Advances in Borehole Geophysics

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1. Summary

Borehole geophysics has undergone transformative advancements, moving beyond its traditional formation evaluation role to become integral for high-resolution imaging, real-time monitoring, and guided drilling. This paper delineates the progress and applications within this field, focusing on three pivotal technological directions: Vertical Seismic Profile (VSP), dynamic monitoring, and the development of SDAS systems. In VSP, breakthroughs in ultra-deep well acquisition (exceeding 10,510 meters), innovative processing for velocity modeling and drilling guidance, and well-driven seismic data processing have significantly enhanced imaging resolution and drilling accuracy. Dynamic monitoring encompasses real-time microseismic and fiber-optic data acquisition, continuous fracture network simulation, joint pre-frac and post-frac analysis, and integrated monitoring within fractured wells to quantify stimulation efficiency and effective stimulated rock volume (ESRV). The development of SDAS, particularly using helically wound cable (HWC), demonstrates a viable solution for high-density, long-term time-lapse seismic monitoring onshore and offshore, offering superior signal clarity and higher resolution imaging compared to conventional methods. These collective advancements provide critical insights for intelligent reservoir management, CCUS safety, and optimized hydrocarbon recovery.

Keywords: Borehole Geophysics, Vertical Seismic Profile (VSP), Microseismic Monitoring, Fiber-Optic Monitoring (DAS, DTS), Hydraulic Fracturing, SDAS, HWC.

2. Introduction

Borehole geophysics, initiated within BGP in 1983, has evolved into a discipline centered on two major technical categories: Vertical Seismic Profiling (VSP) and dynamic monitoring, with a sustained focus on the manufacturing and application of Distributed Fiber-Optic Sensing (DFOS) technologies. These technologies are deployed across critical application scenarios. Smart monitoring includes intelligent reservoir management, utilizing DTS, DAS, pressure, flow rate, velocity, and production data transmitted via big data platforms, and CCUS & engineering monitoring, ensuring the safety and integrity of pipelines, gas storage sites, water finding operations, and CCUS projects. Furthermore, reservoir monitoring directly supports hydrocarbon production through production monitoring (production profiling, high/low production analysis, drainage/injection evaluation), fracturing monitoring (using microseismic and fiber-optics for fluid, proppant, injection, re-frac, and completion monitoring), and time-lapse VSP (enabling dynamic tracking of fluid migration via permanent installations). The continuous evolution of these applications is driven by focused advancements in three core technical areas, which form the basis of this paper.

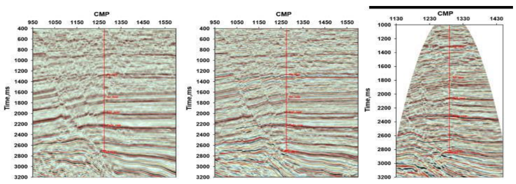
3. Advances and Applications

3.1. Vertical Seismic Profile (VSP)

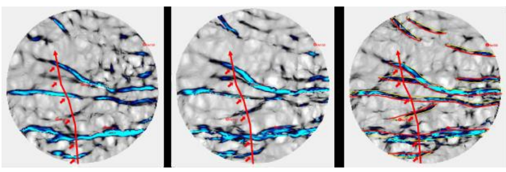
VSP technology has seen substantial progress in acquisition capabilities and data application, fundamentally improving subsurface imaging and drilling precision. This section highlights three representative case studies demonstrating diverse VSP applications.

3.1.1. Borehole Driven Seismic Data Processing (Bohai Bay Basin)

A high-density surface joint 3D DAS VSP acquisition was conducted in the Bohai Bay Basin. Different fiber deployment methods (inside tubing vs. casing, standard fiber vs. weak FBG) were tested, ultimately selecting the fiber optic cable inside the casing due to its superior data quality with less low-frequency interference and higher SNR. A synchronized processing flow for 3D DAS VSP and surface seismic data was developed, leveraging the macro structural trends from surface seismic and the vertical precision from borehole data. Key processing techniques included strain-to-velocity conversion, DAS VSP noise suppression (e.g., ringing interference removal via time-frequency domain anomaly suppression and 2D/3D stacking), borehole and surface unifying reference plane tomography for static correction, and amplitude/wavelet consistency processing. This integrated approach resulted in high-resolution, high-SNR 3D VSP and surface seismic images. The final migration results showed a significant improvement in the ability to identify small faults and sand bodies, demonstrating the value of borehole-driven processing for enhancing surface seismic interpretation. Figure 1 shows that the new processed seismic and 3D VSP results have higher resolution and clearer faults. Figure 2 combined seismic data with lithological bar and synthetics, which shows that DAS 3D VSP and new processed surface seismic data has more details and better consistency with synthetics.

