First variable-depth streamer seismic survey offshore China
Zhang Zhenbo, Wang Shoujun, Li Dongfang, Wang Ruiliang, CNOOC, Jason Sun, Xiao Yongdeng*, Guo Yonghe, Conrad Judd, CGG

Summary
In this paper, we present the first variable-depth streamer seismic survey offshore China. The objective of the broadband survey is to obtain high resolution and high fidelity seismic data in order to better assess the exploration potential in the region. The acquisition and imaging were done on two separated blocks. The initial result is encouraging, and shows the benefit of broadband data to interpretation.

Introduction
The first variable-depth streamer survey in China was conducted in Huizhou and Liwan blocks, in the South China Sea. It is an area of active exploration. Although not far from each other, the Huizhou block is in shallow water, while the Liwan block is in deep water. The two blocks pose different acquisition and processing challenges, and the broadband aspect of the variable-depth surveys provided insights in different ways.

In the first part of this paper, we briefly introduce the geological setting and exploration challenges, and how a variable-depth streamer solution can help. Then we describe the acquisition and processing, in particular, the technical challenges. Finally, we analyze the initial result, and discuss the strength and limitation of broadband technology.

Exploration challenges
The exploration targets in the region are lithologic and stratigraphic traps in Neogene and Paleogene formations. The shallow water area (the Huizhou block) has been well covered by conventional seismic data, which has been useful but at the same time quite limited in resolution. Some exploration targets are deep, with up to 4 km of overburden. The conventional data has a low signal-to-noise ratio in the deep target zones, making it difficult to recognize the depression boundaries and the structure, and to distinguish the hydrocarbon sag. For existing discoveries, the reservoir types and their enclosures need to be better defined.

Deep water exploration in the Liwan block is a relatively new frontier offshore China. Deep water drilling incurs high cost and requires more informed decisions which demand higher resolution and more precise images. There are fewer or even no existing wells in the deep water exploration area. How to effectively predict the reservoir and hydrocarbon potential under little or no well conditions is a challenge.

All the above challenges call for high-fidelity imaging with high temporal and lateral resolutions. Broadband seismic data can potentially provide a solution to these challenges. In conventional acquisition, limitation in data bandwidth is in part due to receiver ghost cancelling signal at certain frequencies, both at high- and low-end. The cancellation of energy at some frequencies shows up as notches in the spectrum. Variable-depth streamer overcomes this by towing a cable at a variable-depth profile, thus generates notches at different frequencies (i.e. ghost notch diversity). A deghosting algorithm that takes advantage of the notch diversity is used to remove the receiver ghost; as a result, it broadens the bandwidth significantly (Soubaras, 2010). As the cable is towed deeper, it also records low frequencies better. This is further enhanced by the extremely high-quality low-frequency response of the Sentinel streamers. Deeper cable also means less swell noise and a better signal/noise ratio. The overall result is a high-resolution image with broad bandwidth. This will benefit interpreting details of geological features and penetrating deeper to explore bigger structures.

Acquisition
The two surveys were acquired by CGG in the South China Sea, approximately 155 km to 325 km southeast of Hong Kong. The 407.9 km$^2$ (full fold) Huizhou survey is the closer of the two prospects to the shoreline, located in shallow water, where water depths range from 85 m to 115 m. The 292.2 km$^2$ (full fold) Liwan survey is located further out, in deeper water with depths ranging from 1490 m to 1820 m in an area free of obstructions. Both surveys were acquired with 8 streamers, each 6000 m in length, separated by 100 m, and towed in a variable-depth configuration with receiver depths varying from 5 m at the streamer head to 50 m towards the tail of the streamer. Figure 1 shows the streamer’s variable-depth profile.

Figure 1: Variable-depth streamer depth profile.
First variable-depth streamer seismic survey offshore China

The Deeper water Liwan prospect was acquired utilizing the Dovetail streamer acquisition solution. This layout helps to distribute coverage more evenly, particularly at the far offsets where large feather variations between adjacent sail lines exist as a result of the variable currents.

Strong currents were encountered on both prospects, which were erratic in both magnitude and direction. Current direction varied within the water column, resulting in a differential in feather direction over the offsets of the variable-depth streamer. Streamer control was maintained by employing streamer steering devices and depth controllers.

