Imaging Conductor Pipes in the Gulf of Mexico Using 3-D High-Resolution Seismic Data: Containing one of the Largest Oil Spills in US History

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***Abstract*—Mississippi Canyon Block 20 (MC-20) was Taylor Energy's oil platform in the Gulf of Mexico, located approximately 19 km (12 mi) from the mouth of the Mississippi River. In 2004, Hurricane Ivan generated an underwater mudslide that overturned the production platform and displaced it approximately 152m (500ft) downslope, leading to a significant oil spill. During the mudslide, the conductor pipes were disturbed and buried in sediment up to 57m (187ft) over the top of the wellhead. Since then, this oil spill has reportedly become the longest running in the history of the United States and one of the largest to date. To assist with remediation efforts, precise detection and visualization of the buried conductor pipes was required. In May 2022, Kraken Robotic Systems (formerly PanGeo Subsea, a subsidiary of Kraken Robotic Systems) was contracted by Couvillion Group to conduct a sub-bottom/below mudline (BML) survey of the MC-20 site using their specialized, high-resolution Acoustic Corer™ (AC) technology. The AC comprises collocated transmitters, low and high-frequency chirps, and a parametric source that covers a frequency range of 1.5kHz to 12.5kHz using a fixed landed survey platform. The acoustics are designed to penetrate the sub-seabed to obtain a 14m (46ft) diameter volumetric "acoustic core" down to 60m (197ft) below the seafloor. To image and interpret the conductor pipes within the MC-20 site, 63 AC surveys were acquired throughout the 205m (673ft) x 60m (197ft) survey area. The AC data processing followed standard seismic procedures using ZoomSpace™ in-house software. Rather than mosaicking the individual acoustic cores, the pre-processed data sets were merged and migrated into a single unified volume which was statically corrected to the same processing datum. This resulted in enhanced resolution and coherency for accurately identifying and representing the conductor pipes. After processing and interpreting the acquired data, the full extent of the conductor pipes was identified, and the locations of all structural and geological features were digitized within the sub-seabed. The upper sub-seabed was dominated by unconsolidated sediments intermixed with blocky clay and the conductor pipes were observed to be reposing onto a highly consolidated basement layer. Specifically, 18 smooth and continuous linear conductor pipes were identified, presenting as a collective bundle, constricting at its center and splaying outward as they continue from the collection dome towards the well bay. A region of acoustic blanking was observed within the survey area northwest of Row 11, near the well bay. The combined application of merging high-resolution seismic data into a unified volumetric data set, as applied in this study, enabled a detailed representation and characterization of the conductor pipes for the first time.**

Keywords—seismic processing, high resolution, SAS, imaging, oil spill, remediation

I. Introduction

Built in 1984 and operated by Taylor Energy since 1995, the Mississippi Canyon Block 20 (MC-20) oil production platform was a fixed, eight-pile structure located 19km off the Louisiana coast (Fig. 1). Situated in 150m (490ft) of water, it contained 28 wells (i.e., conductor pipes) with reservoirs up to 3.35km (2.08 mi) deep. In 2004, an underwater mudslide from Hurricane Ivan toppled the oil platform and shifted it more than 152m (500ft) to the SE of its original location, where it became buried within 46m (150ft) of mud and sediment. This resulted in the abrupt leakage of over 600, 42-gallon barrels of crude oil into the Gulf of Mexico. Since then, oil has been continuing to spill near the MC-20 site making it the longest-running and second largest oil spill in US history, with conservative estimates indicating that millions of gallons of oil were released. In 2019, the Couvillion Group were employed to contain the spill using their in-house designed containment system. While their system was successful at collecting and bringing the oil onshore, the locations of the buried well conductors remained unknown. Thus, to assist with their containment efforts, Couvillion contracted Kraken Robotics to

