Gulf of Mexico Hydrate Mapping and Interpretation Analysis

Project Area 1 Report
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This report satisfies Mapping and Prospect Identification within Area 1 for BOEM award Gulf of Mexico Gas Hydrate Mapping and Interpretation Analysis, which is Deliverable/Milestone #2 (Table 1).

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Table 1. List of required deliverables and figures.

	Deliverable	Figure #
1	A map showing the distribution of shallow turbidite channel levee systems and shallow salt bodies	3, 4
2	A map showing the depth to the BSR and the spatial distribution of BSRs	5, 6
3	Regional seismic cross sections showing the base of gas hydrate stability and the relationship of prospective reservoir intervals to channel levee systems, faults, salt, and other geologic features	8, 15
4	Subsurface geologic/geophysical maps at the base of gas hydrate stability as determined through mapping, modeling and the integration of well log data	3, 7, 10, 16, 18
5	Subsurface geologic maps of one or more seismic reflectors within the gas hydrate stability zone (or that cross the gas hydrate stability zone) that have a high probability of containing coarse-grained sand based on well log analysis and the nature of the seismic reflector. Maps will include both structural and amplitude renderings.	7, 18
6	Interpreted seismic lines that illustrate geologic features related to the prospective reservoirs including BSRs, faults, base of gas hydrate stability, and zones of interest.	9, 11, 12, 13, 14, 15, 19, 20, 21, 22, 23, 24
7	If wells occur in the vicinity of the prospect, annotated well-logs at each gas hydrate prospect showing the thickness of hydrates within the stability zone, interpreted base of gas hydrate stability, and the presence of free gas beneath the gas hydrate stability zone.	25, 26,27, 28

1. Study area and data

Project Area 1 is located in the northeastern Gulf of Mexico at the Mississippi Alabama continental slope in ~300-2400 meters of water (Figure 1a, b). The area is characterized by multiple salt bodies outcropping at the seafloor, and several canyon systems transporting coarse-grained sediments from the shelf delta across the slope and seaward (Figure 1b) (Sylvester et al., 2012).

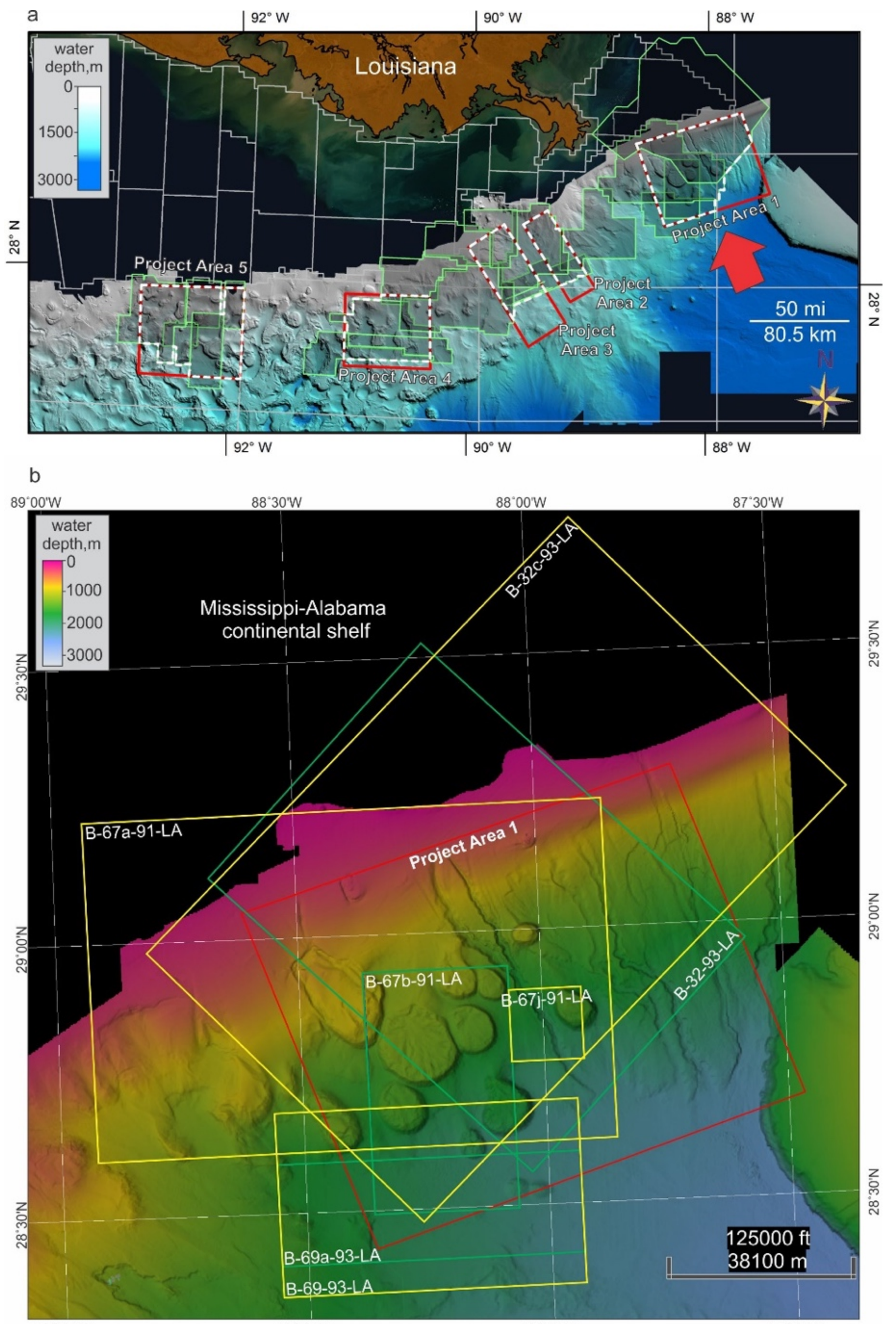

Figure 1 a) Bathymetry map of the northern Gulf of Mexico and five Project Areas. Location of Project Area 1 is defined with the red arrow. b) Bathymetry map and location of seven 3D seismic surveys uploaded from NAMSS for data quality assessment in Project Area 1. Yellow boxes are seismic surveys selected for further data interpretation and analyses. See Table 2 for details. Red box shows Project Area 1.

Within the Project Area 1, seven seismic surveys were uploaded from the NAMSS database for data quality assessment (Figure 1b, Table 2). The total area of Project Area 1 is 6623.5 km^2 of which ~5273 km^2 (79%) show 3D seismic data coverage. Based on spatial coverage and data quality, we selected four surveys, B-32c-93-LA, B-67a-91-LA, B-69-93-LA and B-67j-91-LA (yellow boxes in Figure 1b) to perform further data analyses and interpretation.

Table 2. Details on 3D seismic surveys uploaded for initial data quality analyses within Project Area 1. Yellow color marks surveys selected for further data interpretation.

Survey number	Survey name	Project Area #	Year	Number of 3D volumes	Area of seismic survey (km2)	Frequency range (Hz)	Bin size (m)	Projection	Comments
1	B-32c-93-LA	1	1991-1994	8	13521	5-80	25x25	16N NAD27, feet	
2	B-67j-91-LA	1	1991	1	274	5-54	26x53	16N NAD27, feet	
3	B-32-93-LA	1	1993	3	4391	n/a	25x25	16N NAD27, feet	In depth (ft), low frequency, poor quality
4	B-67a-91-LA	1	1991	9	6397	5-70	26x26	16N NAD27, feet	
5	B-69-93-LA	1	1993	2	2439	7-60	25x25	16N NAD27, feet	
6	B-69a-93-LA	1	1993	2	1736	7-35	7.6x7.6	16N NAD27, feet	
7	B-67b-91-LA	1	1991	2	1849	n/a	53x53	16N NAD27, feet	Depth domain (velocity cube is loaded but has different geometry)

2. Using RMS for mapping bottom simulating reflections

Regional root-mean-square (RMS) amplitude calculations in Project Area 1 were performed independently within three 3D seismic surveys B-32c-93-LA, B-67a-91-LA and B-69-93-LA to help identifying the bottom simulating reflections (BSR). At the stage of regional RMS analyses, the reference horizon was a Seafloor Horizon. Based on the water depth, Project Area 1 was divided into three domains (600-800 msec TWT, 800-1330 msec TWT and 1330-max depth) (Figure 2).

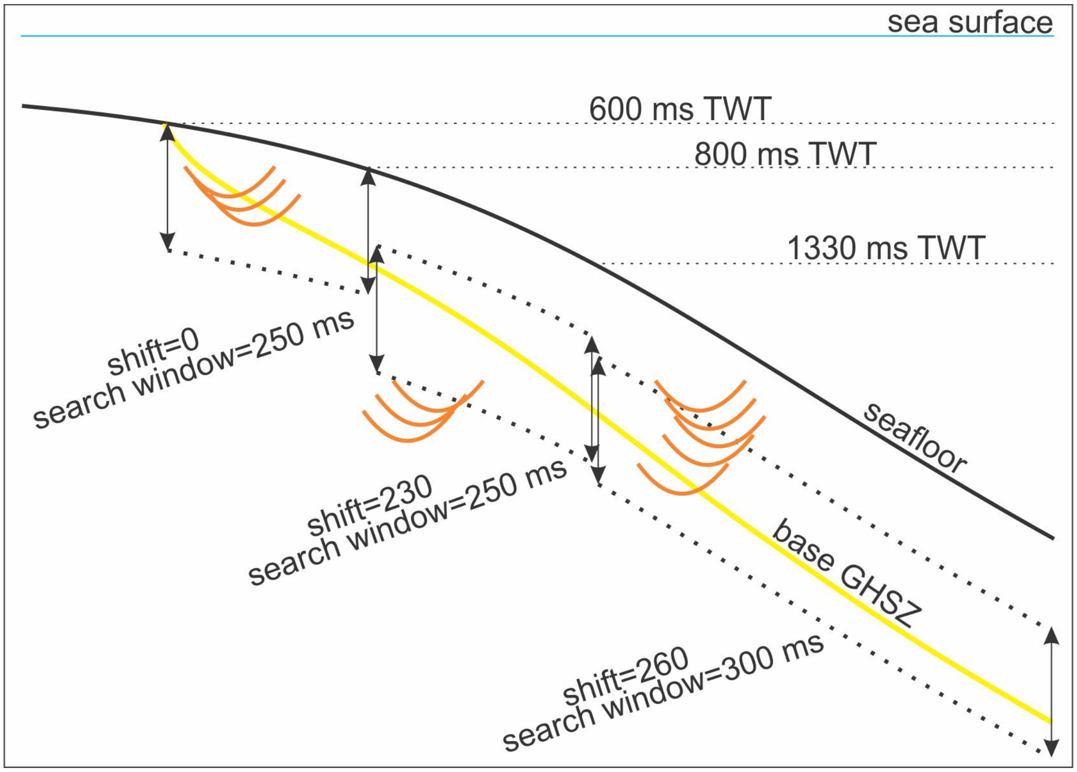

Figure 2. Scheme showing technical approach to regional RMS amplitude mapping at the approximate level of the base of GHSZ. Yellow line shows anticipated base of GHSZ, orange shapes are possible locations of channel systems relatively to RMS calculation windows showing that such approach only captures ancient channels proximal to the base of GHSZ (see text for more details).

Within each domain, we used different set of parameters for RMS calculations (shift below the reference horizon and search window) based on the anticipated depth of the lower GHSZ boundary and therefore potential BSRs. For example, in the shallow domain (600-800 msec TWT) the anticipated BSR depth range varied from 0 to ~250 msec below the Seafloor Horizon, thus this interval was selected for RMS calculations. While in the 800-1330 msec domain, shallow subseafloor sediment section (~230 msec) was excluded from the RMS interval to avoid amplitude anomalies that are not related to the BSR. Later, RMS values in each domain were calibrated for qualitative analyses and potential zones of interest were identified (Figure 3). It is important to note, that such RMS mapping helped to efficiently map channel systems in the Project Area, yet parts of channel systems that were significantly above or below the intervals of interest could not be entirely captured (Figure 2). Additionally, in an attempt to raise the quality of our analyses, for each seismic survey we generated a sweetness volume attribute cube that is typically used for better channel mapping in young sedimentary basins like the Gulf of Mexico (Hart, 2008). We further used the sweetness volume for surface RMS mapping and comparison with the original RMS data from seismic amplitude cubes, however, these results were nearly identical.

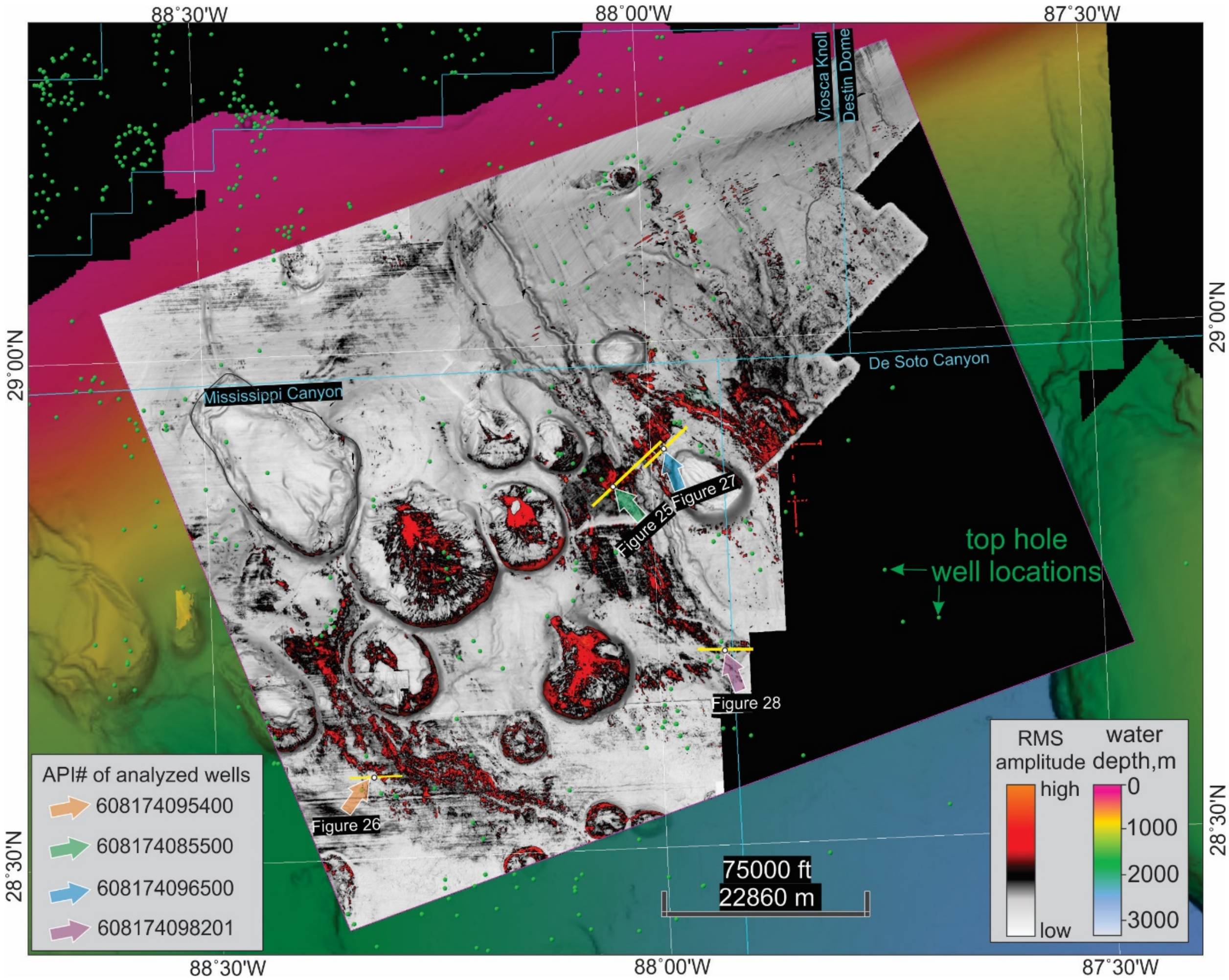

Figure 3. RMS amplitude map at the approximate level of the base of GHSZ within Project Area 1. Green dots show location of the wells drilled in the study area. Four white circles and colored arrows show wells most proximal to high RMS zones and selected for detailed analyses (Figures 25-28).