Processing

Following are the key steps of processing for the Huizhou survey (shallow water case):

- Early signal processing: debubble and source designature.
- Denoise: swell noise attenuation and linear noise attenuation.
- Demultiple: Shallow-Water Demultiple (SWD), 3D SRME, Tau-p deconvolution, and Radon demultiple.
- For variable-depth streamer surveys, demultiple workflow differs from the one for conventional data (Lin et al., 2011).
- Normal and mirror migration, followed by deghosting using joint-deconvolution. (Soubaras, 2010).
- Post migration processing.

For the Liwan survey, the flow is similar but without SWD and Tau-p deconvolution. There is a special issue for Liwan: one of the target areas is close to the edge of the new survey, so legacy conventional data is used to form fully migrated image.

Initial result

The broadband data provided significantly improved images over those from conventional data.

In the Huizhou area, high resolution is achieved with the broadband data. The pinch-out structures in the Neogene are clearly imaged, and the lateral contact is more reasonable. With better low frequency content, the fault and the top basement are better imaged (Figure 2). The boundaries between major units are clearly defined. In addition, the basement shows extensive fracture networks (Figure 3), which are not conclusively defined in conventional data. Although the fractured basement is not the target of exploration at this time, in other parts of the world, the fractured basement typically forms an excellent reservoir. A common issue with shallow water seismic data is the multiples masking data and interfering with interpretation. The new data went through an intensive demultiple flow. The comparison with VSP corridor stack shows that it matches VSP better than legacy data.

In Liwan survey, the comparison with conventional 3D data is restricted to a small overlapping area (Figure 4). The broadband data gives a more detailed definition to the structure of interest, thanks to its wider bandwidth. In the sedimentary basin, the image has a bandwidth of more than 5 octaves (Figure 5). The formation reflection and the impedance characteristic are reliable and reasonable; the lateral contact relation of the data is highlighted. The geological boundaries of deep water sediment and their interior structure are clearer and more reliable. The fault planes about 3000 m beneath the mud line are much sharper. All the above will be helpful in the identification of the source rock and the assessment of trap and reservoir. Furthermore, abundance of low frequency energy makes reservoir inversion more independent of well data, and also increases the reliability and resolution of reservoir prediction for locations away from well.

Discussion

Conventional acquisition has limited bandwidth partly due to source and receiver notch attenuation. The variable-depth streamer acquisition removes the receiver notch and broadens the bandwidth of the recorded data. However, the earth attenuates seismic waves in a frequency-dependent way. High-frequency energy is attenuated more quickly as the reflection from deep target travels through a thick overburden. In the Huizhou survey, one of the targets is a thin sand layer at depth of nearly 4 km below the water bottom. A high-resolution definition of the target layer has not been achieved even with the broadband acquisition, as the high frequency energy has been attenuated by the thick overburden. For deeper targets, the power of broadband acquisition lies in its ability to record extra low-frequency energy. This helps to define faulting planes, top of basement, fracture in basement, and other major structure features in the Liwan and Huizhou blocks.

For shallower targets, broadband data is superior to conventional data in both high- and low-frequency ends. Liwan is a classic example (Figure 5). The rich details give data a texture that helps correlation of sedimentary units across faults or other disruption of lateral continuity. It also revealed a deep reflector in the basement that was not known previously, which helps to understand the geological setting.
**Conclusion**

The first variable-depth streamer survey offshore China was completed successfully. The initial result showed high-quality imaging and benefit to interpretation in many aspects. It also showed potential for wider scope of application than assumed at the beginning of the acquisition.

**Acknowledgement**

The authors wish to thank CNOOC and CGG for permission to publish the paper. Many colleagues contributed to the project. Special thanks go to Chen Zhaoming and Zheng Jinyun at CNOOC, and Lin Dechun, Joe Zhou, Yang Yang, Sun Wenting, Jean-Marie Lapasset and Dong Qiaoliang at CGG.

---

**Figure 2.** Comparison of conventional (left) data and variable-depth streamer data stacks. Variable-depth streamer data shows better top of basement, better fault planes, clear indication of stratigraphic unit, and intra-basement reflections.

**Figure 3.** Extensive network of fractures in the basement is better defined by variable-depth streamer stack.
First variable-depth streamer seismic survey offshore China

Figure 4. Variable-depth streamer image has higher resolution and better definition of structure details, and broader bandwidth.

Figure 5. Variable-depth streamer image has high resolution and excellent definition of structure details, due to broad bandwidth.
EDITED REFERENCES
Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2013 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES