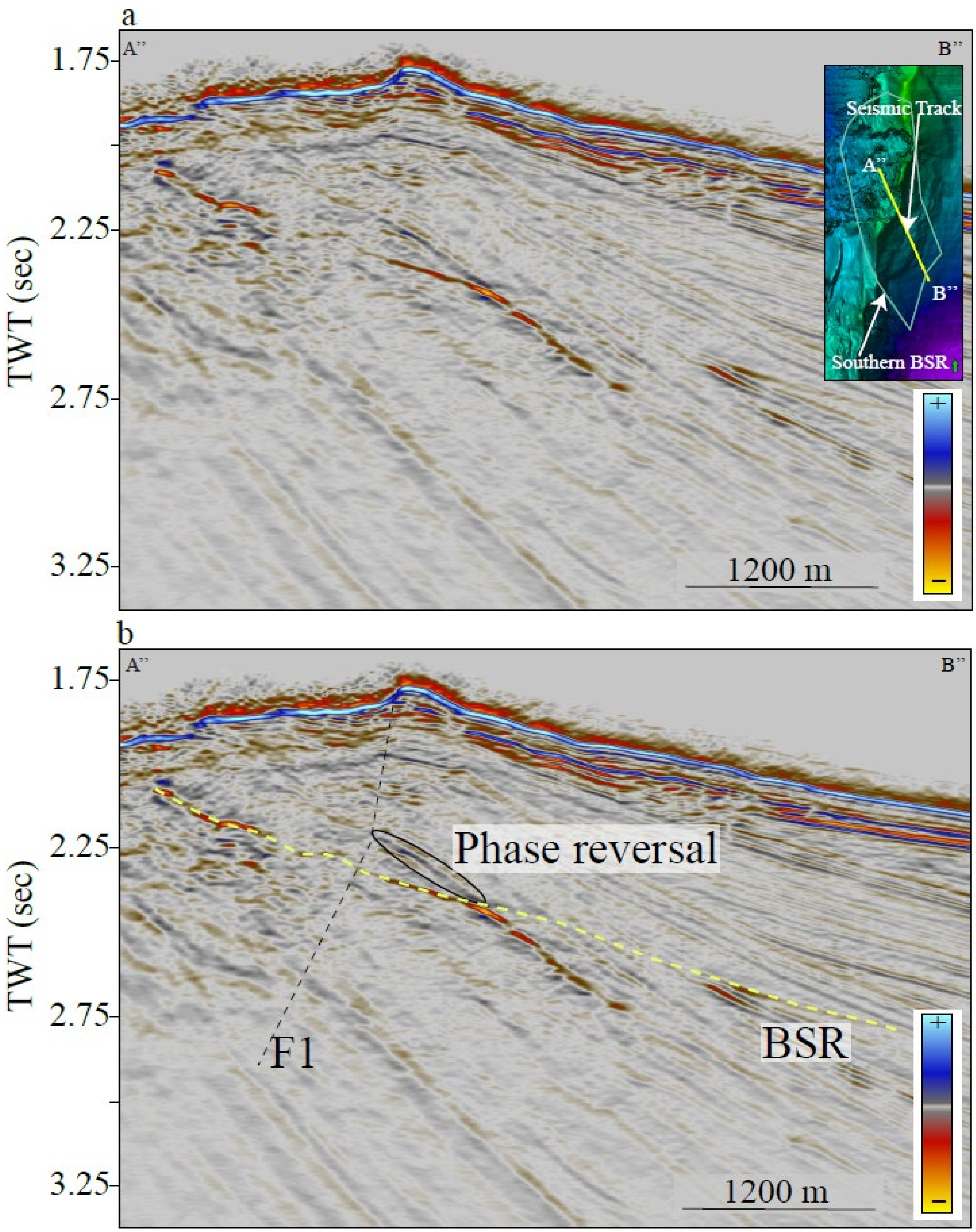

Figure 18: a) An uninterpreted seismic profile (A”-B”) across the southern BSR showing the arbitrary cross-section. Inset shows the profile location across the BSR. b) Interpreted cross-section of the same seismic profile.

