Advances in AUV remote-sensing technology for imaging deepwater geohazards

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Exploration geoscientists continue to make deepwater field discoveries at ever-increasing water depths around the world. Once these discoveries are sanctioned for development, headaches begin for the field development and pipeline engineers. With timelines for first oil or gas from these discoveries averaging less than three years, the need for high-resolution geophysical survey data required for the front-end engineering design (FEED) is paramount. The speed and efficiency with which autonomous underwater vehicles (AUVs) can acquire survey data is vital to meeting deadlines for these projects. This paper provides a brief history, system overview, and planned sensor upgrades for AUVs developed by C & C Technologies. A brief discussion on a 3D AUV microseismic technique is presented.

History. Six years have passed since AUVs have been available commercially for seabed investigations utilizing a suite of high-resolution geophysical tools. Sea trials for the first- generation AUV (Figure 1) took place in August 2000 aboard the *M/V Brooks McCall* with a full crew of system programmers, electrical engineers, ocean engineers, geophysicists, and technicians. These specialists were tasked with interfacing the Simrad AUV control system and the payload systems of multibeam bathymetry, side-scan sonar, and subbottom profiler.

The early sea trial results for the AUV were disappointing; there were numerous failed attempts in the early dive stage. The AUV control system is complex, and more than 100 sensors constantly monitor system health. With each failed mission, the project manager tried to see something positive in the dive to keep the crew morale up. Part replacement and availability became problematic and slowed progress for the factory acceptance testing. Many of the serial numbers for this AUV are less than 10 and parts are scarce or have to be specially machined or built. The first-generation AUV was finally commissioned in January 2001 after five months of sea trials and a less-than-desirable 50% mission completion rate.

Since January 2001, company AUVs have completed more than 75 000 line km of deepwater seabed investigations in the Gulf of Mexico, Mediterranean Sea, Florida Straits, Brazil, and West Africa. The completion rate for 40-hour missions is over 90%, and the AUV technicians have experienced nearly every possible failure. The technical crew can totally disassemble and reassemble any system in less than 10 hours. On one survey when the crew had to replace a component and had parts scattered around the work van, the field company representative reported back to the oil company that it looked like "a bomb had hit the thing." Eight hours later, the system was operational and diving for the seabed. Fully documenting problems and taking corrective action resulted in steady improvement in the mission completion rate over the early years of operation.

System overview. A brief system overview covering the AUV logistics hubs, navigation system, multibeam bathymetry system, side-scan sonar, and subbottom profiler is presented below.

Logistics hubs. The AUV processing tasks can be divided into two primary logistics hubs; the payload and control. Two specially machined titanium spheres house the CPUs for these hubs. The control sphere contains the Simrad electronics and software responsible for the AUV navigation, mechanical motion, health, and power. The payload sphere is where most of the proprietary company software resides. Mission control, guidance, sensor control, and data logging are primary tasks executed on the payload processor. The Linux operating system and C language programs execute commands on the processors.

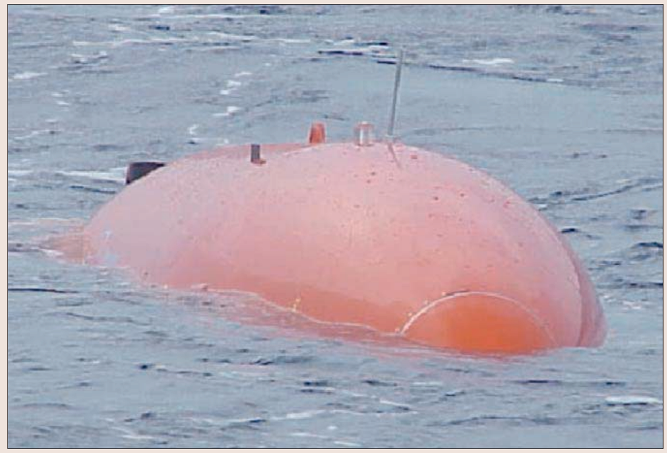

Figure 1. *AUV going through the predive system checks. System measures 6 m in length and 1 m in diameter.*