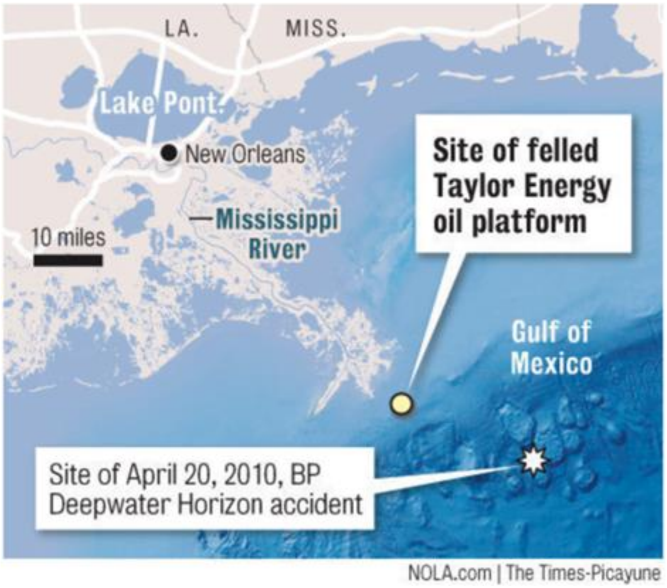

Fig. 1. Geographical location of the MC-20 site

survey the MC-20 site using their Acoustic Corer™ (AC) sub-bottom (below mudline) imaging system. To image and understand the behaviour and complexity of the conductor pipes, Kraken Robotics collected 63 adjacent AC scans within the survey area.

II. TECHNOLOGY

The AC (Fig. 2) employs 3-D multi-facet acoustic imaging to identify buried geological hazards including boulders and deserted oil and gas substructure and mapsub-seabed lithologies (Guigné et al., 2010; Guigné et al., 2012). The AC design consists of two, 6m-long arms (or booms) each equipped with a sonar head comprising a parametric array (Innomar) and two chirp sources; high-frequency (HF) and low-frequency (LF). Together, the various scanning frequencies generate a synthetic aperture that is further enhanced through advanced processing routines. As the boom rotates 180°, a dense grid of acoustic data is collected and a 360°, 14m-wide volumetric core is produced.

Fig. 2. Standard AC deployment configuration

III. SURVEY AREA

A. *Survey Methodology*

The survey area was comprised of soft, low load-bearing sediment (Abbott et al., 2023), which poses a challenge for most seabed deployed survey equipment, including the standard AC configuration (Fig. 2). To overcome this, a 15.8m (52ft) long suction pile was used as a substitute deployment method for the AC (Fig. 3). Using a vessel crane, a suction pile was planted at each AC survey location to a depth of approximately 12.8m (42ft). Prior to landing the pile, beacon readings were taken to ensure proper positioning. After placing the pile, a suction pump was used to place the pile at the desired depth. Every suction pile had a "bullseye" level bubble for monitoring angular motion as well as line markings to denote the penetration depth. The next step involved stationing the ROV directly above each designated pile location and collecting a series of position measurements to obtain precise positional data. A total of five suction piles were available for this campaign, thus, this procedure was executed in intervals of five. Once all five piles were successfully installed, the AC was deployed onto the pile using the AC-attached stab guide, which seamlessly integrated with the pile. Upon the AC's secure landing on the suction pile, a comprehensive set of stability assessments was conducted. Right after the AC's weight had been transferred to the pile, measurements of depth, altitude, and angular movements were meticulously recorded. After confirming that the AC remained steady in its static mode, the system underwent rotation, and the acoustic payloads extended from the booms to their designated positions. Throughout this process, continuous monitoring of angular movements and a clump weight was laid atop approximately 100m (330ft) from the survey location. Upon achieving dynamic stability, the AC was disconnected from the crane hook in preparation for survey. During this phase, the ROV closely observed the system's umbilical cable as it contacted the seafloor, while the vessel remained at a distance of 210 meters (690 feet) from the AC site.