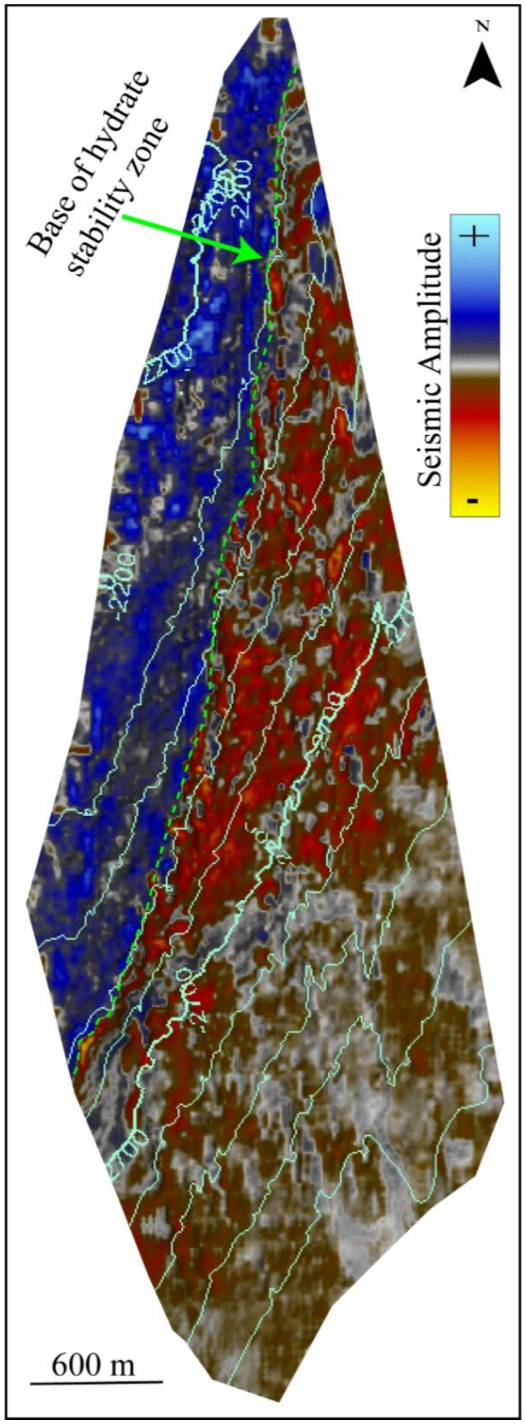

Figure 19: Instantaneous amplitude map along the reflector showing the phase reversal in the southern BSR system in Zone 3 (Figure 15). Here, blue indicates the extent of peak-leading reflections that may be associated with the presence of hydrate and red indicates the likely presence of gas. Contours represent TWT (msec) times of the reflection. The location of peak-leading reflection is shown in Figure 15.

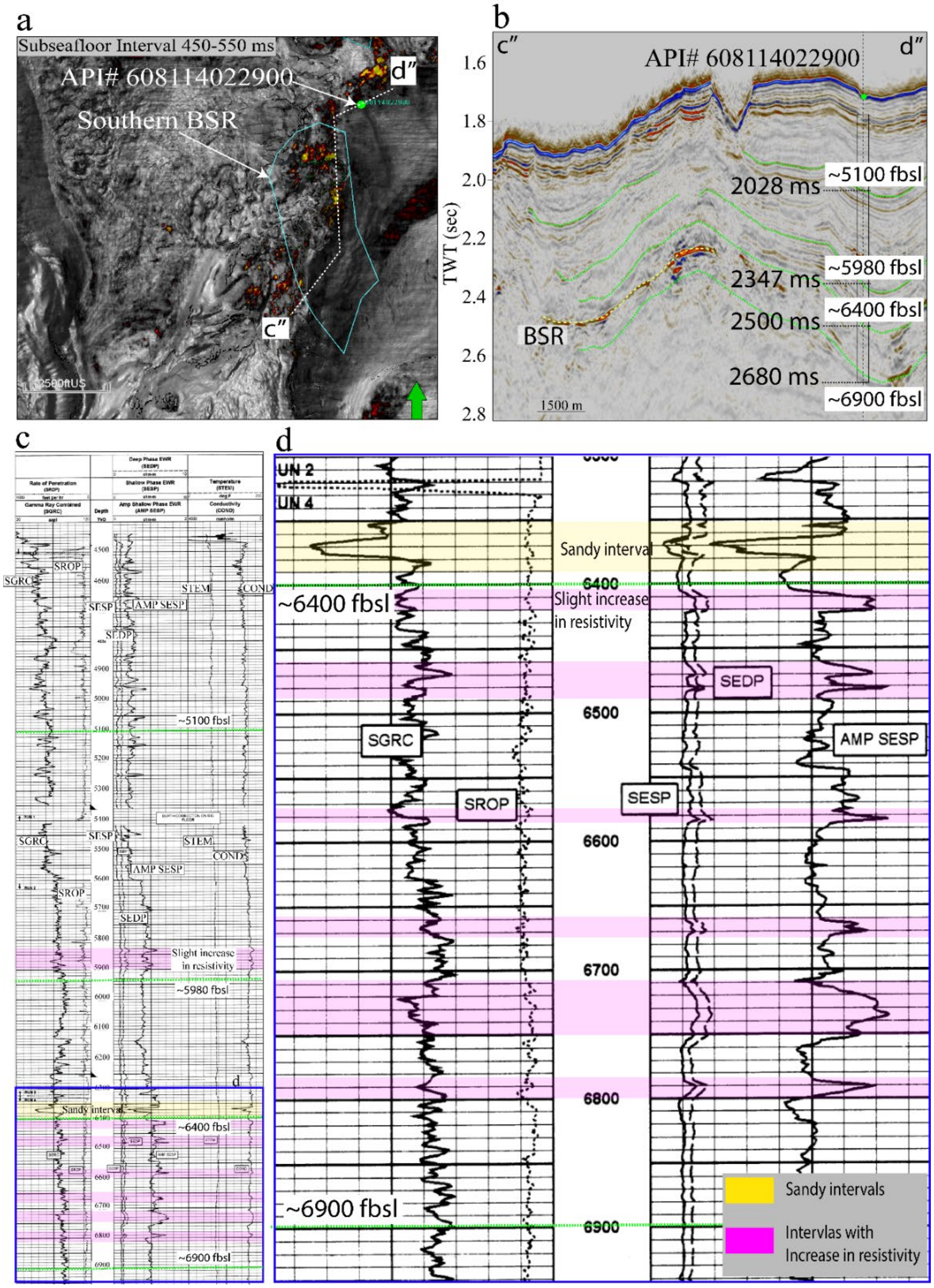

Figure 20: a) The map shows the RMS amplitude near the southern BSR of Zone 3, Project Area 2.2, within the subsurface interval of 450-550 ms. The green circle shows the location of the well with API# 608114022900, and the white dotted line is the track of the seismic profile shown in b). c) The well logs are shown in Figure c. A zoomed-in section of the logs at a depth interval of ~6300-6950 ft is shown in Figure d. Scales: SROP (1000-0), SGRC (20-120), SEDP (1-10), SESP (1-10), AMP SESP (1-2), STEM (0-200), COND (4000-0).

6 Acknowledgement

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

7 References

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