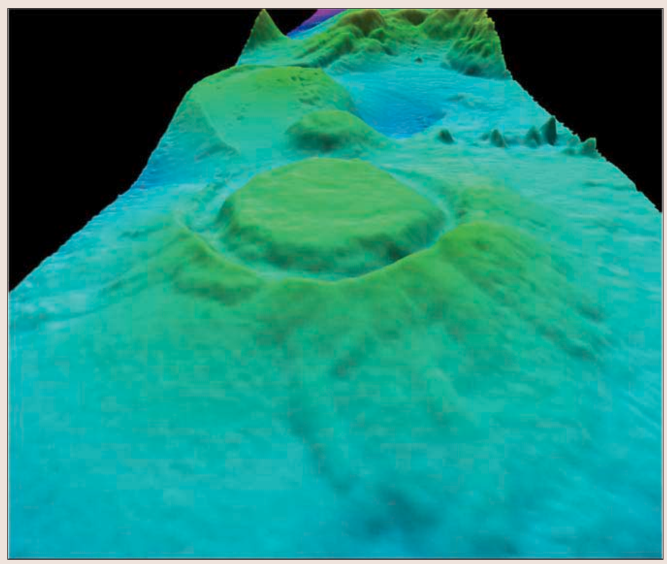

Figure 2. *Fledermaus software 3D seafloor rendering of AUV bathymetry data (3-m bins) depicting a 220-m fluid expulsion feature found in the deepwater Gulf of Mexico (VE = 6x).*

Inertial navigation system. The inertial navigation system used for AUV positioning is one of the most critical subcomponents and has worked exceptionally well. The navigational system accuracy is ±15 m in real time and ±5 m with post-processing. This accuracy at operation depths approaching 2 miles is truly remarkable. The system timing is handled by the inertial system and is critical in georeferencing and time-tagging the data collected by the remote sensing tools. The final positioning results are calculated using a Kalman filter

