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Refined Characterization of Complex Sedimentary Placer Deposits

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Abstract: Abstract The morphology and distribution of nearshore placer deposits exhibit significant diversity. Ultra-high-resolution (UHR) seismic imaging serves as an effective tool for delineating the distribution of these complex sedimentary deposits. However, documented cases of UHR imaging in intricate nearshore sedimentary environments remain scarce, limiting our understanding of their complex distribution patterns. Based on UHR seismic data acquired from a complex nearshore sedimentary environment off the western coast of Hainan Island, this study analyzes and synthesizes key factors for achieving high-quality UHR seismic imaging of placer deposits from three perspectives: seismic wavelet processing, seismic velocity analysis, and multi-scale seismic imaging. The study demonstrates that: (1) When wavelet side lobes are severe and the true structure of thin sand layers is masked in the imaging profile, wavelet processing is necessary. (2) Accurate velocity modeling is crucial for the refined imaging of complex sedimentary sand bodies. (3) Multi-scale seismic imaging is an effective approach to enhance the reliability of sand body characterization. These insights into the seismic imaging of complex nearshore placer deposits provide practical references for placer exploration and other energy resource assessments.

Keywords: Placer deposit; ultra-high-resolution seismic; processing; refined characterization.

1. Introduction

The nearshore waters off the western coast of Hainan Island, China, are rich in placer mineral resources and constitute the target area for this study (Figure 1a). The water depth is approximately thirty meters. Frequent and intense tidal and swell activities present adverse conditions for acquiring high-quality raw seismic data. The subsurface exhibits complex sedimentary features resulting from the interplay of various factors, including variations in terrestrial sediment supply, oceanic currents, bottom current activity, and tectonic controls [1]. Preliminary imaging and geological sampling results indicate significant stratigraphic thickness variations in the study area, ranging from 1 to 17 meters. The sedimentary bodies exhibit diverse morphologies, including small and large paleo-channels, and estuarine muddy progradational sequences. The sediment types vary from coarse sand, medium sand, fine sand, to mud in the study area [2]. To thoroughly characterize the placer deposit features, refined imaging is an essential prerequisite [3].

Seismic surveys are conducted to image subsurface structures by generating waveforms using various sources and recording the Earth's response [4]. Over the past few decades, there has been increasing attention paid to high-resolution seismic methods [5]. They were first introduced in the oil and gas development industry in the early 1900s and are now widely utilized globally for various applications, including oil and gas development, geological mapping, carbon capture and storage (CCS) site surveys, and geotechnical site characterization. A critical metric for refined imaging is resolution. Seismic exploration can be categorized based on resolution into industrial seismic, high-resolution seismic, very high resolution seismic, and ultra-high-resolution seismic [6]. Ultra-high-resolution (UHR) seismic imaging typically involves dominant frequencies exceeding 750 Hz, achieving lateral resolution $\leqslant$ 2 meters and vertical resolution <0.5 meters. Three common UHR methods include sub-bottom profiling (SBP), single-channel seismic imaging, and multi-channel seismic imaging, each possessing distinct advantages. Sub-bottom profiler offers rapid acquisition and the highest resolution due to acoustic source frequencies in the kilohertz range; however, its penetration is limited, with 6 kHz acoustic waves penetrating less than 10 meters in sandstone, significantly less than in mudstone [1]. Single-channel seismic surveys are cost-effective and operationally efficient, utilizing sparker sources with dominant frequencies of several hundred to several thousand Hertz. Single-channel seismic can provide imaging of the upper hundred meters of sediment. However, low signal-to-noise ratios (SNR) can result in blurred or failed imaging. Multi-channel seismic acquisition with similar source frequencies is more expensive but provides high-SNR imaging of the upper hundred meters of strata.

Whereas 3D surveys are complex and expensive, 2D surveys are in common use [7]. In practical 2D UHR seismic imaging, results are often influenced by multiple factors. This study utilizes various UHR seismic datasets, including SBP data, single-channel sparker data, and multi-channel sparker data, integrated with lithological results from borehole sampling. From the perspective of a practical seismic data processor, the study provide specific recommendations for practical UHR data acquisition, and key factors for successful UHR seismic imaging.