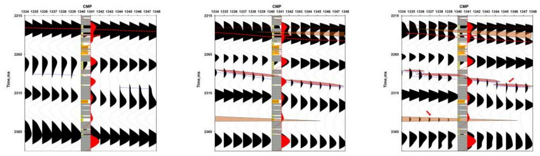


(a) (b) (c)



(d) (e) (f)

Figure 1 The imaging result in time domain: (a) the legacy seismic imaging; (b) the new processed seismic imaging; (c) the 3D VSP imaging; (d)~(e) time slice along the target layer of (a)~(c)



(a) (b) (c)

Figure 2 Combined seismic data with lithological bar and synthetics: (a) the legacy seismic imaging; (b) the new processed seismic imaging; (c) the 3D VSP imaging.

3.1.2. Walkaway-VSP Guided Drilling for Horizontal Well (Sichuan Basin)

In the complex geological setting of the Weiyuan area, Sichuan Basin, where the Qiongzhusi Formation shale gas reservoir is deep (~4400m) with rapid structural changes, micro-faults, and varying dips, traditional geosteering faced challenges. A Walkaway-VSP survey was acquired along a 10° azimuth line with a 12 km line length, 40m shot interval, and 80-level 3C geophone tool deployed in the well. Advanced processing, including intelligent wavefield separation to effectively isolate upgoing P-waves and converted waves, and Minimum Travel Time Pre-Stack Depth Migration (MTT-PSDM) using a multi-template fast marching algorithm, produced a high-resolution depth migration profile (Figure 3). This profile provided a precise and accurate structural image around the wellbore. Based on this detailed image, the horizontal well trajectory was optimized in real-time during drilling (Figure 4). This VSP-guided geosteering enabled an additional 300 meters of reservoir section to be drilled beyond the planned 1500m, achieving a 100% reservoir encounter rate and contributing to the well becoming a high-yield producer with a stable daily gas output of 738,800 cubic meters.

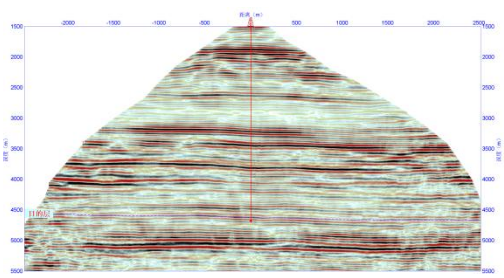


Figure 3 high-resolution depth migration profile

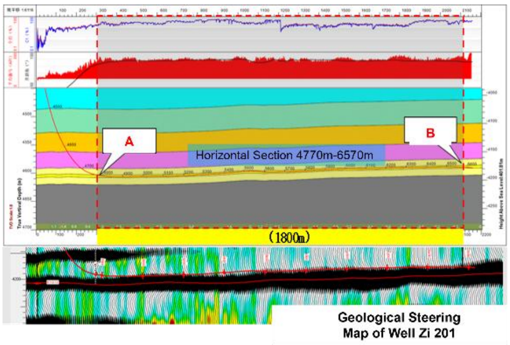


Figure 4 Walkaway-VSP Horizontal Well Geosteering Model Diagram

3.1.3. Joint OBN and 3D DAS-VSP Acquisition (Abu Zakum Field)

A landmark project in the Abu Zakum offshore field involved the world's largest simultaneous acquisition of 3D DAS-VSP data across 13 wells on two artificial islands (6 on North Island, 7 on Central Island) alongside a high-density OBN survey (acquisition geometry as shown in Figure 5).