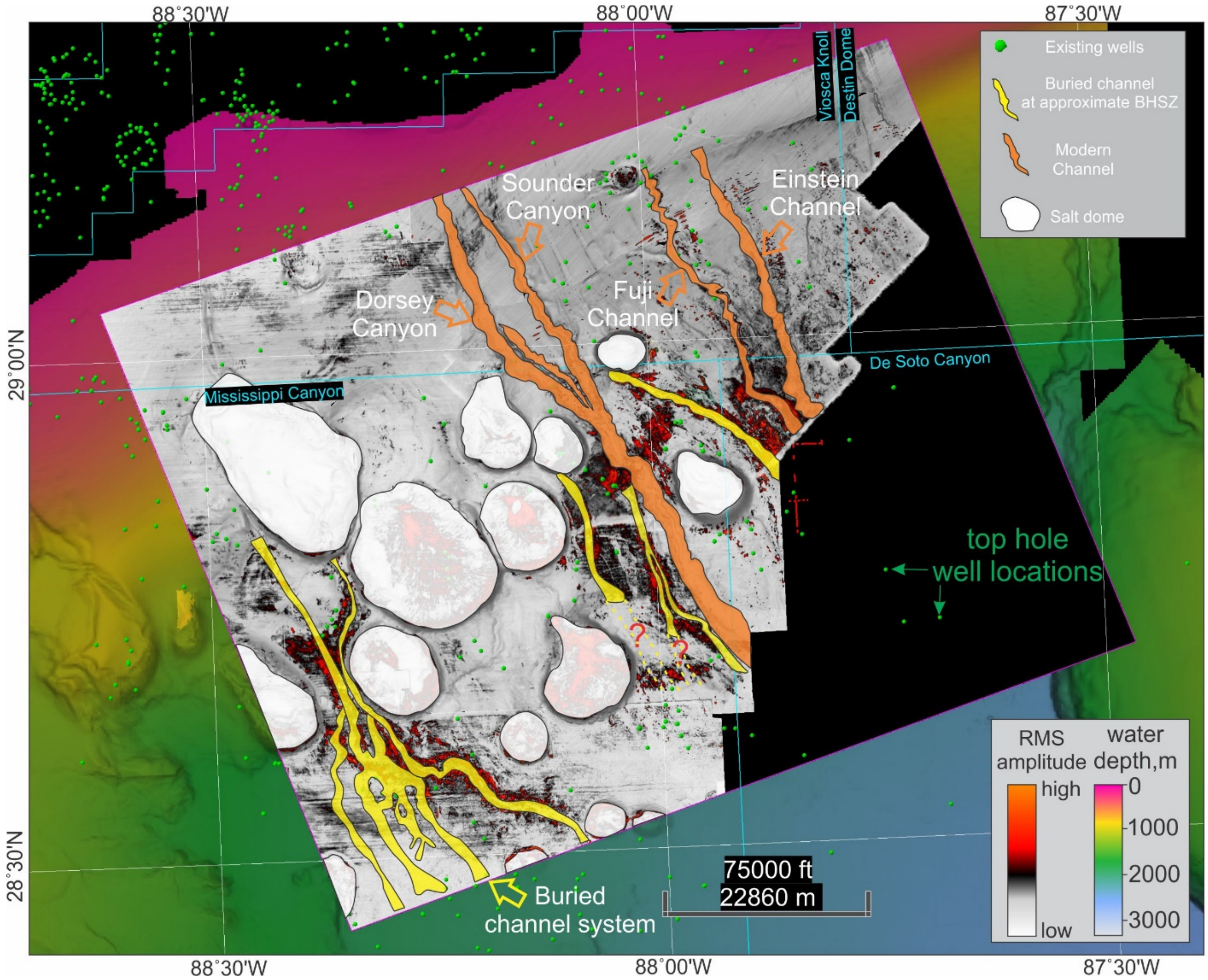

Figure 4. Interpreted RMS amplitude map showing major channel systems and shallow salt bodies within Project Area 1. Green dots show surface well locations.

3. Results in Project Area 1

We map three large channel systems within Project Area 1: the Einstein-Fuji Channel System (expressed on the seafloor) that merges downslope with an unnamed buried channel. The Einstein-Fuji Channel System has been previously characterized (Sylvester et al., 2012); the Dorsey-Sounder Canyon system with several parallel buried channels downslope; and an unnamed, but extensive buried channel system that doesn't have a modern seafloor expression in the SW corner of Project Area 1 (Figure 3, Figure 4). All three systems are potentially gas-hydrate bearing. Detailed analyses of the channel systems showed that in many places, high-amplitude anomalies are produced by the BSRs as was expected. Additionally, there are multiple shallow salt bodies in the Project Area 1 that control the geometry of the channels and some local gas accumulations in structural traps at their margins (Figure 3, 4). Semi-automatic and manual mapping showed that the BSRs are located at ~1800-3400 msec TWT (~100-580 mbsl) (Figure 6). For more detailed mapping and analyses we grouped them into Zone 1, Zone 2 and Zone 3 (Figures 5, 6). Unfortunately, there are no wells drilled directly in the areas of high-amplitude reflections except for the two wells in the western part of Zone 1, that are located close to Jackalope gas hydrate system (Portnov et al., 2020). We selected four wells that are most proximal to high RMS amplitude areas (Figure 3) for seismic well tie and analyses (see chapter 6 for details).

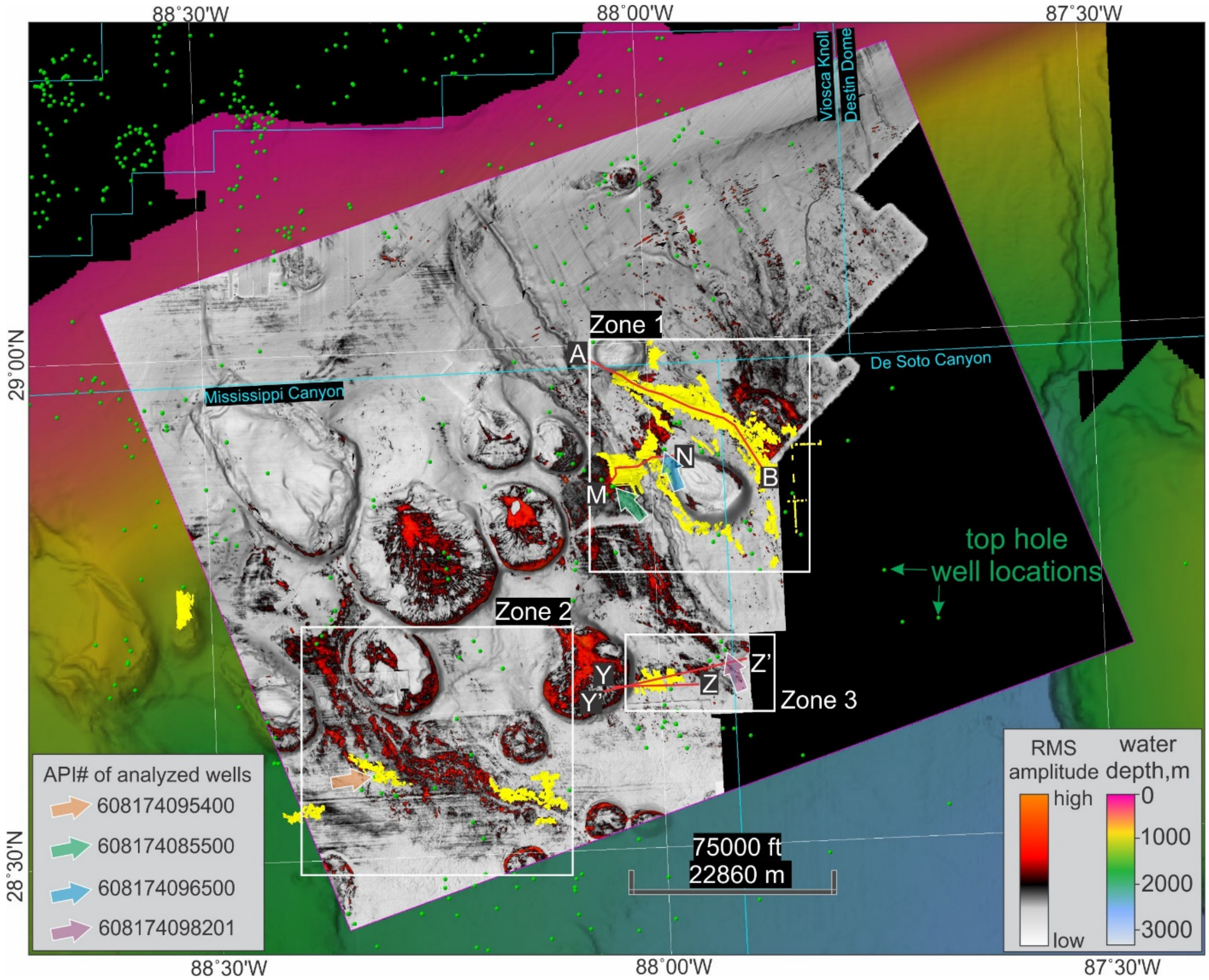

Figure 5. BSR distribution (yellow areas) based on semi-automated mapping. Arrows mark four wells selected for more detailed analyses (see chapter 6 for details).

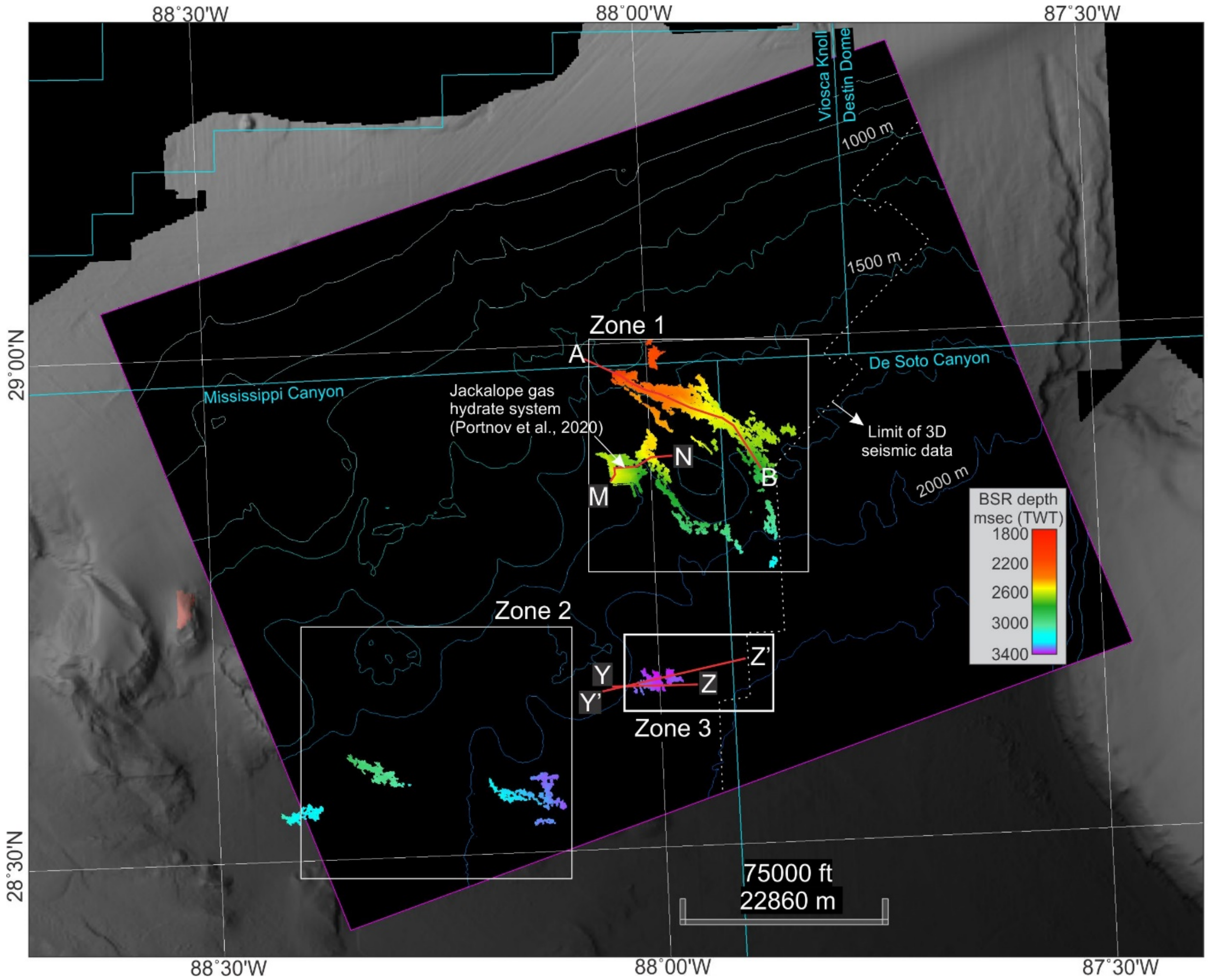

Figure 6. Depth of the BSR (msec TWT) combined with seafloor bathymetry contours.

4. Results in Project Area 1, Zone 1

4.1 BSR in Northern Zone 1

For more detailed mapping of BSRs and potential gas hydrate accumulations in the northern part of Zone 1, the closest coherent seismic reflection overlying the channel system was mapped (Horizon 1, Figure 7a, and Figure 8). RMS mapping within 150 msec below Horizon 1 showed that highest BSR amplitudes concentrate within the channel outer levees (Figure 7b). An exception is a southeastern part of the channel, where it branches and merges with smaller channels that confluence from the east. The BSR there becomes more continuous and extends several kilometers northeast beyond the main channel complex (Figure 7b, Figure 9). Unfortunately, the 3D seismic data extent is limited and it is impossible to track the BSR extension further in the southeastern and northeastern directions (Figure 6). Yet, based on the existing data upstream, this area may show high gas hydrate potential.