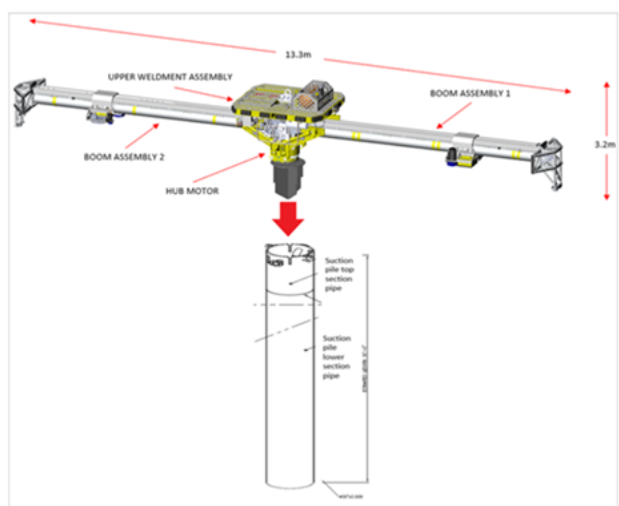

Fig. 3. AC deployment configuration using a suction pile

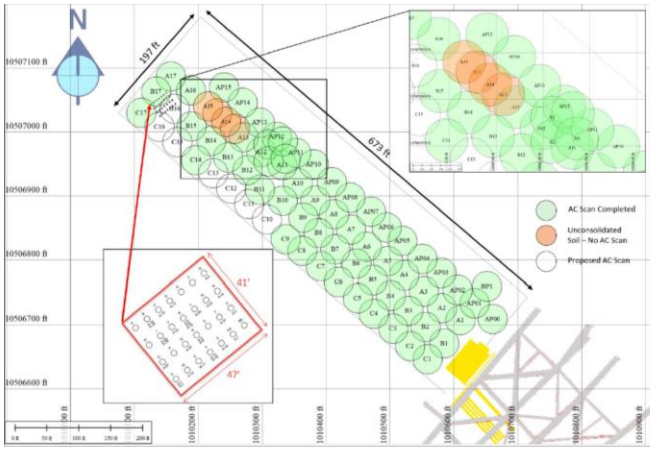

Fig. 4. MC-20 site layout schematic showcasing the 63 acoustic core locations

B. *Data Acquisition*

At each of the 63 AC sites within the MC-20 survey region (as seen in Fig. 4) high- and low-frequency, as well as parametric synthetic aperture sonar (SAS) surveys were conducted. Furthermore, JYG-Cross multifold data, utilizing low-frequency chirp acoustics (as described in Sub-section C), were collected at seven out of the 63 designated sites, specifically: C04, A06, C09, A11, C14, A16, and AP12 (Fig. 4). The initial six JYG-Cross scans were performed to establish a foundational velocity model. The inclusion of the AP12 site occurred later in the survey timeline, identified as necessary for obtaining additional information along an AP row, primarily for the purpose of detecting gas occurrences. Each individual scan required approximately 10.6 hours to complete, and the acquired data were promptly transmitted onshore via GDS satellite communication for subsequent processing and interpretation.

C. *Data Processing*

The data acquisition and processing workflow consisted of four phases, from individual site analysis to a unified migration, resulting in 3-D images that exhibited and helped to detect buried geohazards and stratigraphy. A brief description of the processes involved in each phase is presented below:

Phase 1: Acquisition of 63 AC scans

- Initial processing and velocity model building for each AC site
- Preliminary analysis and interpretation of results and main features of interest
- Reporting of linear targets and stratigraphy

Phase 2: Constructing a comprehensive mosaic of the 63 cores within the entire survey area

- Assembling of all data sets into individual, precise per-core images
- Thorough analysis and documentation of main features of interest

Phase 3: Regional unified migration

- Transform all cores to the same topographical datum through static corrections
- Creation of a single velocity model for the entire survey area
- Regional 3-D migration and generation of final results
- Final comprehensive interpretation and documentation

Phase 4: Visualizing and digitizing the conductor pipes of interest

- Generation of digitized seabed, conductor pipes, and basement layers using OpendTect software
- Data visualization and interpretation in OpendTect and NaviModel software packages

The AC resolves the vertical positioning of linear targets and discrete anomalies by translating acoustic source-receiver pulses into depth, using a site velocity model. This velocity model is generated by performing a velocity analysis of the JYG-Cross data, a method akin to a high-precision multi-channel seismic profile that processes the data to highlight the geological layers within the sub-seabed (Guigné and Blondel, 2017). P-wave velocities throughout the MC-20 site ranged from 1460m/s at the mudline to approximately 1700m/s at depth. Each AC site's velocity profile and landing positions were used in Phase 1 to create extended p-models for each scan location along with interpolated V_{rms} profiles for post-processing depth conversions. For Phase 3, a regional velocity model was generated for the unified migration of the entire survey site using a regional 250m x 125m (820ft x 410ft) p-model grid.