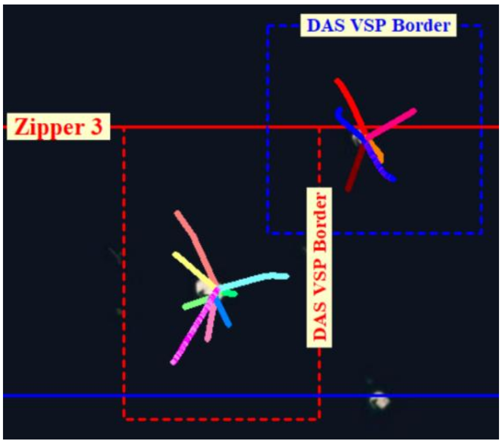


Figure 5 High-Density OBN and3D DAS-VSP Joint Acquisition Geometry

Pre-installed armored fiber-optic cables behind the casing served as the downhole receiver array, recording data from over 5 million airgun shots fired for the OBN survey. The massive dataset presented processing challenges due to production-related noise. An advanced processing sequence was employed: 1) Joint surface seismic and VSP Fresnel tomography was used to build a near-surface and initial velocity model, overcoming limitations of conventional VSP tomography; 2) Joint Domain Full-Waveform Inversion (JDFWI) was utilized to update the velocity model by minimizing traveltime errors in both data and model domains (via Delay-Time Common Image Gathers), effectively mitigating cycle-skipping issues; 3) One-way wave equation migration was applied separately to upgoing waves, downgoing waves (using mirror imaging for marine data), and multiples. Multi-wave migration significantly expanded the imaging aperture beyond the wellbore, and Least-Squares Multi-Wave Migration was applied to suppress crosstalk noise and improve illumination. The final multi-wave DAS-VSP images showed superior quality and resolution compared to legacy OBC data, providing a robust basis for high-precision interpretation and future well planning (Figure 6).

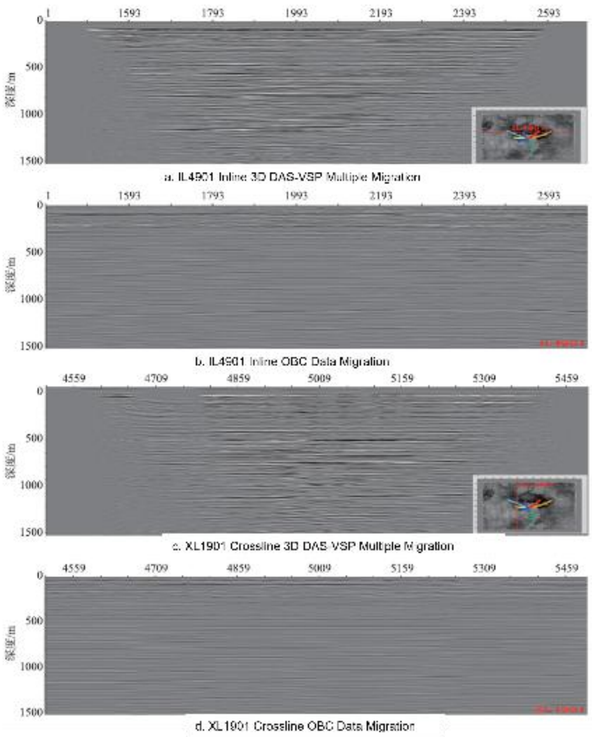


Figure 6 Comparison between the Multiple Wave Migration results of 3D DAS-VSP data from 7 wells on Central Island and the Early-Stage OBC Data Migration results from the Same Survey Lines

3.1.4. Joint OBN and 3D DAS-VSP Acquisition and Imaging in East China Sea

A pioneering joint acquisition project was conducted in the Pinghu oil and gas field of the East China Sea, simultaneously collecting high-density Ocean Bottom Node (OBN) data and 3D DAS-VSP data using armored fiber-optic cables deployed inside the casing of two deviated wells (B5 and B7). The acquisition utilized the same airgun source array for both surface and downhole recording, with the DAS system achieving full-well coverage at a 1-meter channel spacing. Key processing innovations included:

(1) Advanced Denoising

Application of τ-p transform-based techniques to effectively suppress coherent ringing noise inherent in DAS data, significantly enhancing signal quality.

(2) Wavefield Separation and Multiple Imaging

Conventional processing of upgoing waves was complemented by dedicated imaging of downgoing multiples. This approach dramatically expanded the imaging aperture beyond the limited vertical coverage of the deviated wells, providing a comprehensive volumetric image around the boreholes.

(3) Integrated Velocity Model Building

The precise time-depth relationship and interval velocities derived from the DAS-VSP data were used to calibrate and enhance the OBN processing velocity model, improving the overall depth accuracy and resolution of the surface seismic image.

The results demonstrated a remarkable improvement in imaging quality compared to legacy 3D OBC data. The DAS-VSP multiple migration images provided superior structural delineation, especially around the wellbores, with enhanced fault definition and reservoir boundary characterization. The integration of OBN and DAS-VSP datasets enabled high-resolution joint interpretation, facilitating detailed reservoir description and fluid distribution mapping. This case exemplifies the efficiency and cost-effectiveness of joint borehole-marine acquisition, simultaneously yielding high-resolution VSP images and enhancing the quality of marine seismic data through well-driven processing.