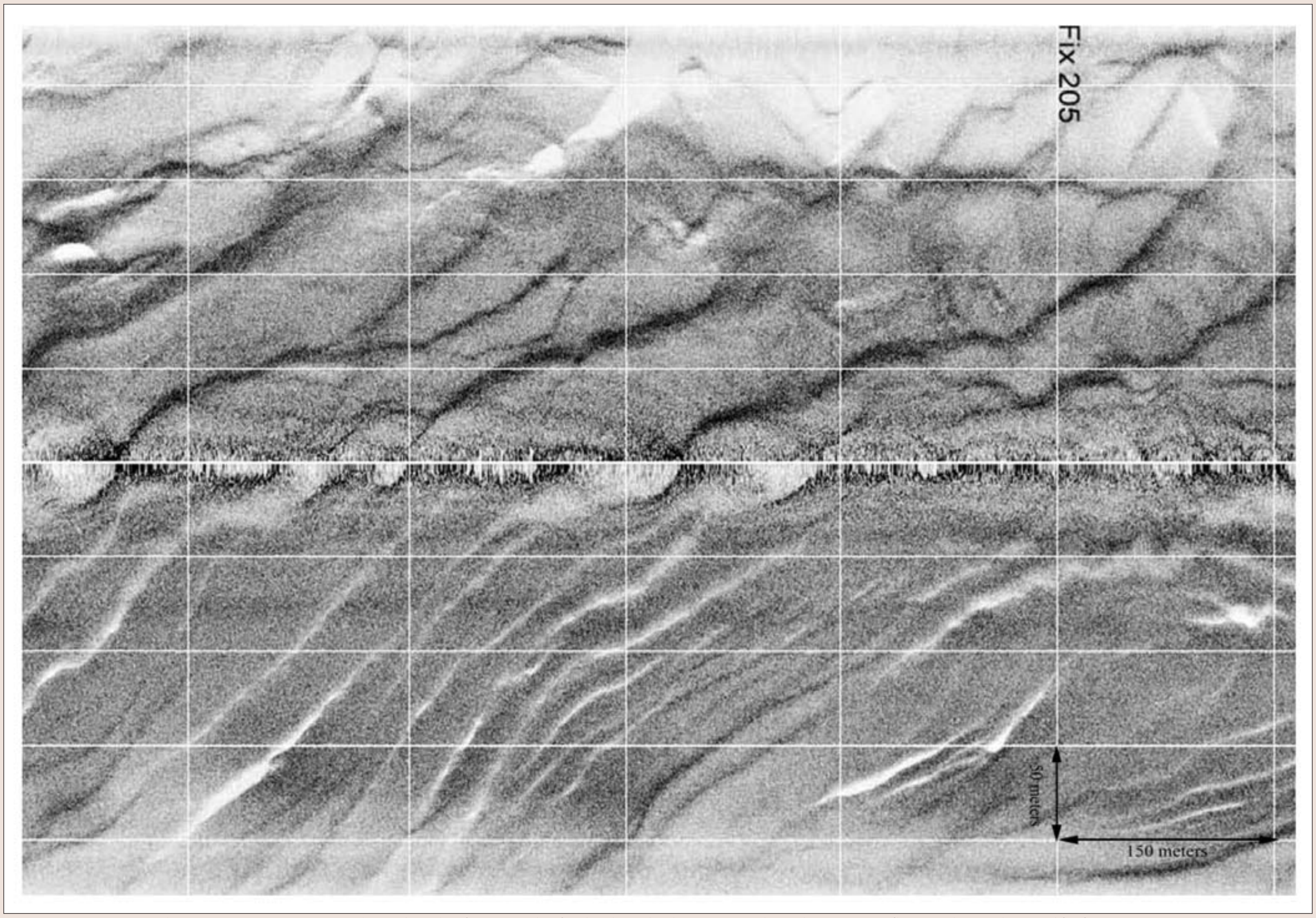

Figure 3. *AUV side-scan sonar imagery (120 kHz) of intensely faulted seabed associated with near-seafloor salt in the Gulf of Mexico.*

running Matlab algorithms. Other inputs for the filter include speed-over-ground measurements from a Doppler velocity instrument and heading from a fiber-optic gyro. The positional drift from the Coriolis effect, which is inherent in inertial systems, is overcome by acoustic updates from a USBL (ultrashort baseline) acoustic navigation system interfaced to a survey-quality DGPS. Two motion reference units record the AUV heave, pitch, roll, and heading information.

Multibeam bathymetry system. The multibeam system provided on the AUV is a Simrad EM 2000 (Figure 2). This 200-kHz multibeam sonar records a swath width of 220 m when the AUV is flying at an altitude of 40 m over the seabed. These soundings are processed and output as a 3-m gridded data set. The multibeam system is capable of producing sounding densities of smaller bin sizes, but the limiting factor is the positioning accuracy. Extensive testing has proven bin sizes less than 3 m will smear the details of seabed features where overlap exists. A median filter is used to decide which of the average 6–7 raw soundings within each bin will be used for the gridding process. The final digital terrain model is used for contour generation, seabed rendering, and seabed profiles. Backscatter imagery of the seabed complements the bathymetry and provides an acoustic picture of the seabed at 1-m bin sizes.

The absolute accuracy of the multibeam system on the AUV is directly related to the precision of the depth transducer. The precision depth sensor used in the multibeam acquisition is accurate to within 35 cm. Relative accuracy is the same as a hull-mounted system operating in water depths of 40 m, the altitude the AUV normally maintains over the seabed. Relative accuracy averages 25 cm for a flat seafloor. Tide corrections are applied to the deepwater bathymetry using algorithms derived by Goddard Ocean Tide Model. These predicted tide curves are generated from satellite altimeter data measurements.

Side-scan sonar system. AUV side-scan sonar imagery is currently collected with a dual-frequency, Edgetech side-scan sonar system (Figure 3). The low-frequency 120-kHz setting is used in normal operation. The system pings about three times per second resulting in a range of 225 m per channel. The high-frequency setting operates at 410 kHz and is used when a detailed survey is required. The AUV is generally run at an altitude of 20 m in this high-frequency mode and the ping rate is increased to 10 times per second, resulting in a range of 50 m per channel. The sonar imagery can be easily interpreted or mosaiced with a variety of interpretation software packages.