Step-by-step processing workflows for the JYG-Cross and SAS data, employing internal software ZoomSpace™ are illustrated in (Fig. 5). The AC data encompasses both specular components (related to stratigraphy) and non-specular components (such as diffractors like pipes). The SAS acquisition predominantly focuses on non-specular imaging due to factors like aperture, trace spacing, and source frequency (Guigné, 2014). Within ZoomSpace™ specular/non-specular filters were used to isolate and enhance the acoustic responses. To optimize imaging the HF chirp was fine-tuned for high resolution visualization of targets in the shallow sub-seabed, while the LF chirp was ideal for imaging deeper targets. The Innomar's narrower acoustic propagation pattern provided sharper and more detailed images of the features, facilitating their interpretation. Confidence in the data interpretation was bolstered through correlation amongst the HF, parametric and LF data sets for each feature and anomalies. Subsequently, the resulting 3-D data sets were analyzed using the OpendTect software.

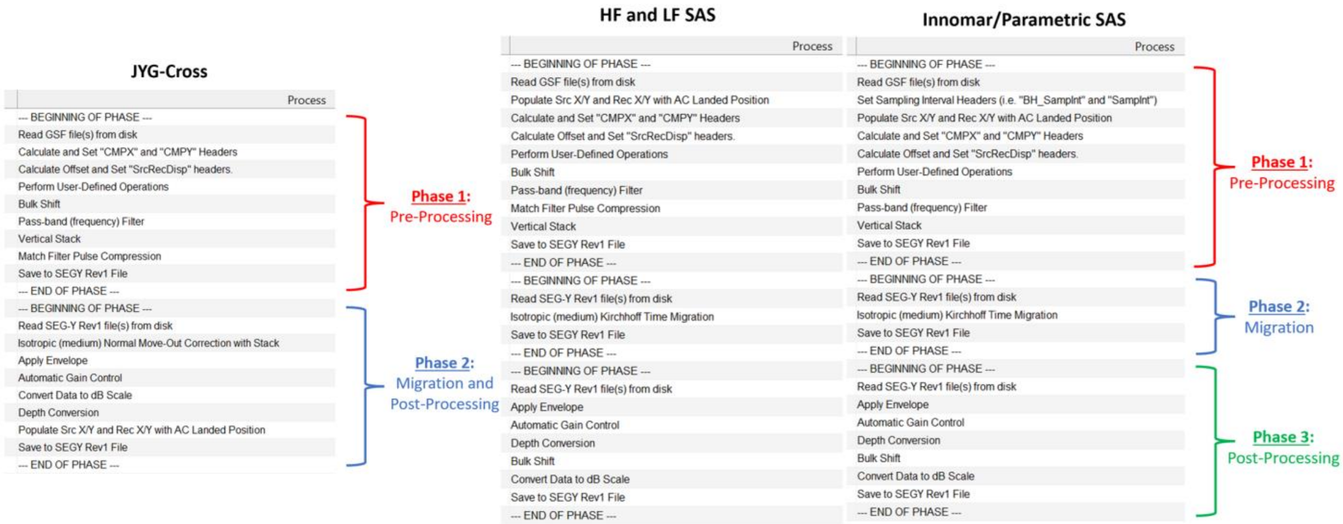

Fig. 5. ZoomSpace™ processing workflows for the JYG-Cross, HF, LF and parametric data sets, respectively

To bring all individual AC cubes together into one regional cube in Phase 3 (Fig. 6), required prior corrections for topography. These topographic static corrections involved establishing a reference level and adjusting the traces accordingly, by an amount Δt. This correction was executed in two stages and applied to all HF, LF, and parametric data sets. In the initial stage, each cube underwent a pitch correction. Every trace in the cube was shifted to a flat reference level determined by the navigation data with the adjustment amount of Δt. This procedure was carried out individually for all 63 data sets. In the second stage of the topographic static corrections, alignment of all 63 cubes was performed relative to the reference level. In the case of the MC-20 survey area site A06, which was the shallowest, served as the reference level. Consequently, all other sites were adjusted to align with it.