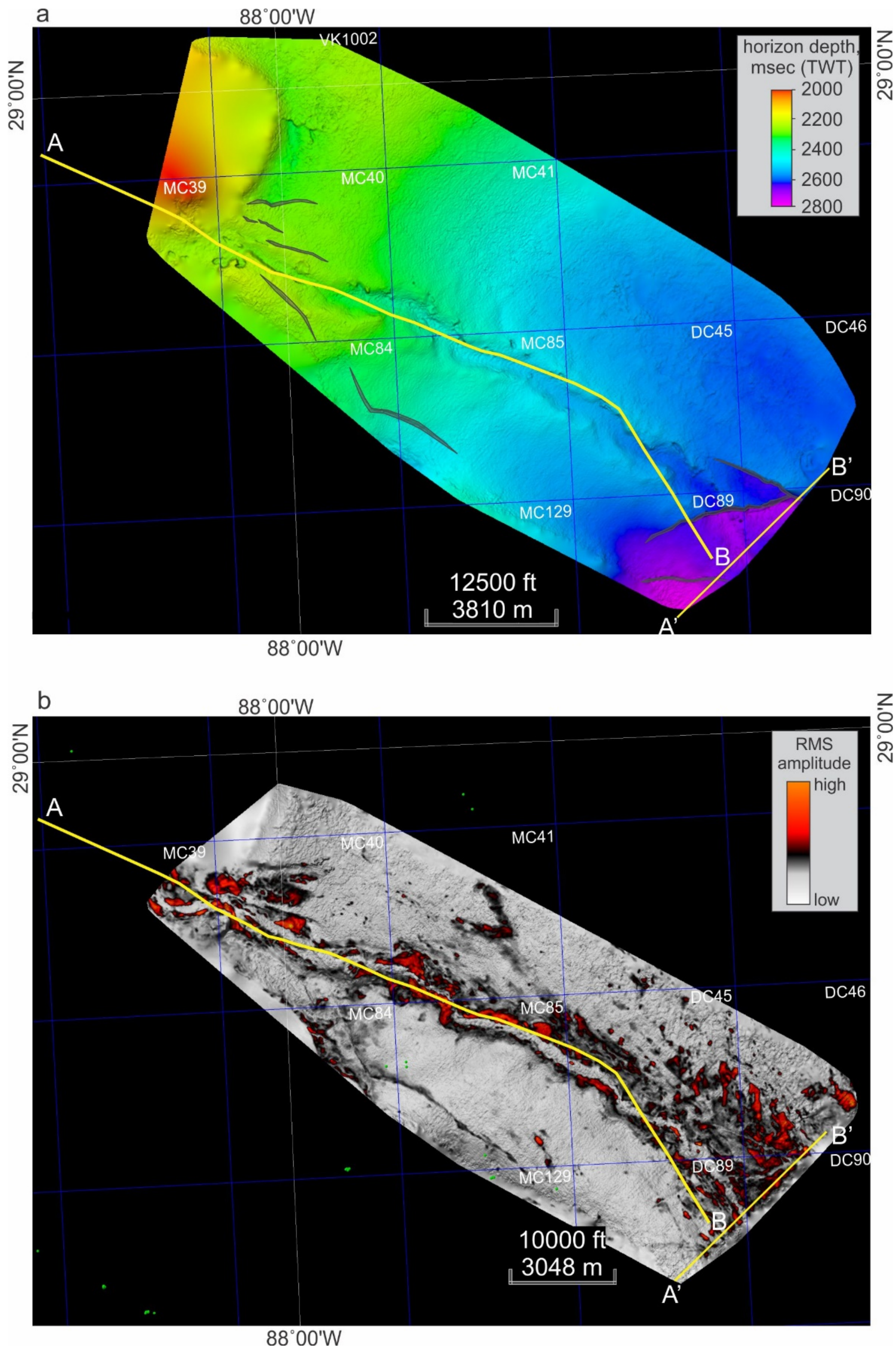

Figure 7. a) Depth structure map of Horizon 1 overlaying the unnamed buried channel system in Zone 1. b) RMS amplitude map for 150 msec interval below Horizon 1 showing geometry of the channel, bypass channel and its outer levee configuration.

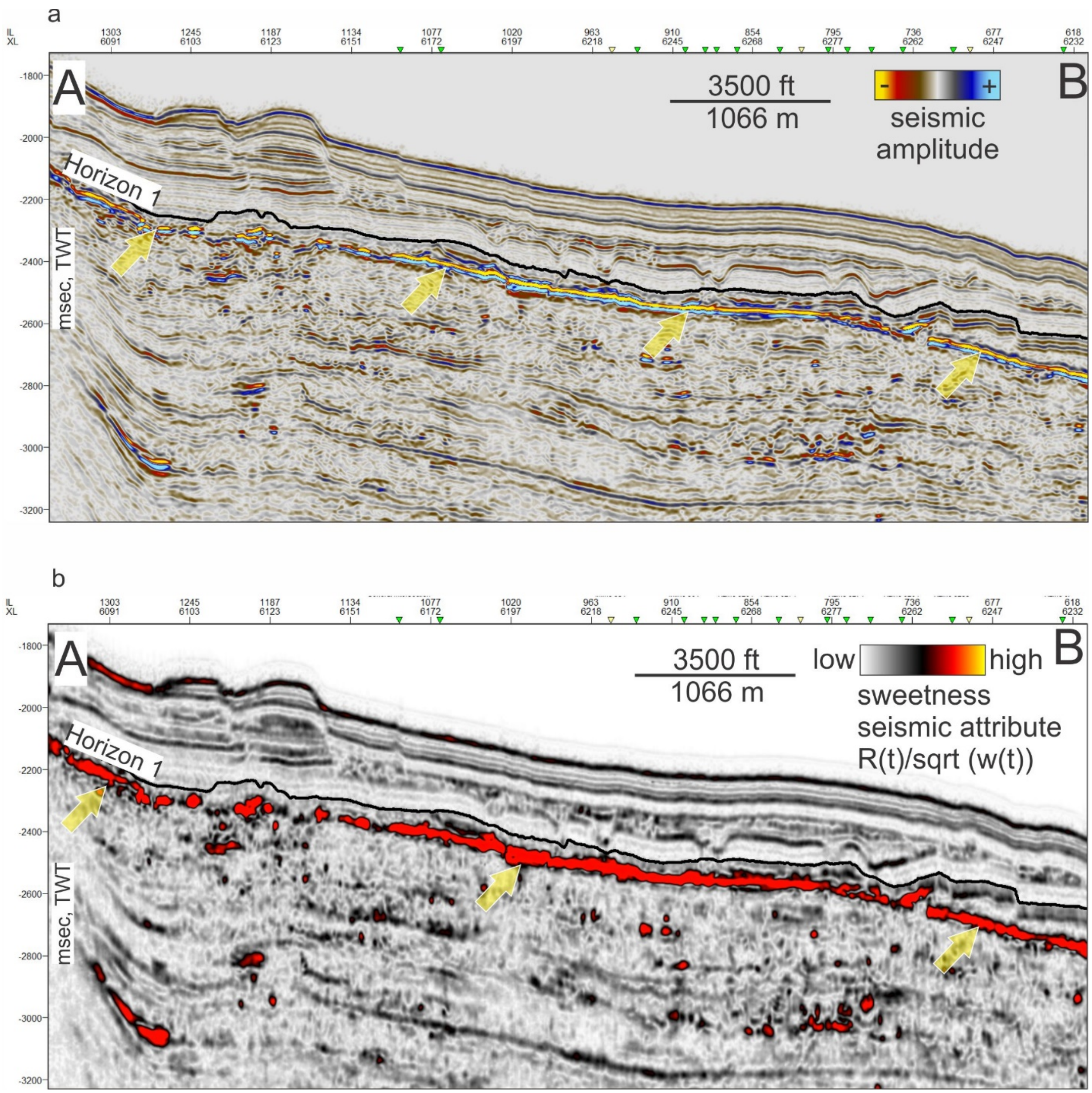

Figure 8. a) Arbitrary seismic cross-section along the channel in Zone 1 showing Horizon 1 and negative-polarity BSR cutting across the channel levee lobes. Location of the seismic line AB in shown in Figures 5, 6, 7. b) Sweetness seismic attribute along the cross-section AB showing the BSR more clearly (higher sweetness highlights the areas with higher amplitude and lower frequency, which is typical for BSRs).

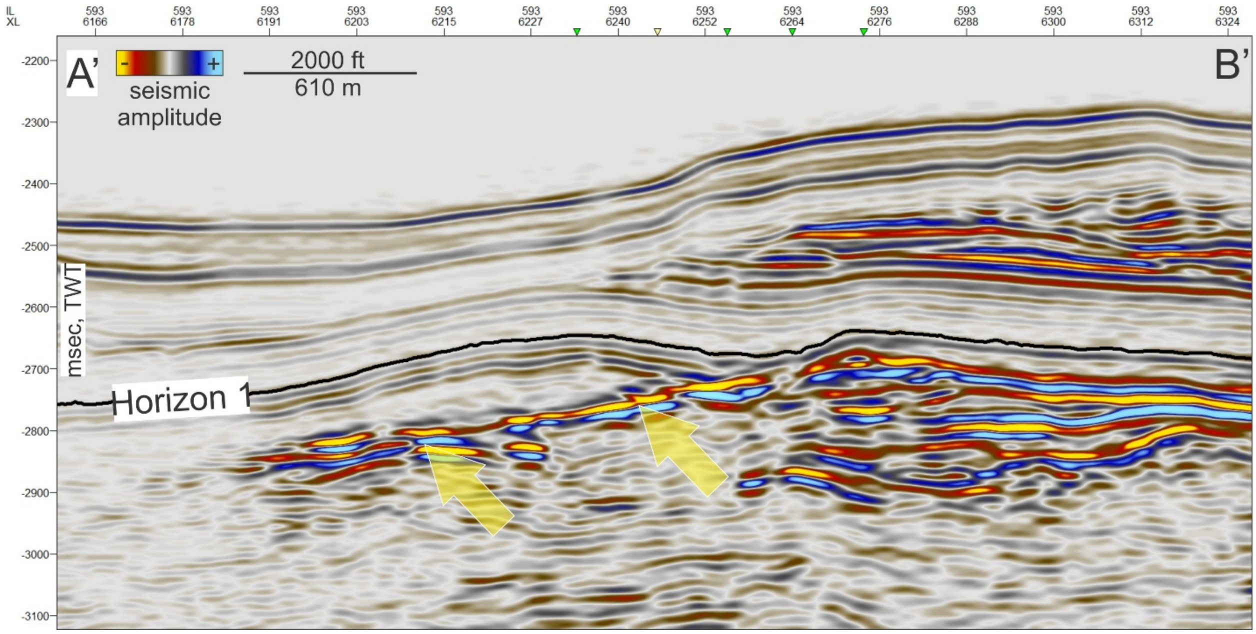

Figure 9. Example of a BSR in the eastern part of Zone 1 along the limit of 3D seismic data coverage. Location of the line is indicted in Figure 7.

4.2 BSR in Western Zone 1

A group of high-amplitude BSRs is mapped under the merged Sounder and Dorsey Canyons (Dorsey Canyon South) in the western part of Zone 1 (Figures 4, 5, 6). These BSRs served as a prospecting tool for a recently documented gas hydrate system, Jackalope that is characterized in details (Portnov et al., 2020). Here, a composite seismic section M-N crossing the Dorsey Channels South shows a prominent BSR and two major sand-prone gas hydrate reservoirs, Saint Petersburg and Columbus (Figure 15). See Portnov et al., (2020) for more details about the Jackalope gas hydrate system.

4.3 Peak-leading reflections above the BSR surface in Zone 1

Mapping peak-leading reflections above the BSR surface helped to allocate high-amplitude positive responses as well as amplitude phase reversals that may be indicative of high-concentration gas hydrate above the base of GHSZ. Figure 10 shows the distribution of average positive amplitudes within 60 msec above a manually mapped and gridded BSR surface. Related seismic cross-sections C-D, E-F, G-H, K-L and M-N (Figures 11-15) show peak-leading reflections some of which change to trough-leading below the base of GHSZ (Figures 11, 13, 15) possibly indicating a transition from gas hydrate to gas legs along dipping sand-prone layers e.g. McConnell and Zhang (2005).

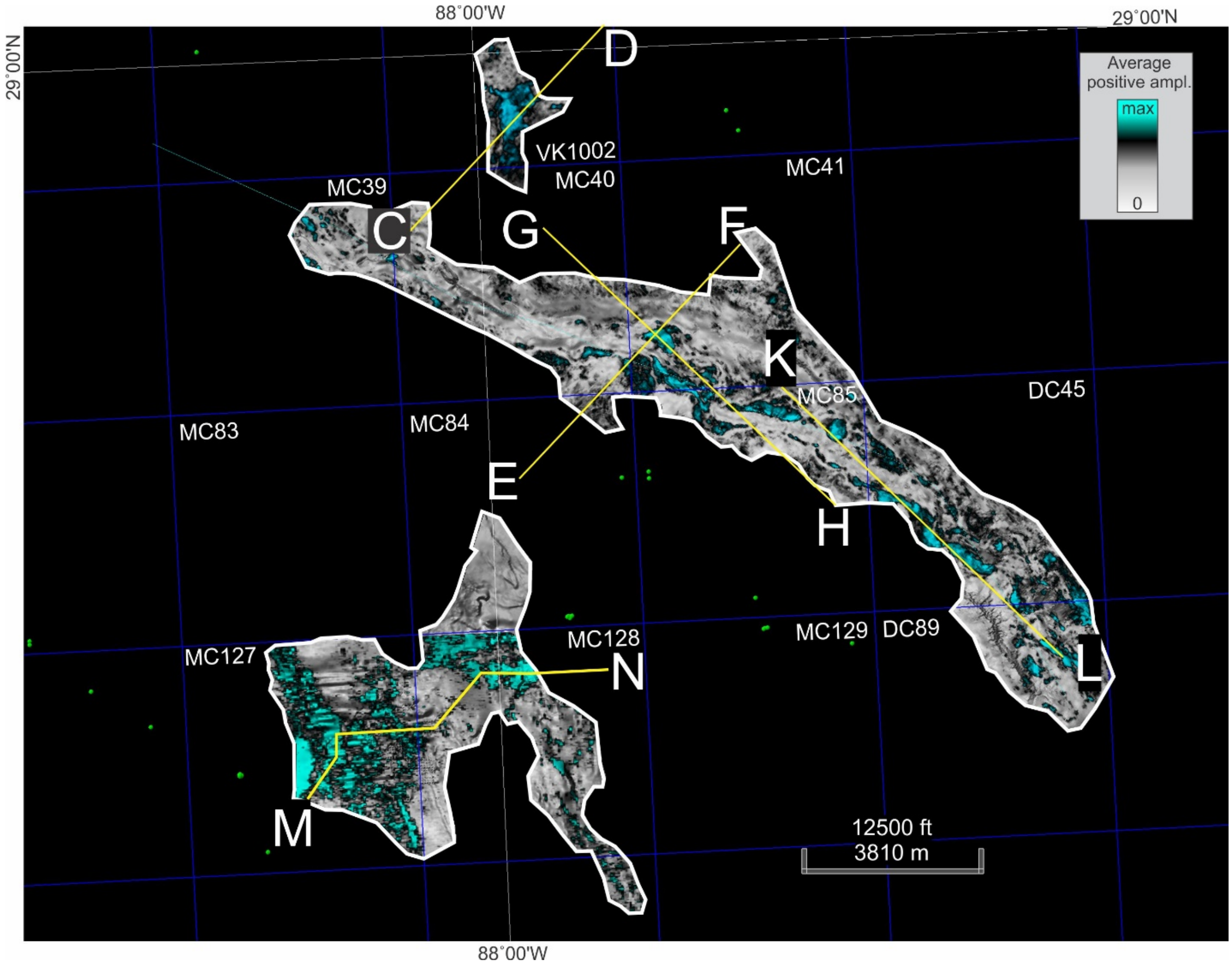

Figure 10. Map of average positive amplitudes within 60 msec above manually mapped and gridded BSR surface. Positive anomalies related to strong peak-leading reflections may indicate high acoustic impedance in gas hydrate accumulations. Most of the anomalies are likely associated with channel levee facies.