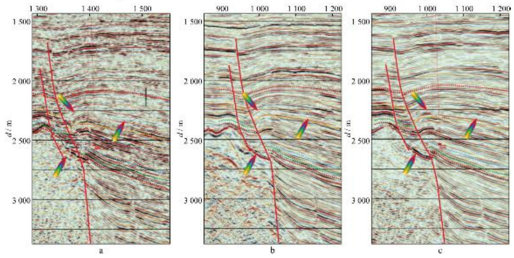


Figure 7(a) imaging results of early OBC data around Well B5, (b) newly acquired 3D OBN data imaging, (c) and 3D DAS GVSP downward multiple reflections data imaging

3.1.5. Ultra-Deep Well Zero-Offset VSP Acquisition Capability

BGP has demonstrated its industry-leading capability in acquiring VSP data in ultra-deep well environments, a critical advancement for exploring deep hydrocarbon reserves. This capability was conclusively proven through the successful execution of a zero-offset VSP survey at a depth over 10,000 meters in Well XX-1. This achievement was made possible by overcoming significant technical challenges through dedicated research and development:

(1) Advanced Downhole Instrumentation

Specially engineered ultra-high temperature resistant borehole geophones were developed to withstand the extreme downhole conditions encountered in ultra-deep formations.

(2) High-Performance Acquisition System

The operation utilized dedicated 10,000-meter cables designed for reliable signal transmission over exceptional lengths and under high pressure and temperature.

(3) Powerful Surface Source

To ensure sufficient seismic energy reached the great depths, four high-output EV56 vibrator sources were deployed, providing the necessary signal strength for high-quality data recording.

The acquired data was processed using advanced 3C vector wavefield separation methods, which effectively isolate the upgoing reflected wavefield from the total recorded wavefield. This processing is crucial for obtaining high Signal-to-Noise Ratio (SNR) upgoing waves, which are essential for building accurate velocity models and providing precise depth calibration for surface seismic data. This breakthrough in ultra-deep VSP acquisition provides a reliable foundation for depth domain processing, precision drilling guidance, and detailed structural imaging in previously inaccessible deep exploration targets.

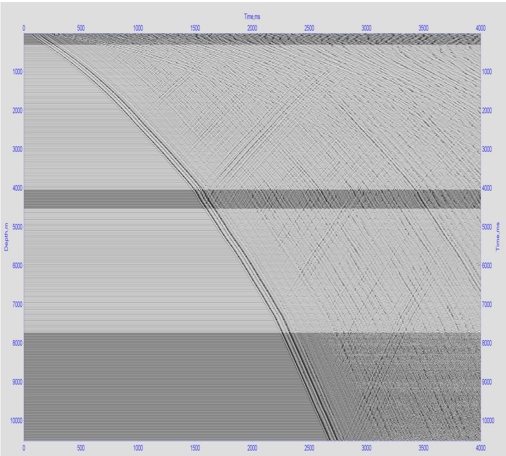


Figure 8 high SNR upgoing waves

3.1.5. Velocity Model Building & Precision Drilling Guidance with Zero-Offset VSP in Well ManShen 8

Zero-Offset VSP is a fundamental technology for refining velocity models and providing critical guidance for drilling operations. A prime example of this application was demonstrated in Well ManShen 8.

The high-fidelity data acquired from the Zero-Offset VSP survey provides the most accurate time-to-depth relationship available, serving as a direct calibration point for surface seismic data. This is crucial for velocity model building, as it allows for the correction and refinement of the interval velocity model used in depth migration processes. The result is a significant enhancement in depth migration imaging quality, yielding a more accurate and reliable structural image of the subsurface surrounding the wellbore.

This refined image forms the basis for VSP-based guided drilling. By providing a precise delineation of the target formation's depth and structure ahead of the drill bit, this technology drastically improves the positioning accuracy of the target. Drillers and geoscientists can use this information to adjust the trajectory in real-time, ensuring optimal well placement within the reservoir zone.

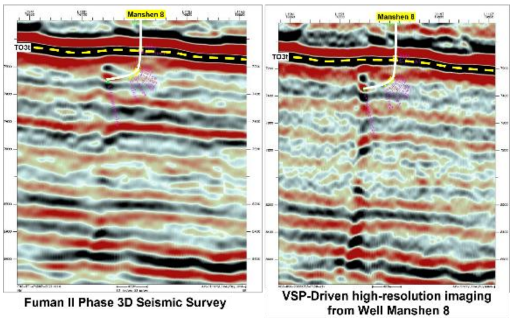


Figure 9 comparison of imaging results

3.2. Dynamic Monitoring

Dynamic monitoring technologies provide a real-time display into reservoir stimulation and production processes, enabling data-driven decisions.