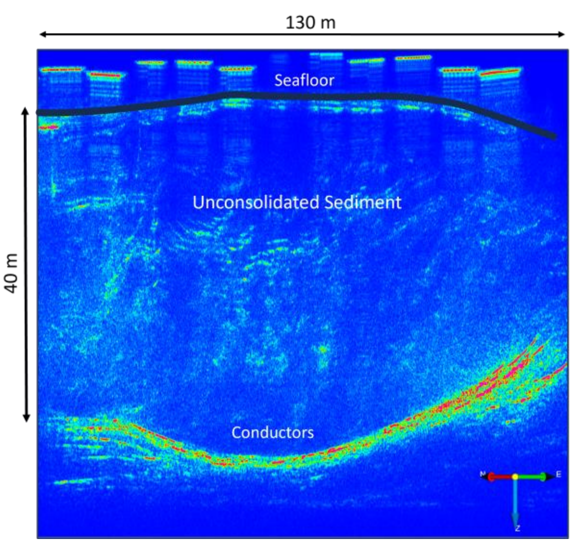

Fig. 6. Cross-sectional view of the unified migrated dataset showcasing the seabed, the chaotic upper sedimentary region and the continuous conductor bundle

D. Results and Interpretation

The acoustic core findings yielded a volumetric image with a diameter of 14m (46ft) depicting the sub-seabed down to a depth of 60m (200ft). Analysis of the data volumes was conducted to identify linear targets and discrete anomalies within a depth range of 0m to 50m (0ft to 165ft) BML. Additionally, a densely consolidated geological basement was observed at depths ranging from 41.5m (136ft) to approximately 50m (165ft) below the seabed, with the precise depth varying by site location (Fig. 7). Within the upper sub-seabed region, the results revealed the presence of chaotic, blocky clay resulting from mudslides, interbedded amid a depositional arrangement of weak, partially consolidated sediment, as shown in Fig. 8.

Upon preliminary examination of each core (Phase 1 and 2), 307 linear targets were identified. These linear targets were characterized as both discontinuous and continuous typical of conductor pipes. In addition, 482 anomalies were identified as shown in Fig. 8. These anomalies consisted of a mixture of discrete, sub-rounded to irregular, and elongated predominantly associated with the upper strata of the sub-seabed geology, along with some debris. More detailed analysis in Phase 3 revealed that the initially identified 307 linear targets were in fact 18 continuous conductor pipes. These conductor pipes reposed onto the basement geology, bundling near their center and rising and splaying outwards towards the well bay and collection dome (Fig. 9). Specifically, they were identified between approximately 28m and 48m (91ft and 158ft) depth, with the greatest concentration existing between 40m and 47m (130ft and 155ft) below the seabed. The shallowest conductor pipe manifested at a depth of 28m (91ft) and extended in a downward direction from the collection dome, as illustrated in Fig. 9.

Evidence of potential leakage from minor localized conductor wall damage was observed at three scan locations, AP08, AP01 and AP0, respectively. The acoustic responses associated with these three unique targets unveiled the presence of gas shown as a vertical, tightly confined flow (Fig. 10). It's

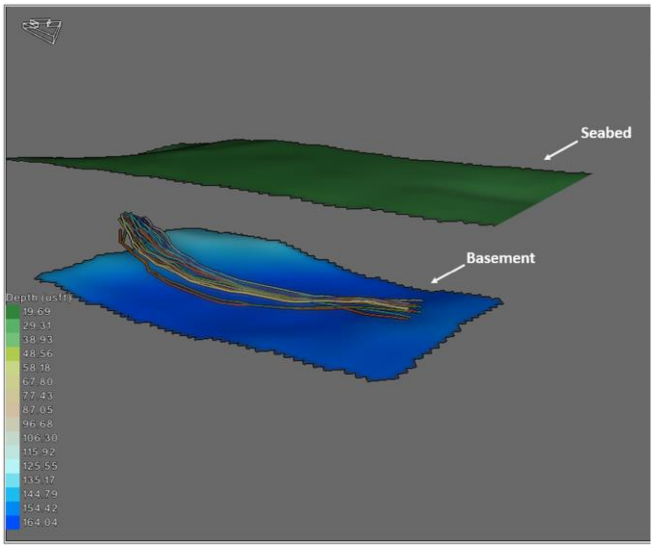

Fig. 7. Digitized seabed, basement and 18 conductor pipes visualized within Navi Model

important to highlight that this flow did not exhibit volatility or display characteristics associated with plume dispersal. Of significance is the fact that site AP0 fell within the confines of the collection dome area, where the boundary of containment is situated.