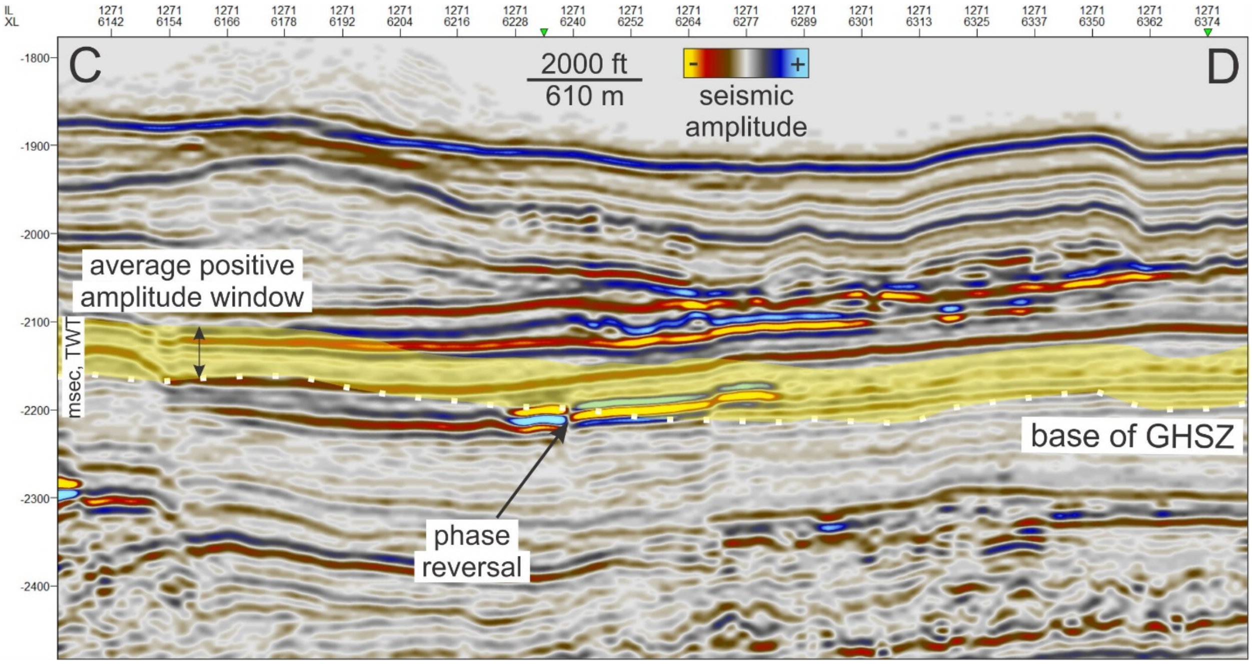

Figure 11. Seismic cross-section C-D showing a phase reversal: peak-leading reflection above the base of GHSZ changing to trough-leading reflection below. Location of the line is shown in Figure 10.

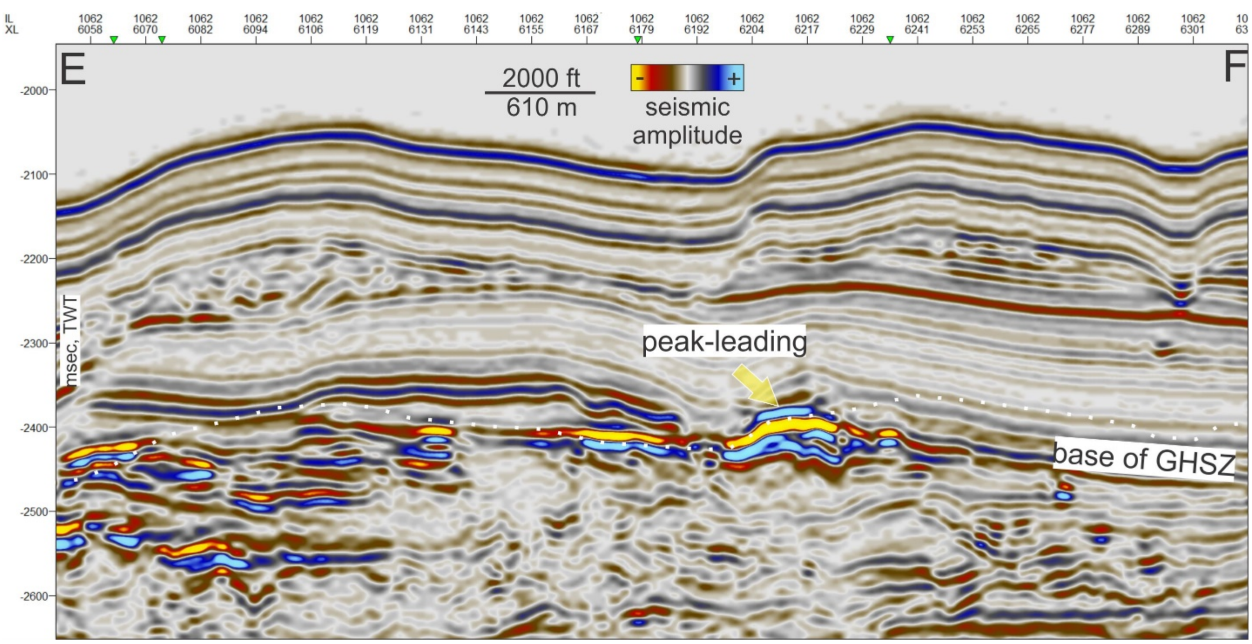

Figure 12. Seismic cross-section E-F across the buried channel showing a BSR and strong peak-leading reflection at the eastern levee of the channel. Location of the line is shown in Figure 10.

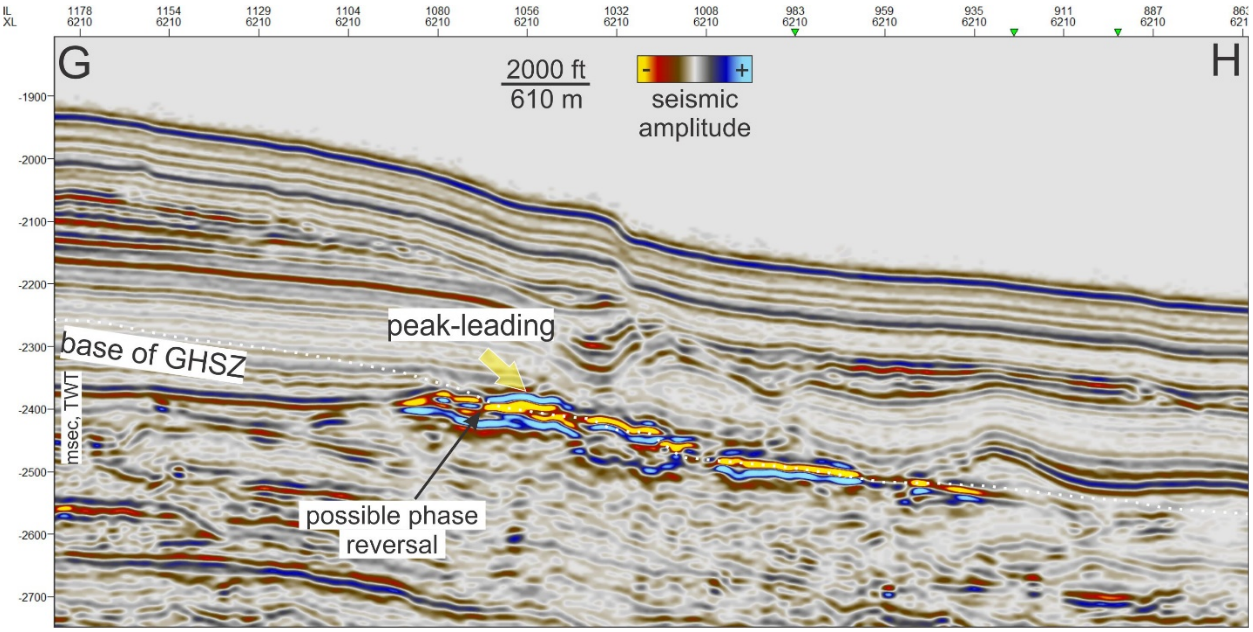

Figure 13. Seismic cross-section G-H along the buried channel showing a BSR, a strong peak-leading reflection and possible phase reversal at the base of GHSZ. Location of the line is shown in Figure 10.

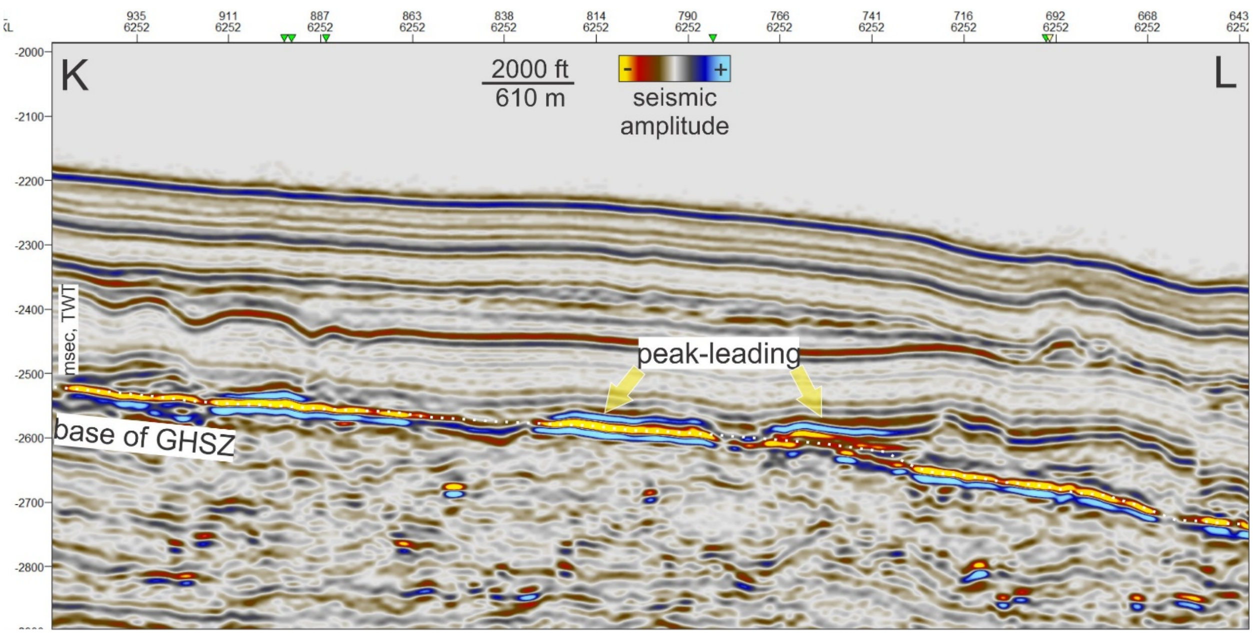

Figure 14. Seismic cross-section K-L along the buried channel showing a BSR and strong peak-leading reflections in the levees. Location of the line is shown in Figure 10.

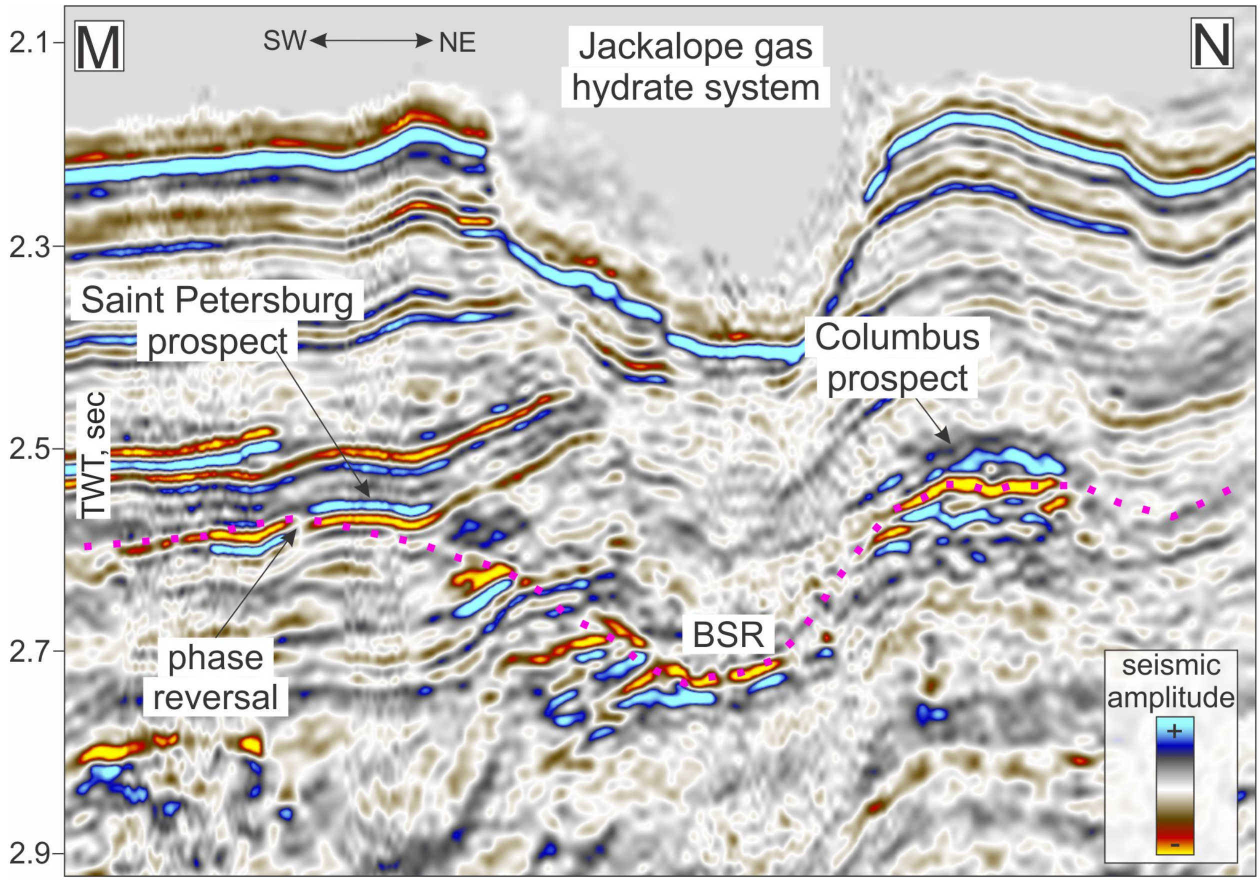

Figure 15. Seismic cross section M-N (location is shown on Figures 5, 6, 10). More details on the Jackalope gas hydrate system are presented in Portnov et al. (2020).