3.2.1. Real-time Monitoring & Processing

The capability for real-time operation is a cornerstone of modern dynamic monitoring. Systems now allow for the real-time acquisition, processing, and visual display of microseismic monitoring results directly on site. These results can be instantaneously transmitted via network for remote analysis. This rapid turnaround enables engineers to assist in updating hydraulic fracturing parameters in real time, optimizing treatment effectiveness on the fly.

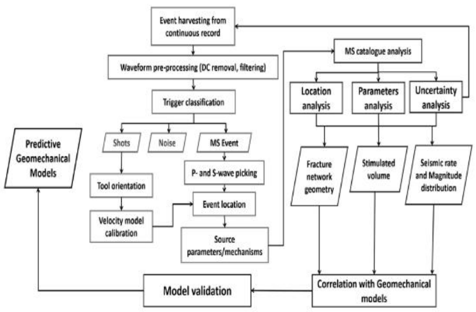
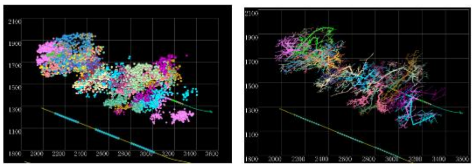


Figure 10 real-time processing workflow

3.2.2. Continuous Fractures Network Simulation

To interpret the microseismic data, Continuous Fracture Network (CFN) simulation methods are used. This technology connects individual microseismic event points according to their chronological order and spatial distribution, thereby constructing a representative model of the hydraulic fracture network morphology. This simulation provides a more continuous and comprehensible visualization of the fracture system created during stimulation.



(a) (b)

Figure 11 (a) microseismic event (b) CFN

3.2.3 Joint Analysis

A comprehensive and integrated analysis workflow is essential for understanding and optimizing the fracturing process across its entire lifecycle. This workflow synergizes data from various sources and stages:

(1) Prediction: This phase involves building a foundational model to forecast fracture growth and assess risks. It typically includes Discrete Fracture Network (DFN) modeling to represent natural fractures, which is integrated into Geomechanical modeling to simulate the mechanical response of the rock under stress and pressure. A key output of this analysis is the Evaluation of fault slip and other geomechanical risks, allowing for the design of mitigation strategies before operations commence.

(2) Monitoring: During the fracturing job, real-time data streams are crucial for monitoring the execution of the treatment. This involves the joint monitoring by microseismic and optical fiber (DAS/DTS). Microseismic mapping provides the macro-scale geometry of the fracture network, while DAS provides detailed insights into cluster efficiency, fluid distribution, and proppant placement, enabling immediate adjustments.

(3) Post-fracturing: After the operation, a comprehensive joint analysis is conducted. This integrates all available data—including the pre-frac model, real-time microseismic maps, DAS/DTS interpretations, and production data—to evaluate the overall effectiveness of the stimulation. The outcomes include a calibrated geomechanical model, a more accurate calculation of the ESRV, and key learnings that are used to optimize the design for subsequent fracturing stages or wells, closing the loop for continuous improvement.

3.2.4 Monitoring in the Fractured Well

Fiber-optic technologies (DAS, DTS) provide unparalleled detail within the wellbore itself. Real-time processing visualizes the status of each perforation and fluid entry. DAS energy measurements are used to quantify cluster-specific flow rates and proppant concentrations (Figure 8). A Uniformity Index (UI) derived from flow distribution assesses the quality of the stimulation. Most powerfully, the joint monitoring by DAS, DTS, and microseismic allows for the calculation of the Effective Stimulated Rock Volume (ESRV), a key metric for evaluating the overall success of a multi-stage fracturing operation.

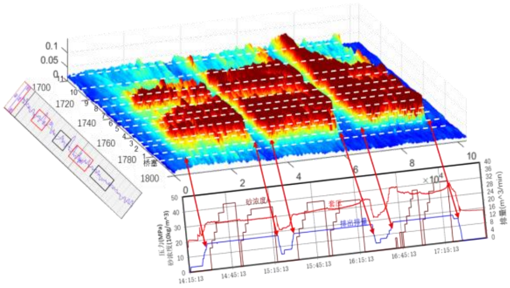


Figure 12 3D display of each cluster by DAS energy & pressure curves in real time monitoring

3.2.5 Cross-well Strain Monitoring

This emerging technology utilizes distributed fiber-optic sensing (DAS/DSS) in offset (adjacent) monitoring wells to measure the subtle strain changes induced by hydraulic fracturing in a target well. It provides a direct measurement of the mechanical interaction between the fracture and the surrounding rock formation.