An abrupt termination of the conductor pipes was observed near Row 11, which is 62m (203ft) from the original platform's well bay (Fig. 8). In this region, the presence of gas in the sediments was observed, which as a result impeded the acoustic signals' ability to reflect and gather data effectively. This was further corroborated during data acquisition, where at several sites between Row 11 and Row 17, significant accumulation of trapped gas was observed near the seabed. Further discussions on the observed conductor behaviour and potential reasonings for the noted acoustic blankening are highlighted in subsequent Section IV.

IV. Discussion

The Phase 1 and 2 results proved useful for gaining an initial understanding of the MC-20 site and the discrete and linear features present within. The unified results of Phase 3 and 4 provided a coherent, detailed representation of the survey area leading to key interpretations related to the shape, alignment and key attributes of the conductor pipes and associated infrastructure.

A cross-sectional examination of the conductor bundle successfully confirmed the presence of 18 out of the 28 original well conductor pipes. The remaining ten conductor pipes could potentially be enclosed within the conductor bundle but remained undetectable due to the compact arrangement of the conductor pipes. It is worth noting that the conductor pipes appeared to extend beneath the dome region.

The gas/oil discovered at the AP0 site further supports the capture of the oil and gas as it is near the containment dome structure. Taking into consideration all findings, there is high likelihood that a significant amount of the hydrocarbons has remained within the conductor pipes and only a small percentage has escaped due to minor fractures.

The apparent termination of the conductor pipes at Row 11 and inability of detection by the Acoustic Corer™, is likely due to one of three possible scenarios:

- The conductor pipes have been damaged near Row 11 and smaller diameter pipes were transporting oil from Row 11 to the collection dome.
- The conductor pipes have been bent downwards at a steep angle.
- The conductor pipes exist between Rows 11 and 17, but their presence and behavior were masked due to gas-saturated soil.

V. Conclusions

Kraken Robotics carried out 63 Acoustic Corer™ surveys as part of their involvement in the decommissioning efforts for the toppled MC-20 platform. The data collection involved a combination of 2-D JYG-Cross data for velocity analysis and 3-D HF, LF and parametric (SAS) data for target identification and interpretation. The parametric acquired data were instrumental in characterizing the shallow sub-seabed region, which was chaotic and unconsolidated as a result of the mudslide flow. Within this region, 482 anomalies were identified, with 88 being indicative of man-made debris and the remainder of geological origin. The regional migrated dataset precisely emphasized the presence and attributes of 18 continuous conductor pipes from the collection dome up to Row 11. The linear and cohesive nature of the conductor pipes suggested that they were generally free from fractures, with the exception of a segment in the AP region, where some minor conductor wall damage was observed. This damage was identified by the observation of oil/gas moving vertically upwards from the conductor bundle at sites AP0, AP01 and AP08. Lastly, a well- defined basement floor was discerned, on which the conductor pipes were resting onto and closely followed its trend. This campaign provided useful insight for the Couvillion Group to further assist with their remediation efforts at the site of the MC-20 oil spill.

Acknowledgment

Thank you to the offshore team of Kraken Robotics for the collection and quality control of the data sets. Additional thanks to Couvillion Group for their support throughout the campaign and for providing permission to showcase the results herein.