5. Results in Project Area 1, Zone 2

A reference Horizon 2 was mapped within Zone 2 to perform a more accurate mapping of high-amplitude reflections at an anticipated depth of GHSZ base (Figure 16, 17, 18). The RMS amplitude map shows a complex network of heterochronous channels. Manual channel mapping combined with the RMS amplitude map defined at least three major channel systems that we named Pink, Orange and Yellow (Figure 17). Orange system shows multiple merging and splitting channels, some of which likely end up as terminal lobes. Given the moderate seismic data quality, more precise channel mapping would be challenging. The Pink and Yellow systems are single channels to the east and west of the Orange system (Figure 17). The Yellow channel is the most recent and it immediately predates Horizon 2 (Figure 17b). Likely it was the most active channel, because it significantly eroded the paleo seafloor, generated an up to 200-250 msec deep channel valley (Figure 17b, 18) and massive outer levee build-ups on its margins (Figure 18).

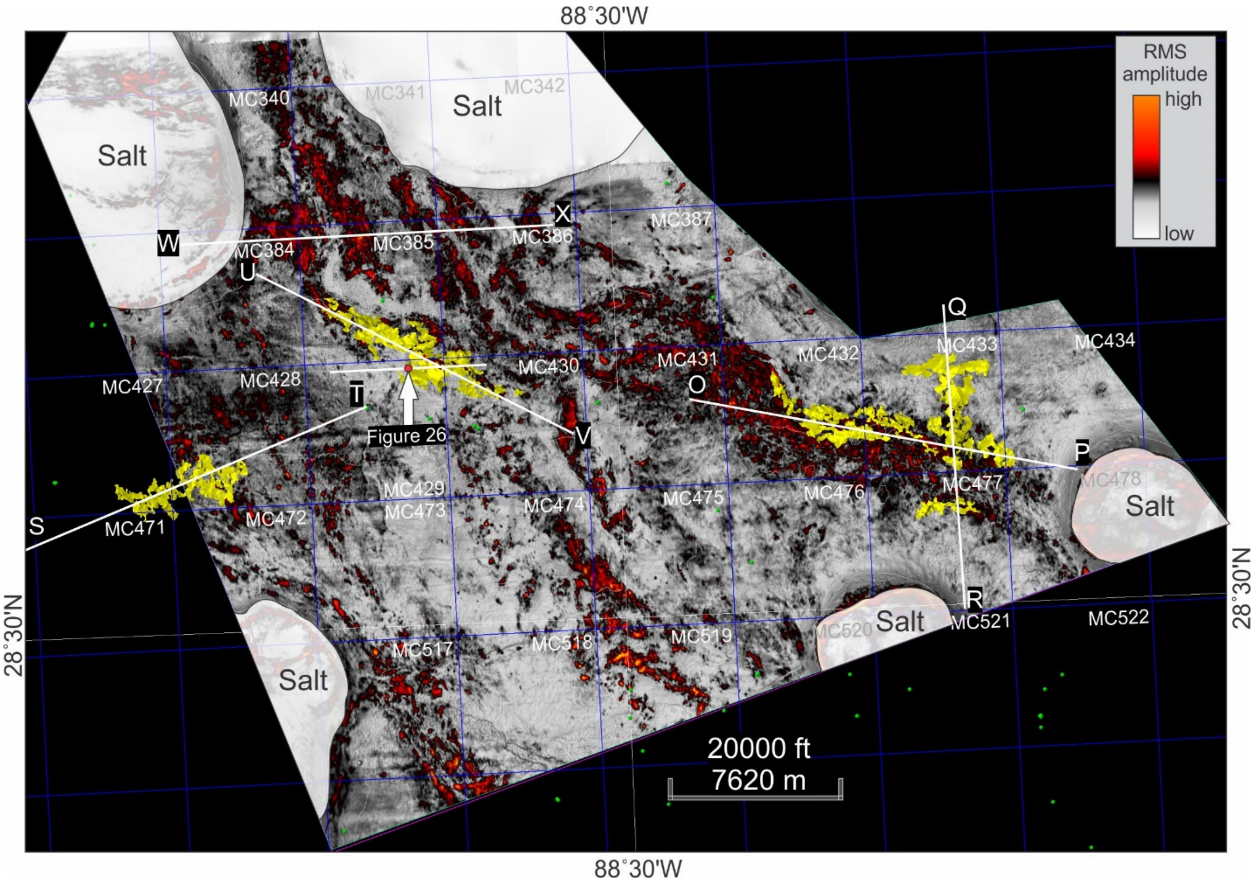

Figure 16. RMS amplitude map calculated for a 150 msec window below Horizon 2 (coeval with the most prominent yellow channel system, see Figure 17 for details). High RMS values show complex internal architecture of the channel system in Zone 2. Yellow areas indicate manually mapped BSR. White semi-transparent areas are salt diapirs. An arrow indicates the location of 5400 well (608174095400) in Figure 26.

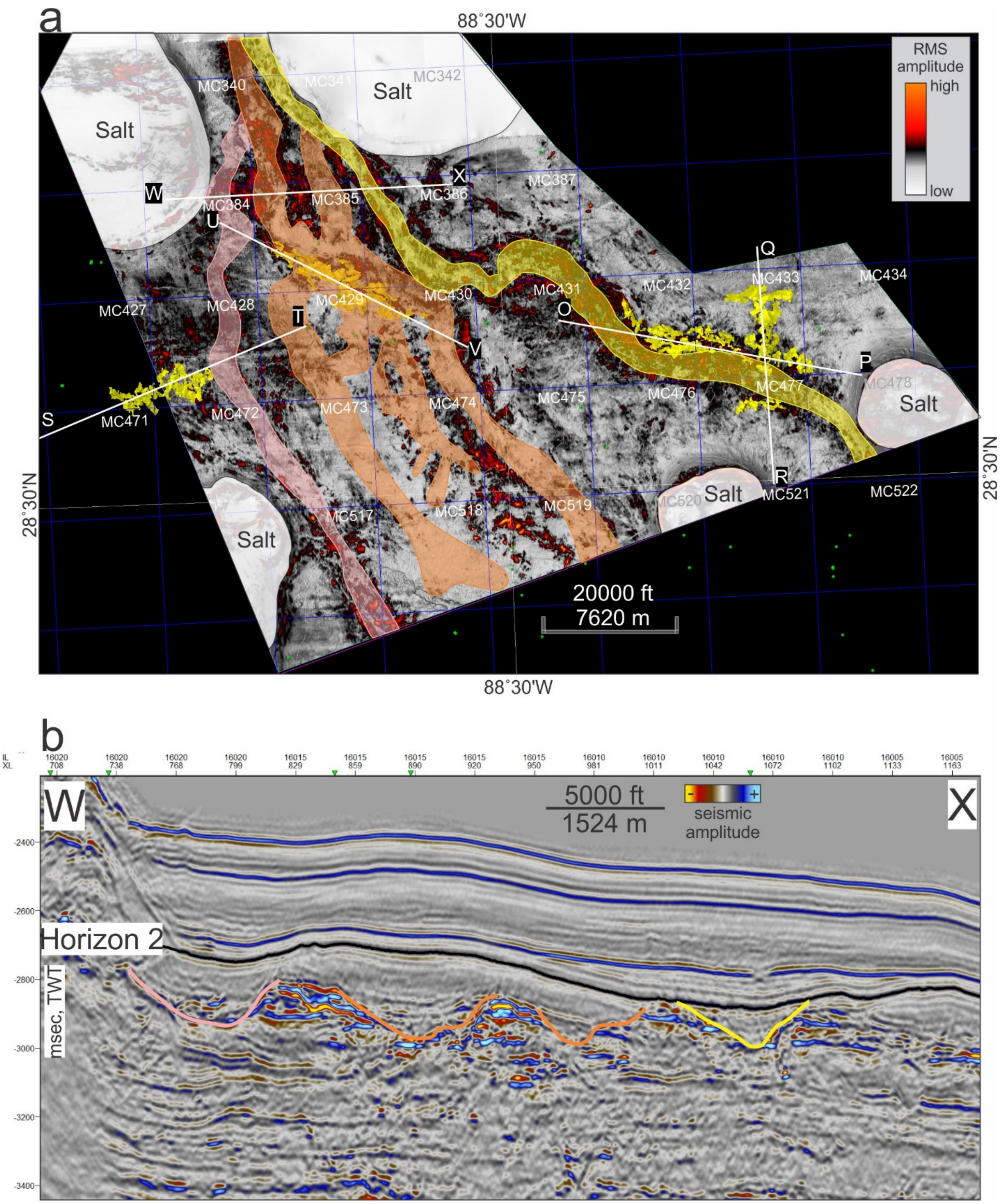

Figure 17. Channel interpretation within Zone 2 based on the RMS map (Figure 16) and manual channel mapping in the 3D seismic data (Figure 17b). Western and central channel systems (Pink and Orange) likely initiated first. The yellow channel is younger and it significantly eroded and modified the preexisting depositional system, generating massive outer levee build-ups (reaching 250-300 msec) on top of the pre-existing turbidite complexes of the orange channel system (Figure 17 ,18).

Major gas hydrate potential in Zone 2 occurs on both flanks of the Yellow channel where scattered BSRs are interpreted in the seismic data (Figure 18). Cross-sections O-P and Q-R show possible gas hydrate accumulations in the downstream part of the Yellow channel system (Figures 19, 20) mainly attributed to its northern levee build-up.

The highest confidence BSR within Zone 2 is associated with the massive levee complex at the southwestern margin of the Yellow channel (line U-V in Figure 18), where it overlaps the older depositional system of the Orange channel that could also contribute to the formation of a capacious coarse-grained methane reservoir (Figures 18, 21).

Cross-section S-T shows a possible pluming BSR in the western part of Zone 2 that extends outside of the Project Area 1 (Figures 18, 22). This possible BSR is located within a seismic unit with chaotic reflections potentially indicating sand-rich layer or mass transport complex.

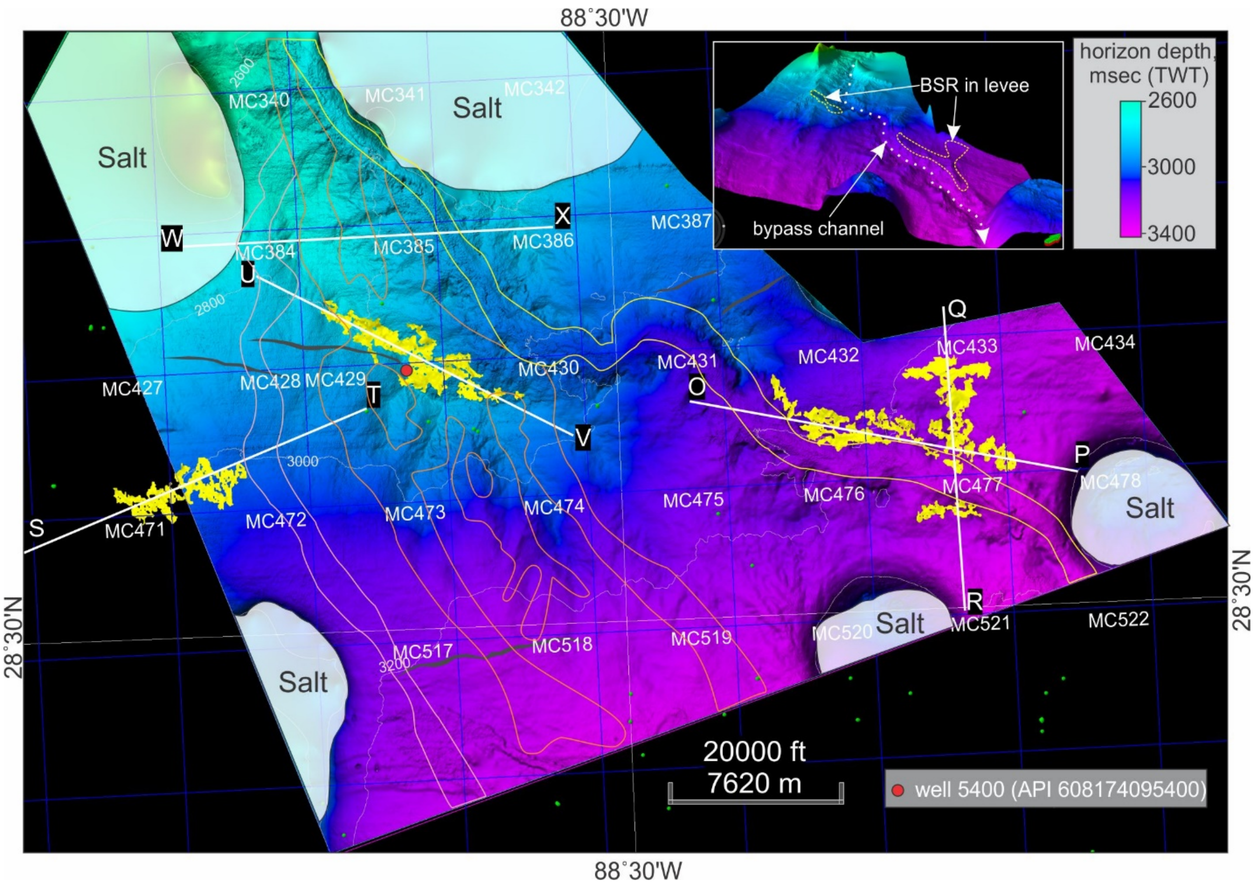

Figure 18. Horizon 2 structure map. Colored areas show channel systems in Zone 2: Yellow, Orange and Pink. The yellow color shows BSR distribution based on semi-automated BSR mapping. Note that the eastern and central BSR clusters belong to the levee complexes of the Yellow channel (inset map Figure 17). The central BSR appears within a very complex depositional system likely comprising several generations of levee build-ups.