2. Data and Methods

To facilitate a robust comparison of different survey methods, acquisition was conducted along coincident target lines using different techniques. Three survey lines were acquired (Figure 1b), corresponding to sub-bottom profiler, single-channel seismic, and multi-channel seismic using a 1400 J source. Minor discrepancies exist between the actual and planned survey lines, and it ensures the validity of comparative data analysis.

Sub-bottom profiler data were acquired using a German INNOMAR SES-2000 Light Plus parametric sub-bottom profiler. The secondary frequency was 6 kHz with a beam angle of ±2°. The transducer was deployed approximately 3 meters below the sea surface. The output envelope data incorporated the instrument's built-in swell filter, though residual swell effects remained. SBP data processing included spherical divergence compensation, a 4 ms static time shift correction, spectral shaping, residual swell correction, band-pass filtering (50–100–1000–1800 Hz), and suppression of high-amplitude noise bursts.

The single-channel seismic recording system was an IxBlue Delph Seismic system. The source was a SIG 2Mile unit with an energy output of 750 J, and the receiving streamer was a GEO-SENSE24 hydrophone array. The shot interval was 1 s, the record length was 497.834 ms, and the sampling rate was 0.166 ms. The tow depth of both the source and the streamer is approximately 0.75 m. Single-channel data processing included swell correction, spherical divergence compensation, and band-pass filtering (50–100–1500–3000 Hz).

The multi-channel seismic acquisition system was a MULTI-TRACE system. The source was a Dutch GEO-SPARK 2000X sparker system, and the streamer was a 48-channel GeoSense48 lightweight hydrophone cable with a 3.125 m group interval. The shot interval was 1 s, the record length was 499.9 ms, and the sampling rate was 0.1 ms. The source tow depth was 0.12 m, and the streamer depth was 0.5 m. Navigation is a prerequisite for accurate imaging [6]. In this study, navigation data included accurate source positioning but lacked individual receiver group positioning. Fortunately, due to favorable acquisition conditions, streamer feathering angles were small, and receiver depths were relatively stable, resulting in actual positions closely approximating the designed geometry. Multi-channel seismic data processing included spherical divergence compensation, filtering, wavelet processing, velocity analysis, stacking, and post-stack time migration.

3. Results and Discussion

3.1. High-Resolution Wavelet Processing

The signature of the sparker source, generated by a negative discharge principle, exhibits good stability under ideal conditions. However, strong swells can distort waveforms [8], and this is detrimental to wavelet consistency and effective wavelet processing. Furthermore, low signal-to-noise ratio (SNR) data are detrimental to wavelet processing. In order to obtain high SNR data, seismic data acquired during periods of relatively low swell activity. In stacked sections without wavelet processing, a single stratigraphic interface may appear as multiple parallel reflection events, a phenomenon attributed to severe wavelet side-lobe effects (Figure 2). As is common in many nearshore multi-channel surveys, the streamer depth in this acquisition was controlled by only a few floats, resulting in imperfect depth control. Unstable streamer depth leads to variations in the ghost reflection characteristics, so wavelet consistency deteriorates, and processing results degrade. In summary, multiple factors cause the actual wavelet to deviate significantly from an ideal min-phase wavelet, and these substantially increase the difficulty of practical wavelet processing. Achieving a high-quality wavelet result requires a synergistic approach between acquisition and processing. Wavelet processing may introduce noise, particularly in areas with complex wavefields, where these side effects can be amplified. Therefore, an optimal wavelet processing result represents a balance between resolution enhancement and SNR preservation.

In this study, predictive deconvolution was applied for pre-stack wavelet shaping [9]. While the pre-stack wavelet-processed gathers exhibited some noise, stacking effectively enhanced the SNR. Compared to the section without wavelet processing (Figure 2), the post-stack migrated section after wavelet processing (Figure 3) shows significant suppression of wavelet side lobes. The primary reflection events become more prominent and continuous, substantially improving seismic data resolution. For example, key impedance boundaries of sand bodies become clearer, buried small paleo-channels are successfully imaged (red box), the bottom of a buried paleo-climate channel is clearly delineated (orange box), weak reflection interfaces become more apparent (yellow arrow), previously obscured internal structures are revealed (green box), and contact relationships within the composite structure are clearer and geologically more reasonable (cyan arrow and box).