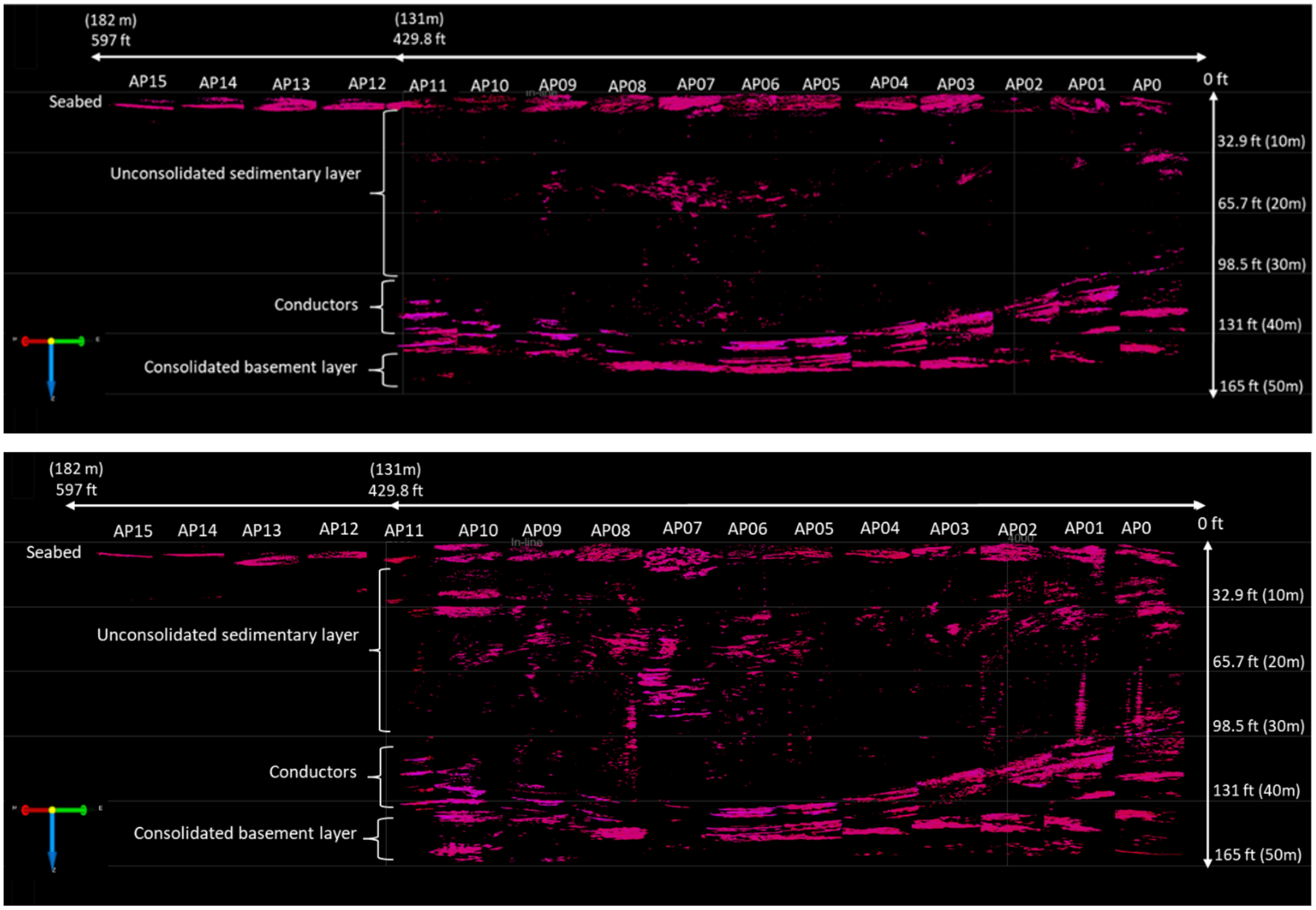

Fig. 9 Comparison of the mosaiced HF data set (top) with the parametric data set (bottom) for the AP line, where it can be clearly observed that the parametric source better defined the chaotic characteristics of the unconsolidated sedimentary layer within the upper most sub-seabed.