(1) Fracture Propagation & Hits: Real-time strain monitoring can accurately track the arrival, closure, direction, and relative width of hydraulic fractures as they propagate towards the monitoring well. The distinct strain signature recorded provides unequivocal evidence of fracture "hits" or communication between wells, which is critical for assessing interference and optimizing well spacing.

(2) Fracture Geometry Evaluation: The complete strain rate changes recorded along the fiber can be inverted through geomechanical models to quantitatively evaluate far-field fracture geometry, including height, length, and overall complexity. This offers a complementary and often more direct measurement of the fracture footprint compared to microseismic mapping.

(3) Early Warning for Wellbore Deformation: By providing a continuous, high-resolution profile of subsurface deformation, cross-well strain monitoring serves as an effective early warning system for potential wellbore deformation or integrity issues in offset wells caused by excessive strain from nearby fracturing operations. This allows for proactive mitigation strategies to protect assets.

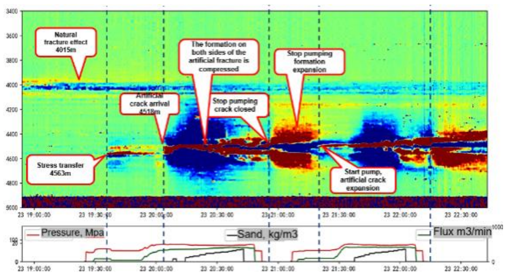


Figure 13 sross-well strain monitoring diagram

3.2.6 Double-well HFM of Shale Oil

The application of multi-well microseismic monitoring arrays significantly enhances the accuracy and resolution of hydraulic fracture mapping (HFM). A case study of shale oil development involved deploying monitoring instruments in two adjacent wells (Well A and Well C) during the fracturing of target Well B. This double-well monitoring setup recorded a total of 3673 microseismic events (2324 from Well A covering stages 1-23, and 1349 from Well C covering stages 11-23). The dual perspectives provided a more comprehensive and accurate delineation of the fracture network geometry, overcoming the azimuthal limitations and location uncertainties inherent in single-well monitoring, thus offering a more reliable basis for evaluating stimulation effectiveness and well interference.

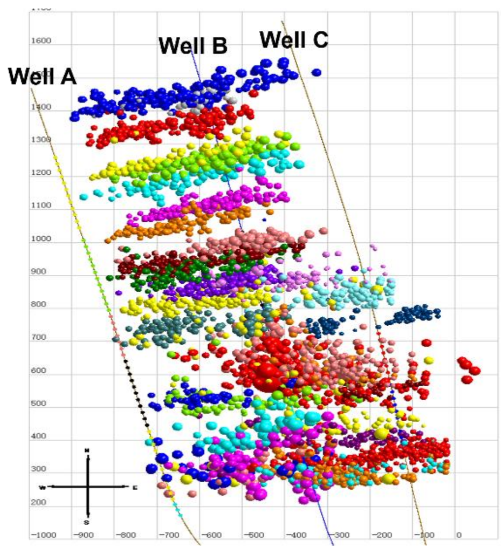


Figure 14 top view of Double-well HFM results

3.2.7 Source Mechanism and Effective Event Selection

Advanced analysis of microseismic data extends beyond simple event location. Utilizing double-well monitoring data, the focal mechanism of microseismic events can be calculated, providing insights into the source kinematics (e.g., shear, tensile, or complex failure) and in-situ stress alterations. Furthermore, a critical step involves differentiating effective rock-breaking events from ineffective noise. This is achieved by calibrating the microseismic data against direct physical measurements. For instance, the density of microseismic events within a 50-meter radius of a cored well was matched against the actual fracture density (with a spacing of 10m) observed in the core. This correlation helps determine a magnitude or energy threshold for selecting effective microseismic events. The Continuous Fracture Network (CFN) is then simulated based on the precise timing and spatial distribution of these validated effective events, yielding a more accurate representation of the created fracture network.

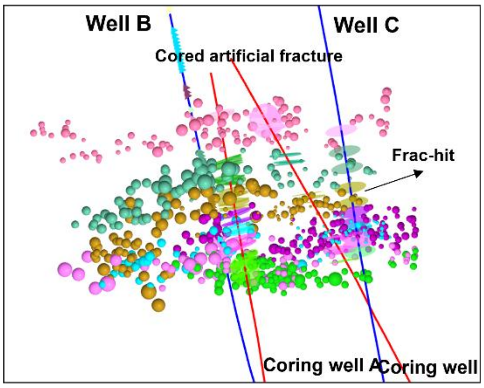


Figure 15 effective event & Core fracture & frac-hit

3.2.8 Joint Analysis with 3D Seismic

A comprehensive understanding of the factors impacting hydraulic fracturing effectiveness requires the integration of microseismic data with 3D surface seismic volumes. Microseismic event clouds often show correlation with the development of natural fractures and faults imaged by seismic attribute analysis. These pre-existing geologic discontinuities can significantly alter the propagation path of hydraulic fractures, sometimes acting as conduits for complex network growth and other times acting as barriers. Joint interpretation allows engineers to anticipate fracture containment, identify potential fault reactivation risks, and explain why certain stages exhibit atypical microseismic patterns, ultimately leading to more geologically-informed completion designs.