3.2. Construction of a Refined Velocity Model

The UHR seismic data utilized in this study were acquired during relatively calm sea conditions, minimizing swell-related noise. Consequently, residual static corrections for common-midpoint (CMP) gathers were negligible and did not significantly impact imaging. While previous UHR seismic processing studies have often emphasized residual statics correction, the impact of an accurate velocity field on UHR imaging has sometimes been overlooked. This oversight can be attributed to two main factors: (1) the common use of short streamers in UHR seismic surveys, which limits velocity analysis accuracy due to insufficient far-offset information; and (2) relatively simple sedimentary environments where imaging is less sensitive to velocity accuracy. In such cases, a constant velocity model of approximately 1.5 km/s is often used for stacking or migration. The data contain far-offset and complex sedimentary wavefield information, which facilitates the construction of an accurate velocity model and the analysis of the influence of velocity on imaging.

An accurate velocity field is crucial for high-fidelity imaging. In practical tests, both the temporal location of velocity picks and the picked velocity values influence the final image. For imaging complex zones, even minor depth or velocity discrepancies can lead to significant differences in the resulting image. Velocities are typically derived from velocity spectrum analysis. Factors influencing velocity spectra include spread length, fold, SNR, muting, time window width, velocity sampling density, choice of coherency measure, deviation from hyperbolic normal moveout (NMO), and data bandwidth. Consequently, velocity spectra can vary under different analysis parameters. Through careful parameter testing, satisfactory velocity spectra were obtained, though non-unique energy clusters may exist within the target depth interval (Figure 4).

To analyze the impact of velocity on UHR seismic imaging, imaging results corresponding to two different velocity fields were compared. The seawater velocity is 1530 m/s, and two distinct root-mean-square (RMS) velocity fields were picked from the velocity spectra (Figure 5). The differences between the two RMS velocity fields (V1rms and V2rms) are concentrated mainly within the target window (highlighted in Figure 5), while the background velocity field outside this

window is identical. The corresponding stacked sections (V1stk and V2stk) are shown in Figure 6. Compared to V1stk, the V2stk section exhibits a marked improvement in imaging quality. Such as, reflections are more focused, events are more continuous, the structural image is clearer and more geologically coherent, and the overall section SNR is higher. Small velocity errors can lead to blurred or even absent structural images in complex zones. Therefore, a refined velocity field is a necessary condition for achieving high-quality UHR seismic imaging. When imaging appears blurred in complex areas, it is advisable to employ finer velocity scanning increments or denser velocity analysis grids. Under these conditions, the final velocity is the velocity with the best imaging.

3.3. Multi-Scale Refined Characterization of Placer istribution

Seismic sections represent "images" of the subsurface, reflecting the seismic wave response of geological media. This response is influenced not only by subsurface properties but also by other factors, including ambient noise during acquisition, instrument response, and processing methodologies. Consequently, Seismic imaging inherently suffers from non-uniqueness. During seismic interpretation, enhancing the reliability of the imaging results is paramount.

This study explores the use of multi-scale imaging to improve reliability. Imaging results obtained at different scales may exhibit different characteristics. To analyze these differences, three imaging results from the study area are presented: a 2019 sub-bottom profile image (Figure 7), a 2019 single-channel seismic image (Figure 8), and a 2020 multi-channel seismic image (Figure 9). For the interface indicated by the yellow arrows, the SBP image shows a continuous reflection, the single-channel image appears quite blurred, while the multi-channel image clearly resolves the interface. Based on this multi-scale result, a reflector is predicted at the location marked by the yellow arrow. The blurred appearance in the single-channel image is likely due to a low SNR in the raw data. To further validate the existence of this interface, a sediment borehole was drilled at this location. Drilling results (superimposed on Figure 9) confirm an impedance boundary at the location of the yellow arrows, with fine sand overlying medium-to-coarse sand. This demonstrates that multi-scale imaging provides complementary perspectives, reducing interpretation ambiguity and serving as an effective tool for enhancing the reliability of refined sand body imaging.