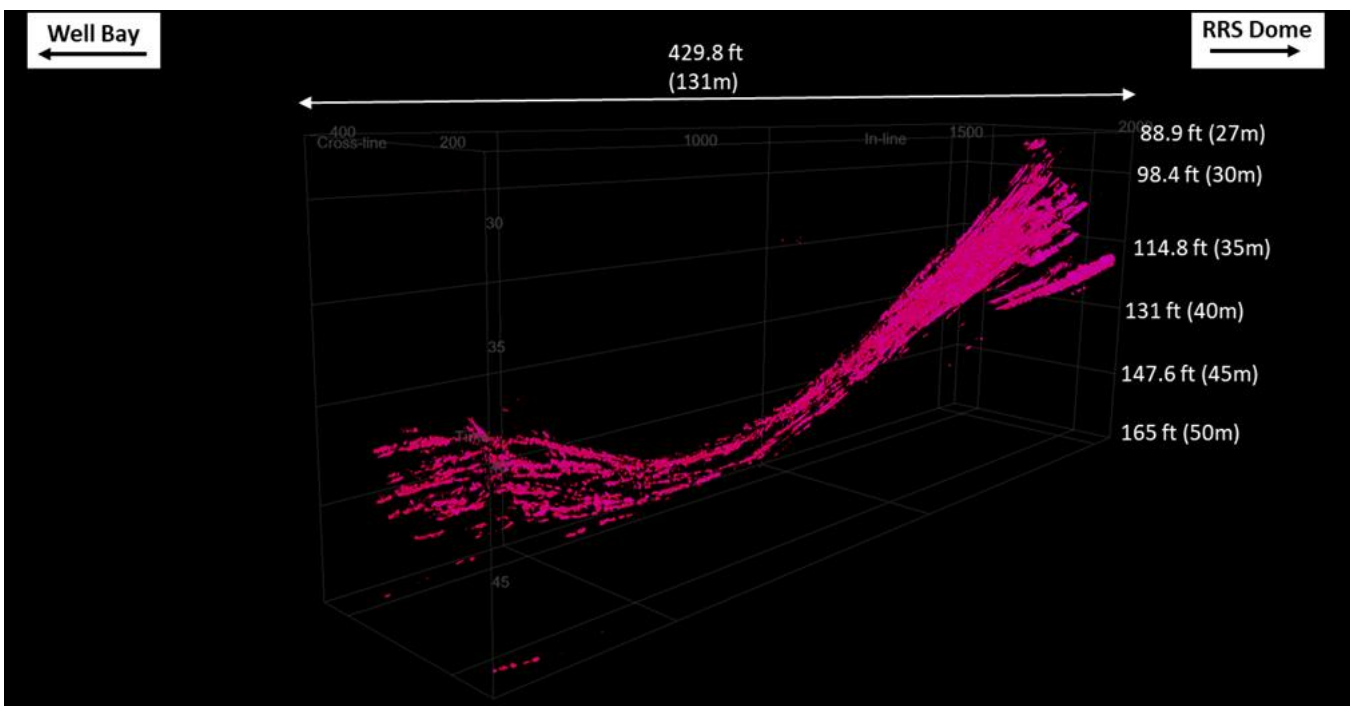

Fig. 8. Conductors as discerned within the unified migrated volume, where they converge at the center and splay outwards.

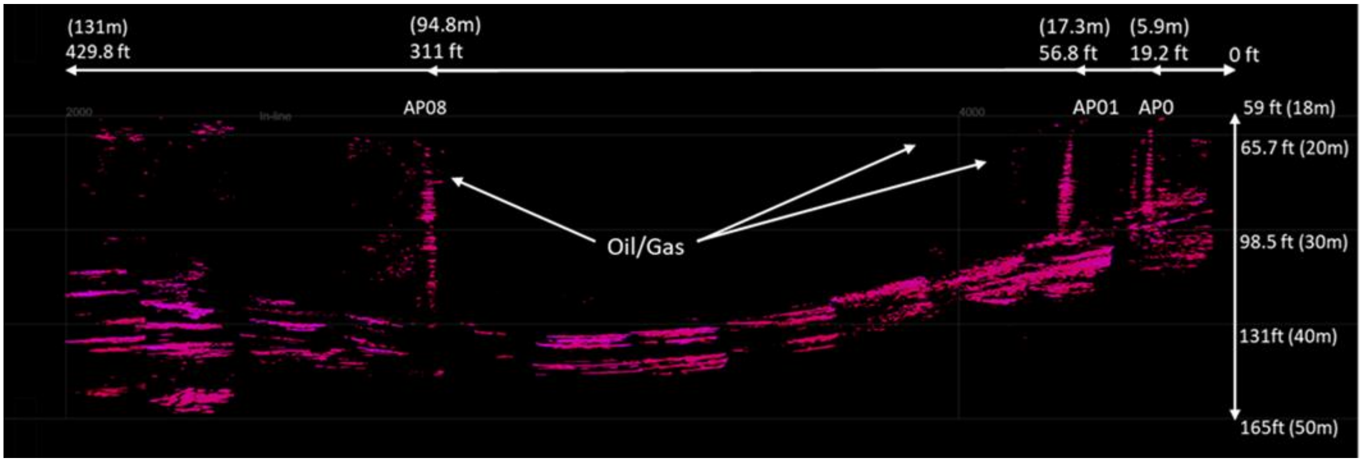

Fig. 10. Parametric 3-D profiles of sites AP0 throughAP08 displaying the conductor pipes alongside the corresponding oil/gas vertical features.

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