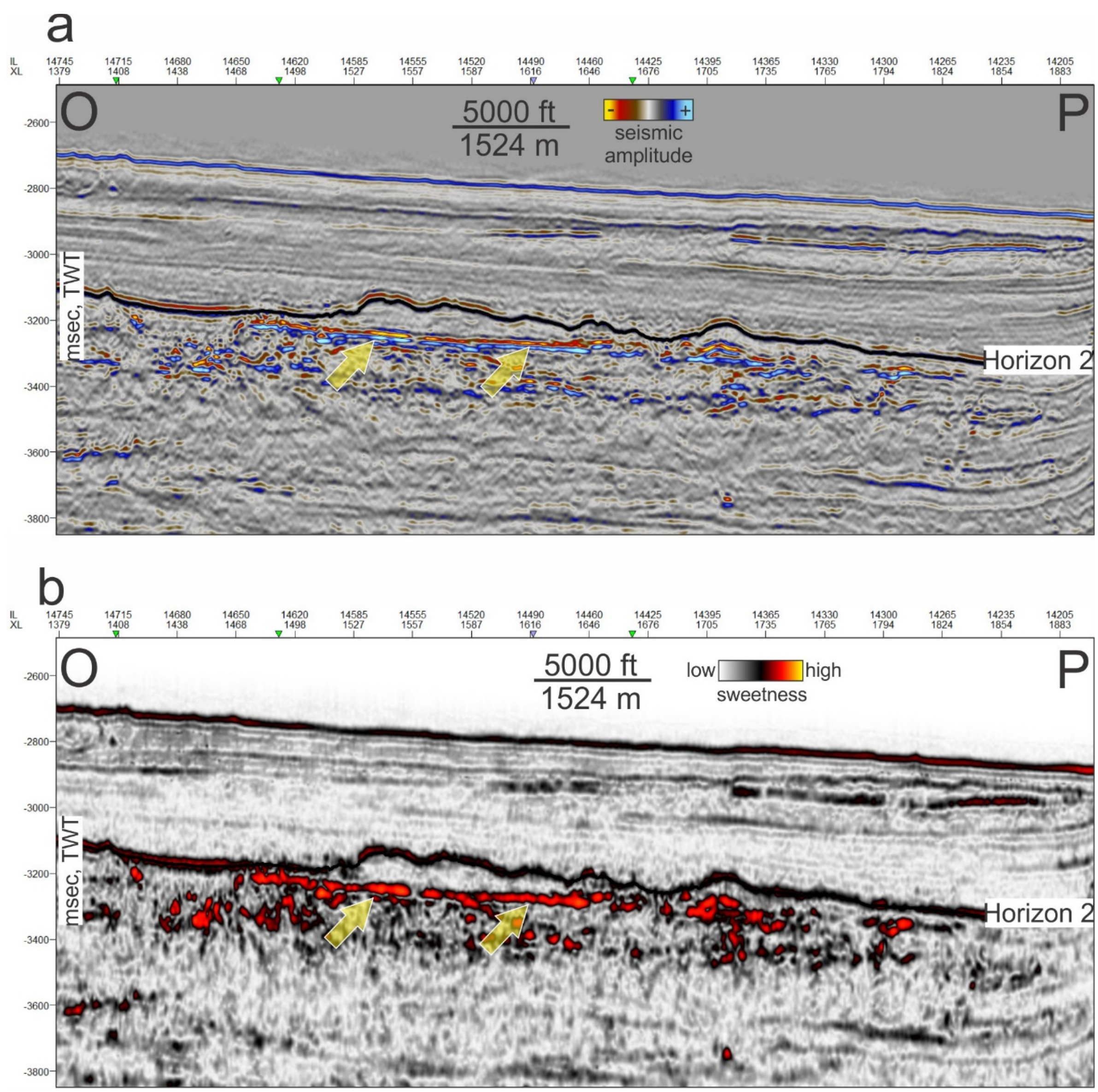

Figure 19 a) Seismic amplitude cross-section O-P along the eastern flank of the Yellow channel system showing a continuous BSR and reference Horizon 2 b) Sweetness attribute cross section O-P along the eastern flank of the Yellow channel system showing a continuous BSR.

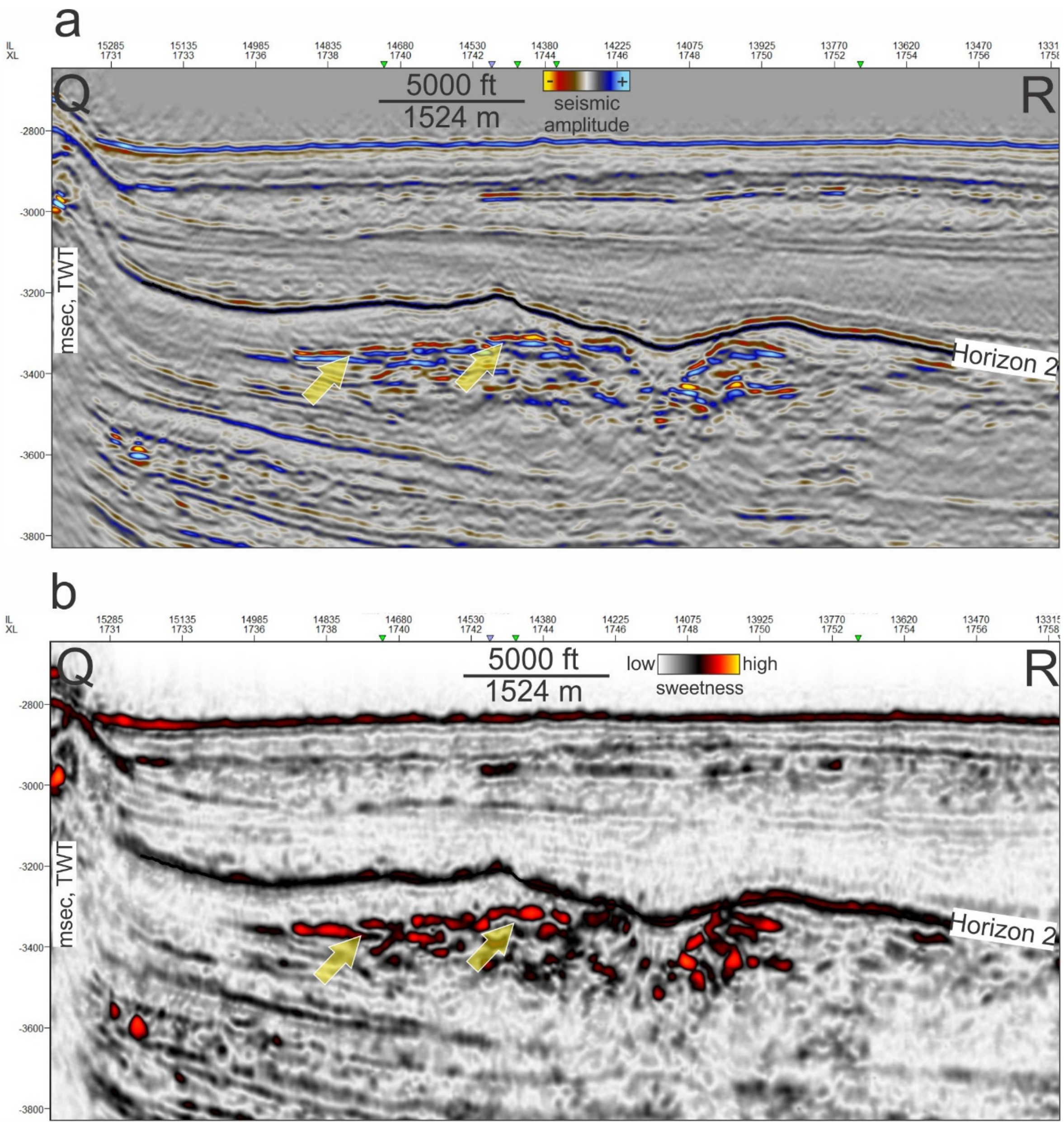

Figure 20 a) Seismic amplitude cross-section Q-R across the Yellow channel system showing a likely BSR in the outer channel levee and reference Horizon 2 b) Sweetness attribute cross section Q-R across the Yellow channel system showing a likely BSR.

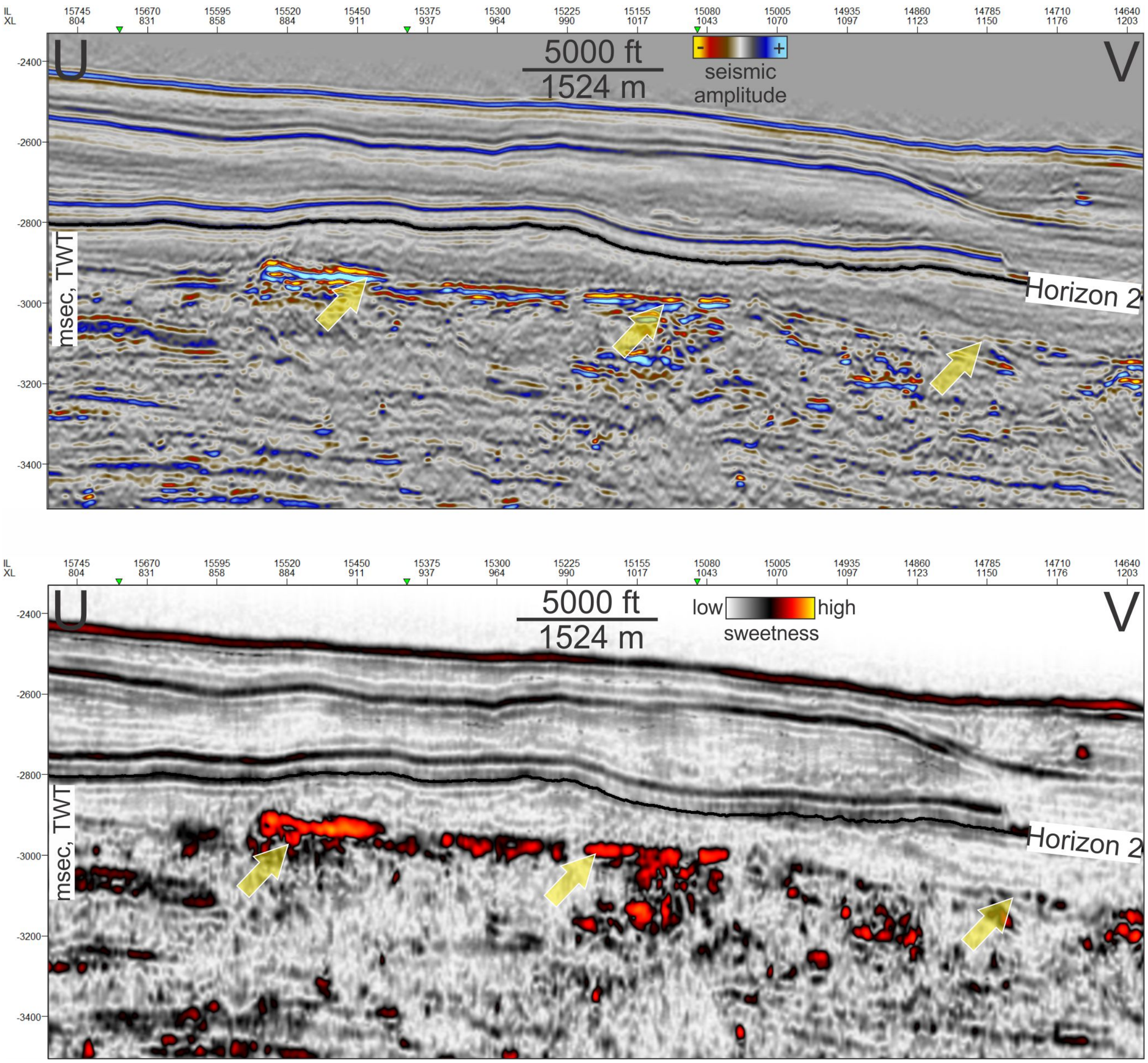

Figure 21 a) Seismic amplitude cross-section U-V along the western levee build-up of the Yellow channel showing the BSR and reference Horizon 2 b) Sweetness attribute cross section U-V along the western levee build-up of the Yellow channel showing the BSR and reference Horizon 2.

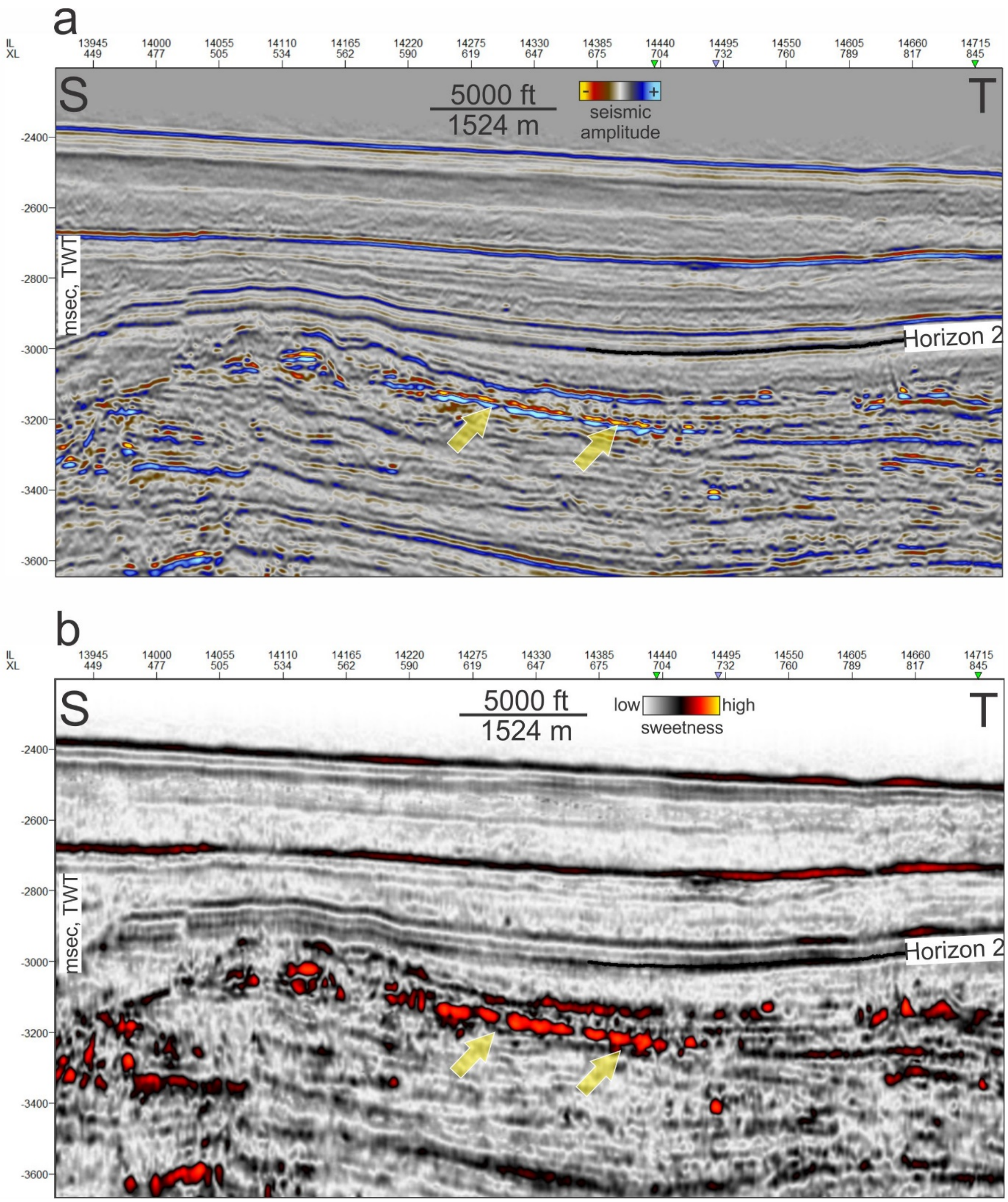

Figure 22 a) Seismic amplitude cross-section S-T along the westernmost BSR cluster in Zone 2 showing a likely pluming BSR and reference Horizon 2 b) Sweetness attribute cross section S-T along the westernmost BSR cluster in Zone 2 showing a likely pluming BSR.