Given the complexity of placer sedimentation and the limited availability of ground-truth sampling data, only a selected portion of the study area was interpreted for detailed placer distribution mapping to establish a refined characterization methodology. Based on borehole data and multi-scale imaging results, an interpretation of placer distribution within the dashed box area in Figure 9 was performed (Figure 10). Interpretation indicates that the shallow subsurface strata comprise fine sand, medium-to-coarse sand, and mudstone. Due to abundant nearshore sediment supply and the combined action of runoff and marine processes, the seafloor surface hosts rich placer deposits. Areas unaffected by channel incision are characterized by earlier-deposited mudstone. This refined characterization of placer distribution provides valuable foundational data for resource evaluation and potential exploitation.

4. Conclusions

To achieve high-quality delineation of placer deposit distribution, this study employed UHR seismic imaging methods. Calm sea conditions and a stable acquisition geometry are essential prerequisites for achieving high-fidelity UHR seismic imaging. Compared to mudstone, sandy sediments exhibit higher acoustic attenuation coefficients. Therefore, to achieve deeper penetration for placer exploration, a high-energy seismic source is necessary and also beneficial for acquiring data with a higher SNR. Leveraging borehole calibration data, this study establishes a refined and reliable methodology for characterizing placer distribution, encompassing high-resolution wavelet processing, refined velocity model building, and multi-scale UHR seismic imaging.

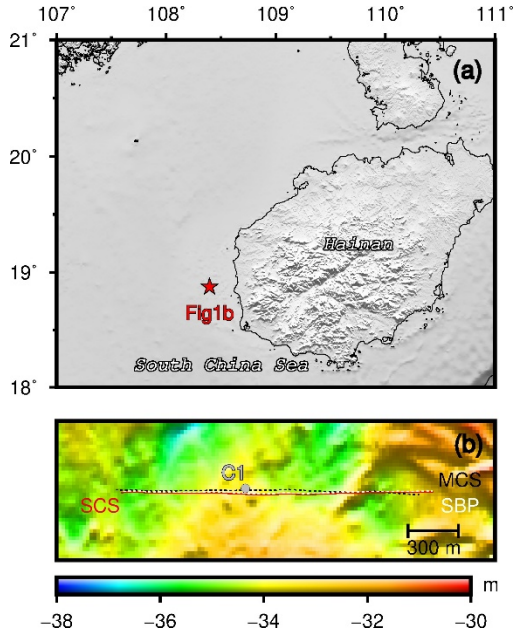


Figure 1. Location map of the study area and distribution of survey lines.

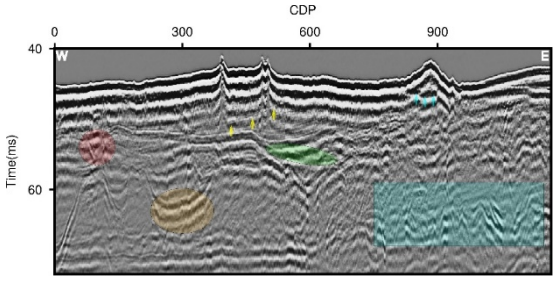


Figure 2. Post-stack migrated section before wavelet processing.

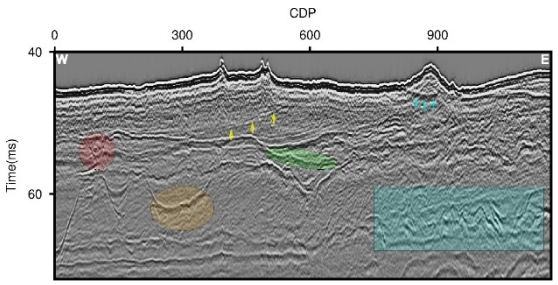


Figure 3. Post-stack migrated section after wavelet processing.

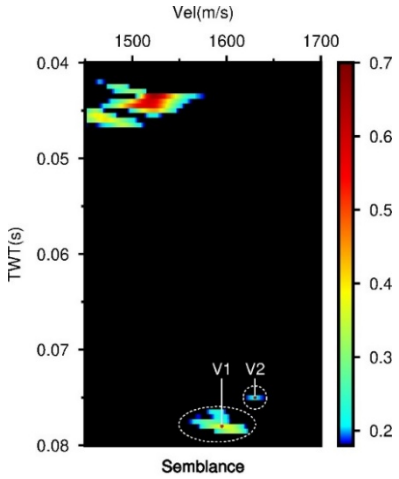


Figure 4. Example of a velocity spectrum analysis result.