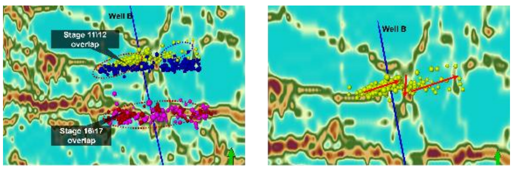


Figure 16 Combined analysis of micro-seismic events and seismic attributes (fracture attributes)

3.2.9 Long-term MSM for UGS Safety

Microseismic monitoring (MSM) plays a vital role in ensuring the long-term safety of Underground Gas Storage (UGS) facilities. Continuous downhole monitoring is deployed to detect and locate induced seismicity associated with gas injection and withdrawal cycles. For example, over a five-month monitoring period in a UGS field, 3292 microseismic events with moment magnitudes ranging from -2.36 to -1.9 were recorded. The spatiotemporal distribution of these events is critical: for instance, if events are predominantly clustered in a specific area (e.g., F1 fault zone) and absent in another (e.g., F2 area), with deeper events occurring at the intersection of fault systems, it provides invaluable insights into pressure front propagation and fault stability. This data serves as an early warning system to adjust operational parameters and avoid the activation of large-scale faults.

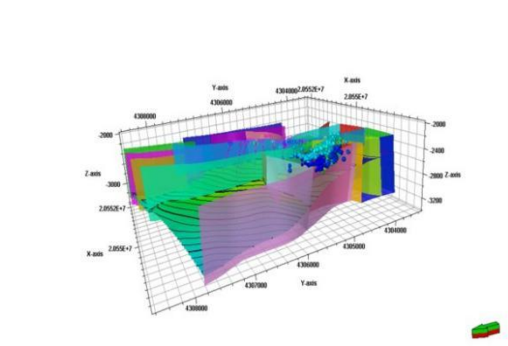


Figure 17 3D view of geological model & events

3.2.10 Production & Injection Optimization

Dynamic monitoring directly translates into production gains. By analyzing data from DAS and DTS during energized injection operations, engineers can quantify fluid intake profiles and efficiency across different zones in real-time. This insight allows for precise optimization of injection parameters. For instance, by increasing injection rate and liquid volume specifically into under-injected zones, a uniform injection profile can be achieved across all target layers. This data-driven optimization has been shown to significantly enhance production, with one case reporting a 50% boost in output following the implementation of a DAS/DTS-guided injection strategy.

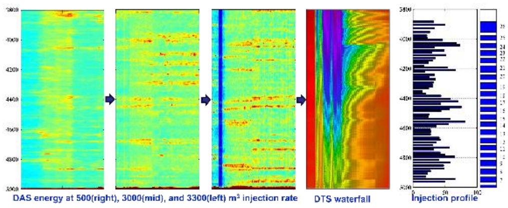


Figure 18 injection monitoring diagram

3.2.11 DAS & DTS Monitoring

Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS) have become cornerstone technologies for comprehensive hydraulic fracturing and production optimization. Fiber-optic monitoring provides a continuous, high-resolution data stream along the entire wellbore, enabling a multitude of critical applications:

(1) Fracturing Monitoring

This encompasses monitoring operations in real-time, imaging perforation inflow and diversion as they happen to assess cluster efficiency, and tracking fluid and proppant volumes entering each fracture stage. Additionally, it provides the capability to detect leaks and seal failures in the completion string during the treatment, allowing for immediate remedial action.

(2) Cross-well Strain Monitoring (Low-Frequency DAS - LF-DAS)

By utilizing fiber in adjacent monitoring wells, this application measures far-field strain changes induced by fracturing. It is instrumental in determining fracture growth direction and azimuth, calculating fracture geometry (height and length), analyzing the interaction with natural faults and fractures, and ultimately guiding well spacing optimization for full-field development.

(3) Backflow & Production Monitoring

Following the fracturing treatment, DAS and DTS are crucial for monitoring the fracture fluid backflow process. During production, they enable per-perforation fluid production profiling, revealing which clusters are contributing hydrocarbons. They also provide continuous surveillance of wellbore temperature and pressure dynamics, which is essential for production optimization and identifying issues such as water breakthrough or mechanical failures.