6. Results in Project Area 1, Zone 3

Poor data quality in the southern part of B-67a-91-LA seismic survey does not allow us to track paleo channels south of Jackalope with high confidence (Figure 4). However, it is likely that several of them extend further downslope towards Zone 3, where we observe high-amplitude trough-leading reflections roughly parallel to the seafloor and slightly shallowing close to the salt dome. Additional data is needed to better map this area and assess gas hydrate from peak-leading seismic responses.

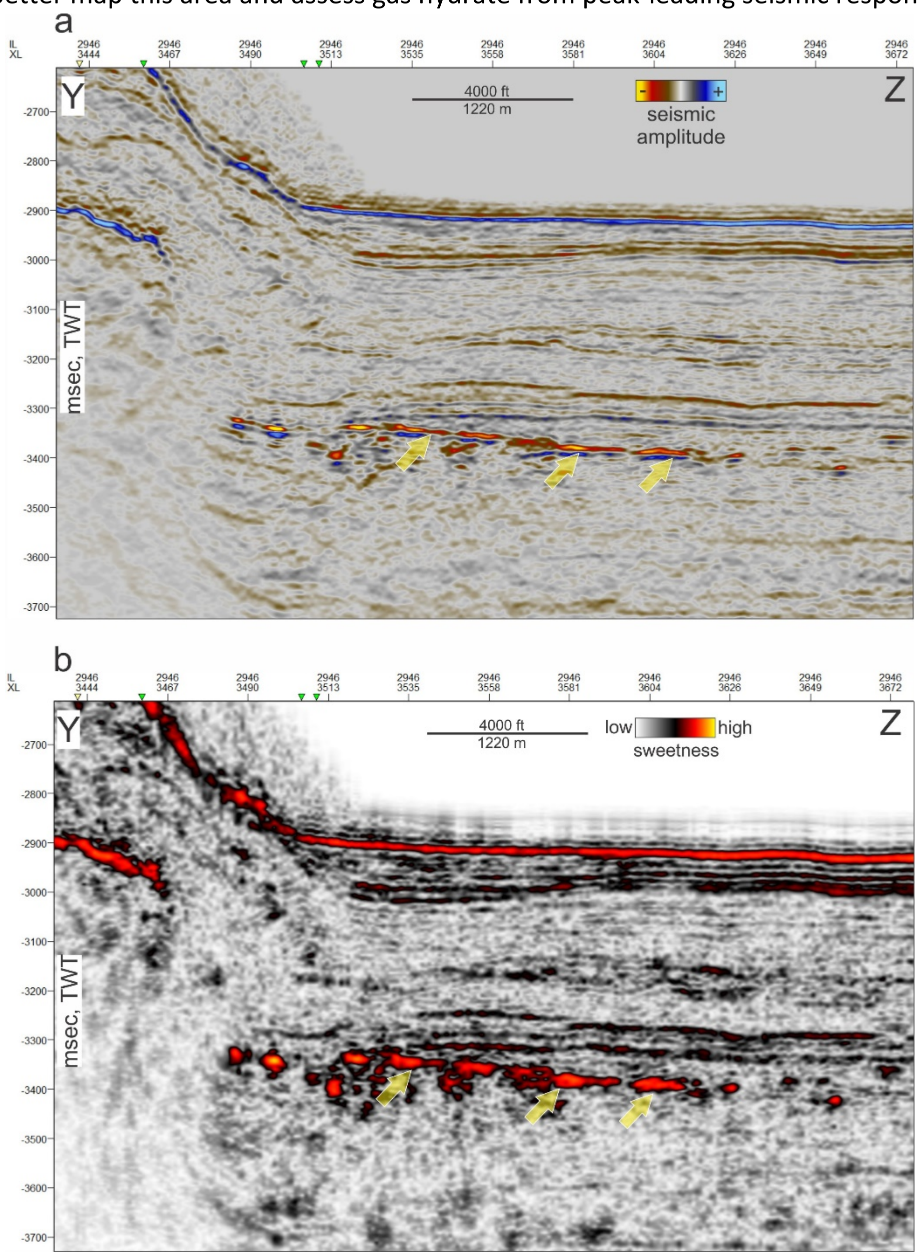

Figure 23 a) A possible BSR along the seismic amplitude cross-section Y-Z in Zone 3. Location of the line is shown in Figures 5, 6 b) Possible BSR along the sweetness attribute cross-section Y-Z in Zone 3.

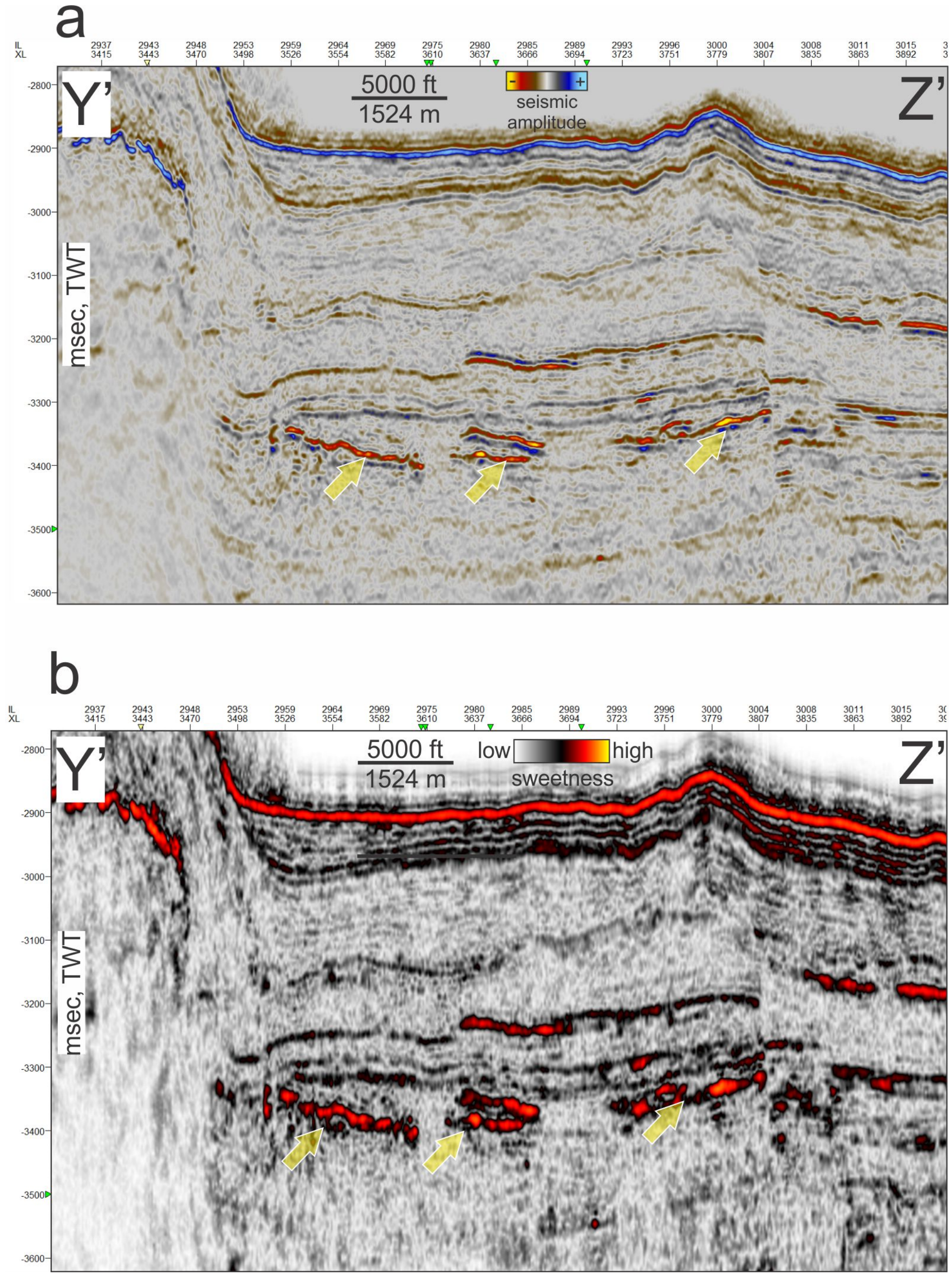

Figure 24 a) A possible BSR along the seismic amplitude cross-section Y'-Z' in Zone 3. Location of the line is shown in Figures 5, 6 b) A possible BSR along the sweetness attribute cross-section Y'-Z' in Zone 3.

7. Examples of well logs in Project Area 1

Out of 462 wells drilled within Project Area 1 (Figure 3, 5), none directly penetrated seismic BSRs or peak-leading reflections identified herein. We selected four wells to analyze electric resistivity and gamma ray logs in areas most proximal to the zones of high-amplitude seismic reflections and mapped BSRs (Figure 3, Figure 5). Moreover, three out of four wells were classified as 'B' category wells gas hydrate wells by Majumdar et al., (2017), which means these wells likely contain gas hydrate. Due to the absence of sonic logs in the wells in the upper sediment section, logs were approximately tied to seismic using an estimated P-wave velocity derived from Cook and Sawyer (2015) that provides a reasonable velocity model for the upper 1000 meters of sediment cover in normally compacted marine sediments.

Well 5500 (API 608174085500) was drilled at the southern edge of Jackalope gas hydrate system, where a resistivity spike of 8 Ωm is observed above the approximate level of GHSZ providing additional evidence for hydrate accumulation in Saint Petersburg reservoir (Figure 25; see Portnov et al. (2020) for more details). This well is marked as category B in Majumdar et al. (2017).

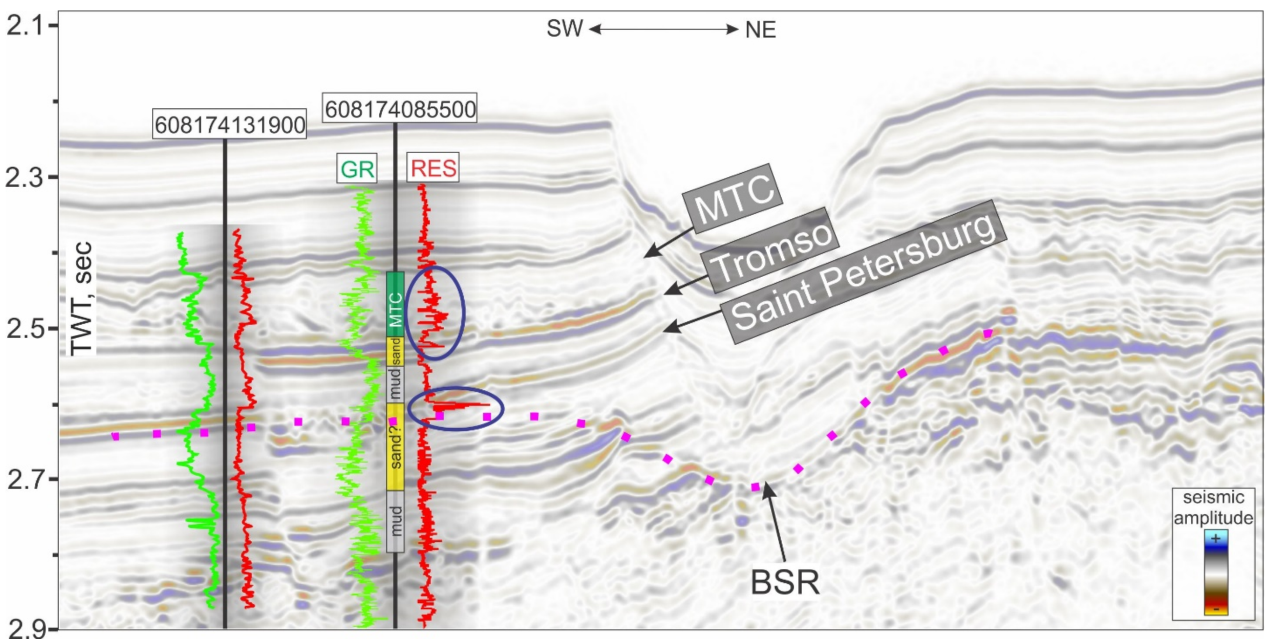

Figure 25. Seismic cross section across the Dorsey Canyon South showing well 5500 (API 608174085500) located at the southern edge of Jackalope gas hydrate system. Location of the seismic line is indicated in Figure 3.

Well 5400 (API 608174095400) is proximal to a BSR cluster in a channel levee complex in Zone 2 (Figure 3, Figure 5, Figure 18, Figure 26). This well is marked as category B in (Majumdar et al., 2017) due to a resistivity increase to 16 Ωm (deep phase 42 in) at ~3.2 sec TWT (8070-8116 ft MD). Yet, this resistivity increase is observed ~0.1 sec below the approximate BSR-derived depth of GHSZ (Figure 26). This suggests that the accumulation identified in Majumdar (2017) is either 1) not hydrate or 2) is hydrate but incudes higher-order hydrocarbon gasses, similar to accumulations documented by Paganoni et al. (2016). Offshore Borneo.