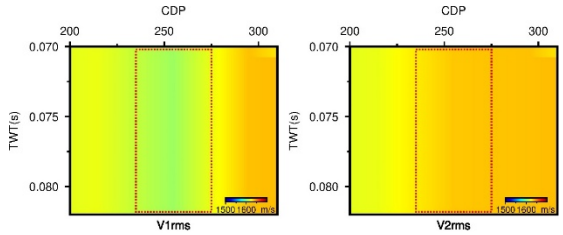


Figure 5. RMS velocity fields V1rms and V2rms corresponding to picked velocities V1 and V2.

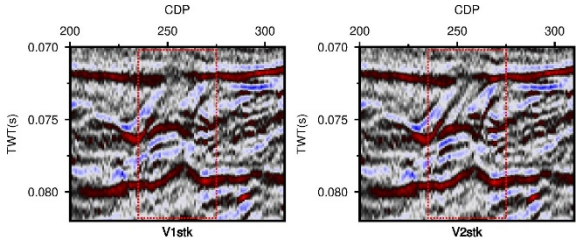


Figure 6. Stacked sections V1stk and V2stk corresponding to RMS velocity fields V1rms and V2rms.

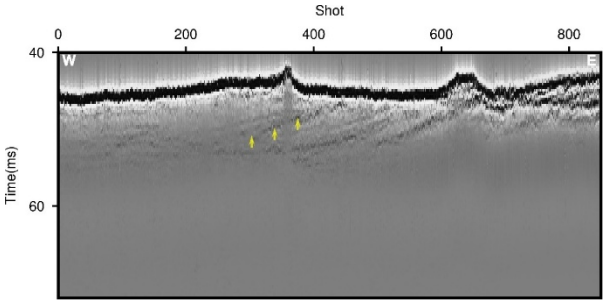


Figure 7. Multi-scale imaging: Sub-bottom profiler.

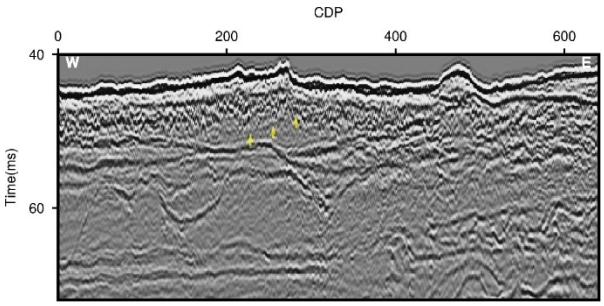


Figure 8. Multi-scale imaging: Single channel seismic.

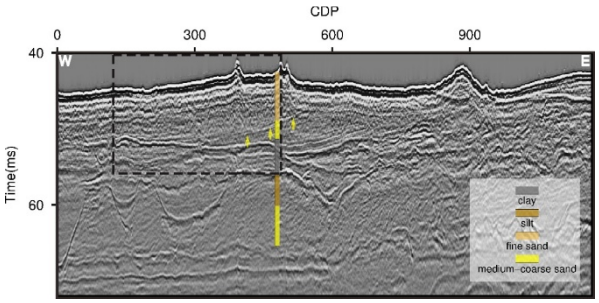


Figure 9. Multi-scanle imaging: Multi-channel seismic.

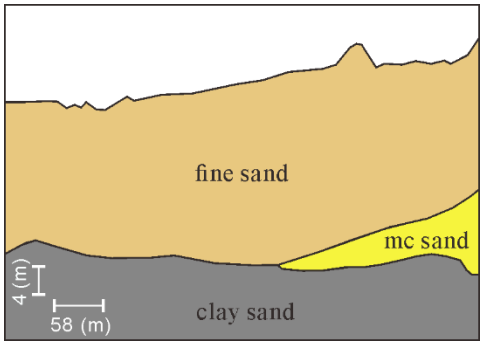


Figure 10. Result of refined placer deposit distribution characterization.

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