The integration of these capabilities facilitates real-time imaging, adjustment, and evaluation of the stimulation, enables detailed fracture propagation analysis, and provides continuous production profiling and analysis throughout the life of the well, solidifying the value of fiber-optic technology in modern reservoir management.

3.3 SDAS Development

The development of SDAS systems addresses specific challenges in seismic acquisition for monitoring applications.

(1) HWC Technology and Pilot Test: The helically wound cable (HWC) is designed for both seafloor and onshore time-lapsed (4D) seismic data acquisition.

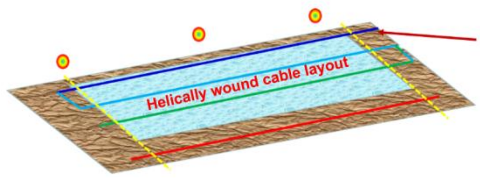


Figure 19 helically wound cable layout

It solves inherent limitations of standard fiber by enhancing sensitivity to signals beyond the axial direction, making it suitable for high-density acquisition and long-term dynamic monitoring. A pilot test was conducted with a specific observation system (e.g., HWC trace space of 0.71m vs. surface geophone at 25m) and vibrator specifications (e.g., linear sweep from 3-96 Hz), establishing the feasibility of the system.

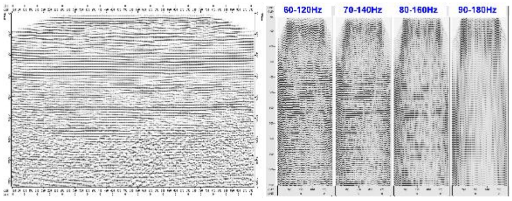
Sensor Type	Trace Space (m)	Survey Line Length (m)	Shot Line Azimuth	SP Space (m)	Shot Line Length (m)
Surface Geophones	25	500	243°	20	1000
HWC	0.71	500	243°	20	1000

Table 1. Pilot Test Acquisition Geometry

Model	Num of Vibrator	Number of vibrations	Sweep type	Frequency (Hz)	Time Length (s)	Drive amplitude(%)
BV620LF	2	1	Linear increase in frequency	3-96	16	70

Table 2. Vibrators Sepcification

(2) Signal Quality and Imaging Performance: Data comparisons revealed that while surface waves dominate in all cases, the arrivals of P-waves and reflected waves are clearer in HWC cables. The 60° HWC design demonstrated a stronger capability for receiving seismic signals. It is deemed feasible for high-density surface seismic imaging, with high frequencies reaching up to 80Hz. Crucially, imaging comparisons show that HWC acquisition possesses a distinct advantage in achieving higher resolution compared to conventional surface seismic imaging results, validating its value for detailed time-lapse monitoring.



(a) (b)

Figure 20 (a) HWC 2D surface seismic horizontal stack (b) HWC 2D surface seismic horizontal stack of sweep results

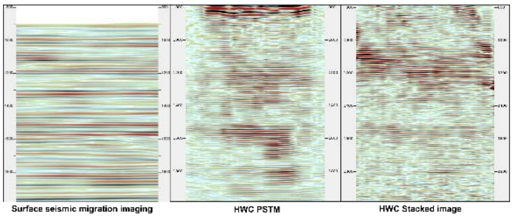


Figure 21 HWC imaging compares to Surface seismic migration imaging

4. Conclusion

The advancements in borehole geophysics presented herein—spanning VSP, dynamic monitoring, and SDAS development—demonstrate a clear trajectory towards higher resolution, real-time decision-making, and long-term monitoring capabilities. The three VSP case studies illustrate its versatility: from driving high-resolution surface seismic processing in Bohai Bay, to enabling precise geosteering in complex deep shale plays in Sichuan, to facilitating massive-scale multi-well imaging offshore Abu Dhabi through joint acquisition with OBN. Dynamic monitoring has transformed hydraulic fracturing into a data-rich, optimized process, allowing for quantitative evaluation of stimulation effectiveness. The development of HWC-based SDAS systems offers a powerful new tool for high-fidelity time-lapse seismic monitoring. Together, these technologies form a robust toolkit for addressing the complex challenges of modern resource development, intelligent reservoir management, and safe CCUS operation, ensuring that borehole geophysics remains at the forefront of subsurface characterization. Future developments will likely focus on further integration of these technologies, automation of data analysis through machine learning, and continued hardware miniaturization and robustness for even more challenging environments.

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