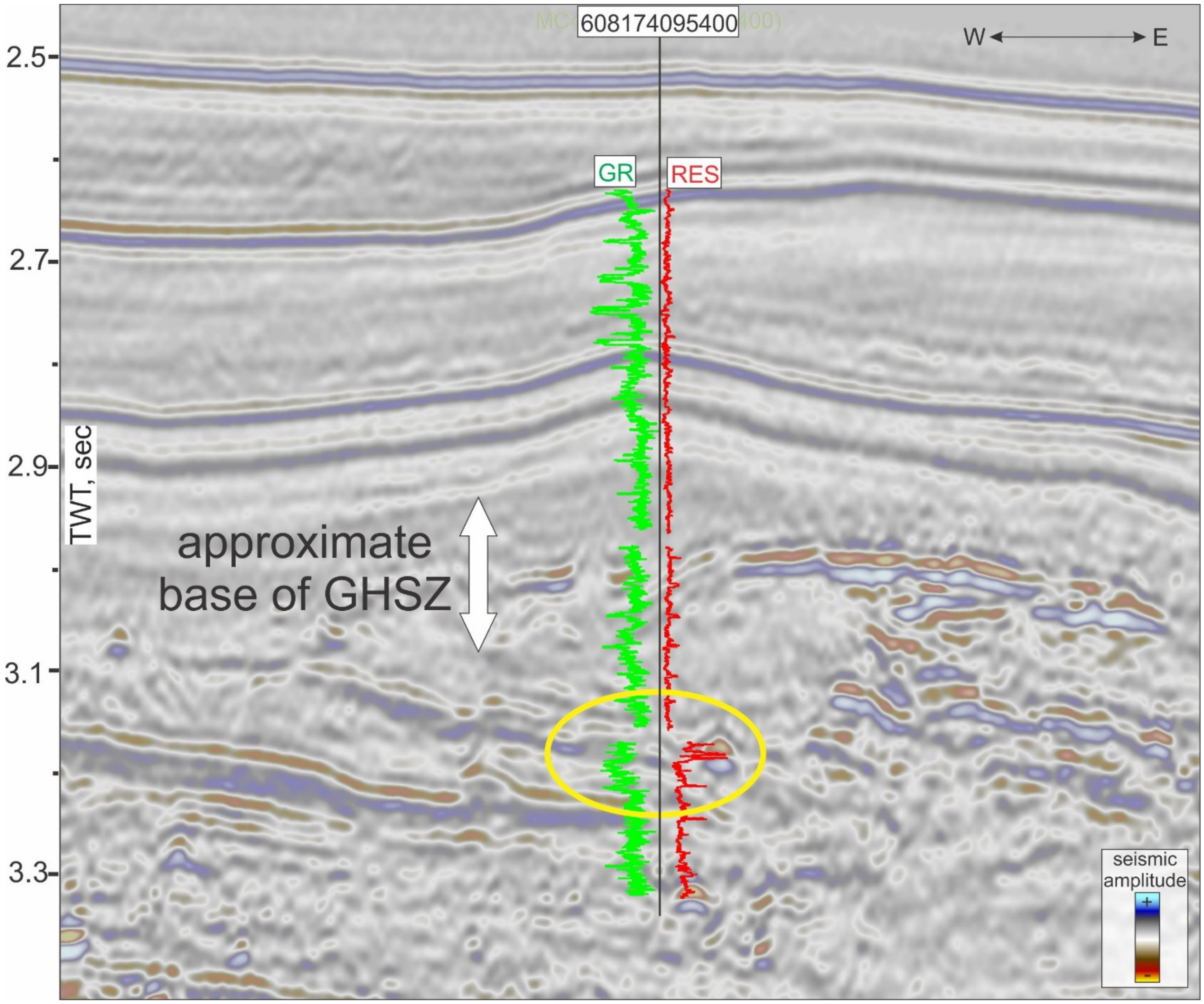

Figure 26. Seismic cross section across well 5400 (API 608174095400) proximal to a BSR cluster in a channel levee complex in Zone 2. Yellow oval shows interval with increased resistivity below the GHSZ. Locations of the seismic line and well are indicated in Figure 3 and Figure 18.

Well 6500 (API 608174096500) was drilled in Zone 1 ~1500 m east from the high RMS amplitudes and clustered BSR related to Columbus prospect of Jackalope gas hydrate system (Figure 3, Figure 5, Figure 27). There is an observed increase in resistivity from 1 to 2.5 Ωm above the approximate base of GHSZ, that could be related to minor concentration of gas hydrate or may be related to the mass transport complex at this depth (MTC). Similarly, however, resistivity increases associated with MTCs were observed in the Terrebonne Basin, and were found to be associated with gas hydrate accumulations in near-vertical fractures in marine muds (Hillman et al., 2017).

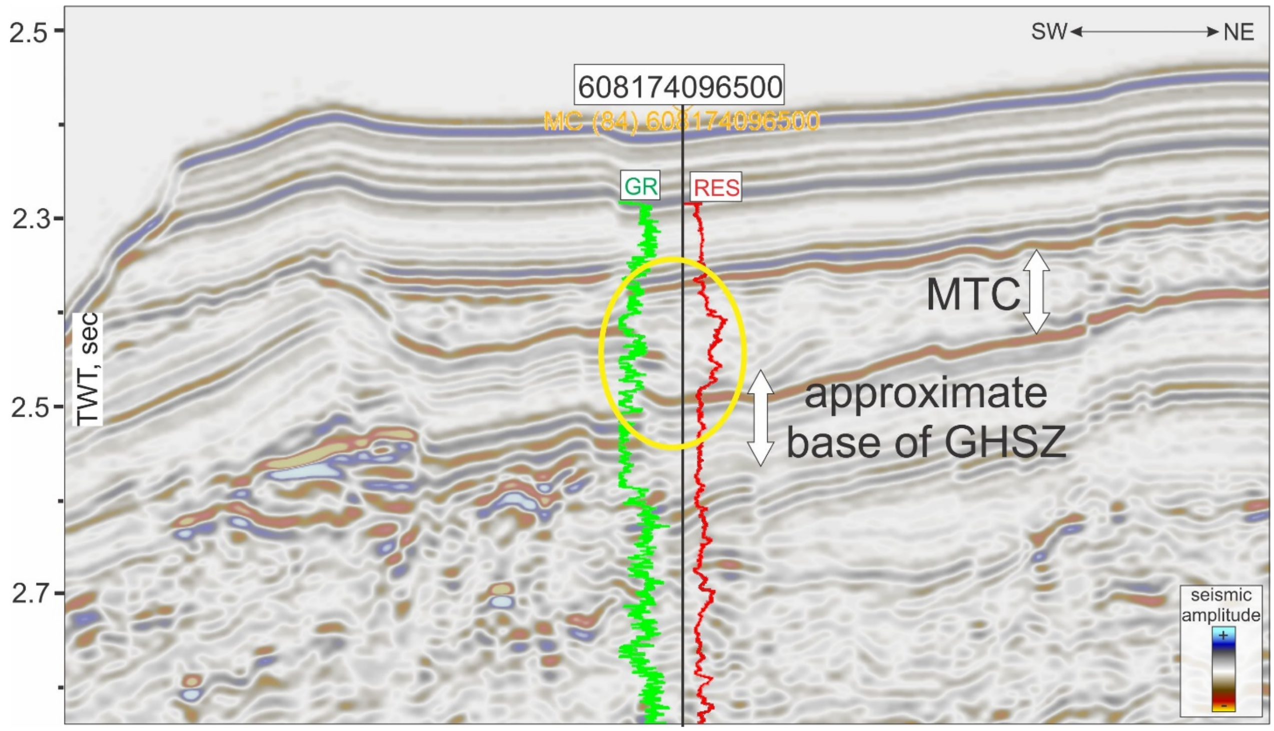

Figure 27. Seismic cross section across well 6500 (API 608174096500) in Zone 1. Yellow oval shows interval with increased resistivity within the GHSZ. Locations of the seismic line and well are indicated in Figure 3 and Figure 5.

Well 8201 (API 608174098201) was drilled in Zone 3 where it penetrates the distal part of buried channel observed close to the base of GHSZ (Figure 3, Figure 5, Figure 28), but far outside of a mapped BSR. This well is a category B well in Majumdar et al. (2017), however the observed resistivity increase (from 1 to 12 Ωm in 40 in deep phase measurement) occurs significantly below the base of GHSZ derived from the BSR depth in Zone 3 (Figure 6, Figure 28). Two zones showing slightly increased resistivity (from 1 to 2.5 Ωm) are also observed within the GHSZ and could indicate low-saturation accumulations of gas hydrate.

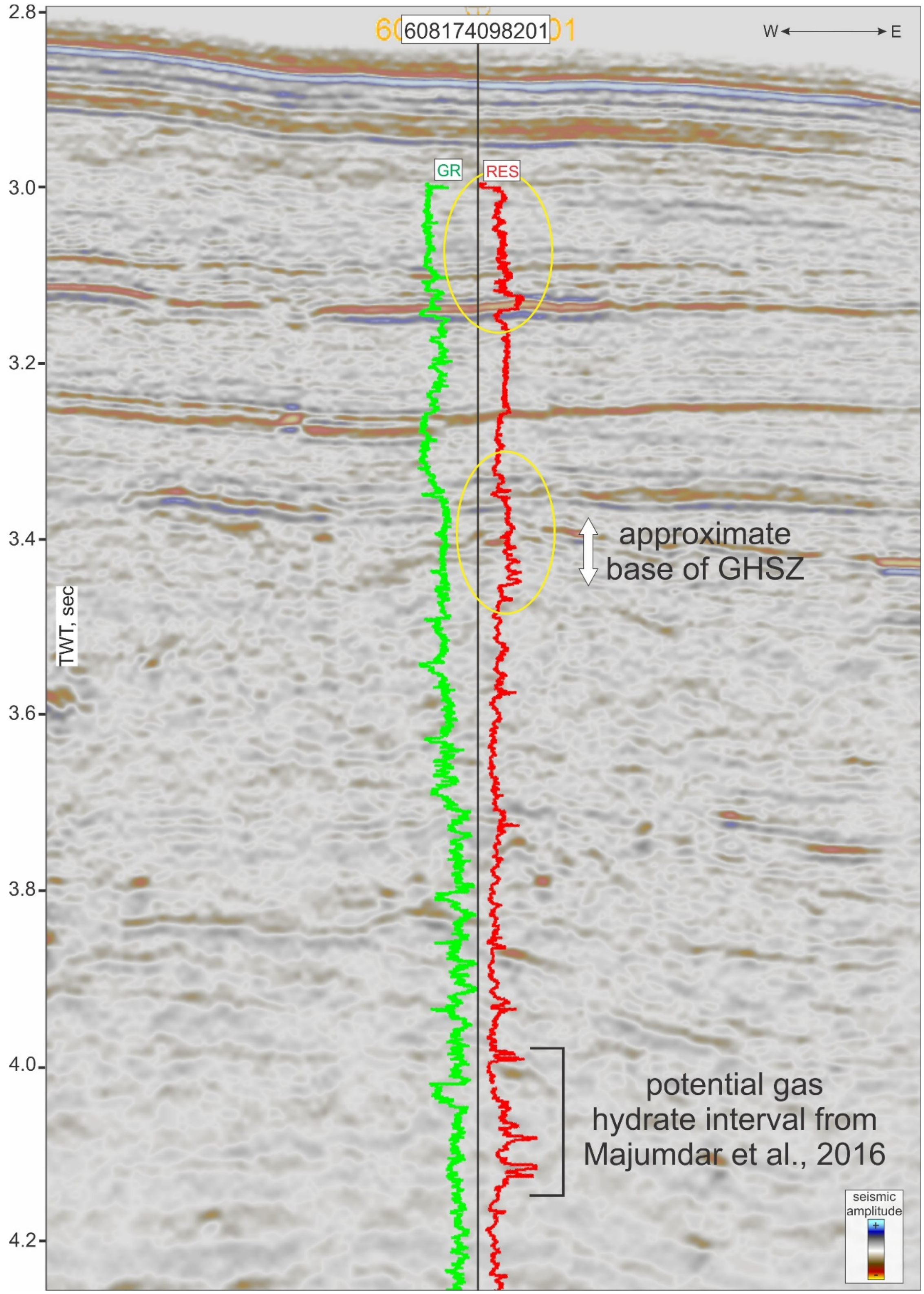

Figure 28. Seismic cross section across well 8201 (API 608174098201) in Zone 3. Yellow ovals show intervals with increased resistivity within the GHSZ. Locations of the seismic line and well are indicated in Figure 3 and Figure 5.

8. Natural gas resource estimates

Zone 1

We calculate high and low estimates for the high-confidence gas hydrate accumulations within Zone 1 based on the total area of peak-leading reflections above the BSR (Figure 10). The low estimate is based on a 10 m-thick sand layer, 30% porosity, and 50% gas hydrate saturation. The high estimate assumes 30 m-thick sand layer, 40% porosity and 90% gas hydrate saturation. Therefore, the area of strong peak-leading reflections for new prospects identified in Zone 1 occupies ~3.748 km^2 resulting in minimum and maximum gas resource estimates of 0.92 and 6.64 BCM respectively at STP (standard temperature and pressure) conditions (which uses a gas hydrate to gas conversion factor = 164).

In addition, gas in place resources for the Jackalope gas hydrate system (Figure 6) were assessed earlier and range between 1.47 and 10.62 BCM (Portnov et al., 2020). In summary, our total gas in place resource estimates for Zone 1 at STP conditions range between 2.39 and 17.26 BCM.

Zone 2 & 3

Similar resource estimates for Zone 2 and 3 were not conducted because the seismic data quality does not allow for precise mapping of peak-leading reflections above the BSR. Attempts to produce such maps resulted in chaotic distribution of peak-leading reflections that could not be attributed to sedimentary facies observed in the seismic data (e.g. channels levees, lobes).

9. Conclusions

Potential gas hydrate occurrences in Project Area 1 are associated with several modern and buried channel systems and widespread salt tectonics (Figure 4). Multiple BSRs marking the base of GHSZ are observed at various depths (Figure 6). Importantly, average subseafloor BSR depths were significantly shallower compared to those predicted by the GHSZ modeling likely indicating elevated regional geothermal gradient (up to 45-50 °C/km) in this part of the Gulf of Mexico.

Zone 1 features highest gas hydrate potential associated with the Jackalope gas hydrate system previously characterized in Portnov et al., (2020) and several newly discovered scattered accumulations in the outer levees of a paleochannel (Figure 10). High seismic data quality allowed for detailed mapping of peak-leading reflections, phase reversals and gas–water contacts at the base of GHSZ that are good prospecting criteria for gas hydrate. If additional 3D seismic data exist in the SE corner of Project Area 1, we recommend analysis of the seaward extension of the buried channel system showing an apparent BSR at the very limit of public 3D seismic data coverage that likely extends further in SE direction (Figure 7, Figure 9).

Zone 2 features a complex paleo channel 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 a reservoir level, yet this area definitely warrants additional attention when new seismic and borehole datasets may become available.

Zone 3 does feature a discontinuous BSR likely associated with paleo channel facies, and slight resistivity increase in a well outside of a mapped BSR (Figure 4, Figure 5), yet poor seismic data quality precludes a more accurate interpretation in this region.

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