Subbottom profiler system. A subbottom profiler (DW216) manufactured by Edgetech is presently utilized for seismic imaging of the near-seabed sediments. The system is frequency modulated between 2 and 8 kHz. A record length of 300 ms and a 63-ms sampling interval are used for seismic data recording. The subbottom profiles are output in SEG-Y format. Static offsets for the AUV depth are added in postprocessing to eliminate as much of the water column as possible from the data set.

4500-m AUV system upgrades. The oil and gas industry is continually pushing production toward the 3000-m water depth, the depth limitation of the first-generation AUV. With a favorable future market outlook, an order was placed with Simrad in early 2005 for an AUV platform rated to 4500 m.

The longer AUV shell and larger electronic bottles and other system upgrades for the second generation AUVs were sent from Norway and mobilized on the *M/V Northern Resolution* in Port Fourchon, Louisiana, USA. Sea trials for the AUV began in August 2005 and integration of the 3000-m geophysical instruments took less than two weeks, a testament to crew experience and engineering modifications made over the years. Geophysical sensors rated to 4500 m had longer order lead times and were not ready for the August 2005 mobilization. The 2006 workload in the Gulf of Mexico for this second AUV has been nearly 100%.

In addition to the 4500-m depth specification, other improvements and system upgrades to the AUV platform were incorporated. An improved launch and retrieval van was built and mobilized on the vessel. The larger aluminum-oxygen fuel cell adds several hours to a normal mission and more reserve power for future sensor upgrades. Faster computers and larger disk storage drives are incorporated into the new system electronics in the logistics hubs.

Sensor upgrades for the 4500-m depth-rated third-generation AUV are scheduled for the first quarter of 2007. Significant research for improvements to the side-scan sonar and subbottom profiler systems was performed prior to making the final decisions on the upgrades.

Side-scan sonar upgrade. Including the most recent technological advances for the 4500-m depth-rated side-scan sonar was a project upgrade goal. Side-scan sonar engineers are in a design paradox for their transducer arrays, because interpreters want detailed imagery data in both the near and the far field. Long arrays are needed to image objects clearly in the far field, and short ones are required for high resolution in the near field. Across-track resolution is generally not an issue with sonars, as this is a function of the frequency and bandwidth of the transmitted pulse. Along-track resolution is dependent on several parameters such as the sonar speed, beam width, transducer length, and sonar range.

Dual-frequency side-scan sonars are usually produced with low and high frequencies of about 100 and 500 kHz. Optimal system performance is limited for dual operation by incompatibility of ping rates and ranges. Simultaneous operation of the dual-frequency system requires the concurrent firing of the low- and high-frequency transducers. The high sonar frequencies are usually attenuated at 75-m range and the low sonar frequencies are capable of ranges over 200 m per channel. The high-frequency data in the simultaneous operation mode are compromised in the along-track and across-track directions by long ping rates resulting in low data density and lack of far-field resolution.

Consideration was given to implementing *synthetic aperture sonar (SAS)*, but the technical review team decided SAS technology was too new and risky for AUV platform integration. SAS systems require long, segmented transducer arrays and vast amounts of data storage and processing power. The computer processing and data storage requirements for implementing SAS are estimated to be at least an order of magnitude greater than our current sonar processing and data storage requirements. Another area of SAS concern is the AUV attitude measurements, because the precision of these measurements is critical to SAS processing and target resolution. It is questionable whether the attitude measurements would have the precision needed for SAS implementation.

To overcome the sonar transducer size versus range resolution dilemma, Edgetech engineers designed a segmented transducer array for implementation in the third- generation AUV design. Adjacent transducer elements are used for imaging the near, mid, and far field. One transducer element images the near field and all the transducer elements transmit simultaneously to create a long array for far-field imaging. In this manner, optimal sonar images of the near, mid, and far fields are obtained. The array is also slightly curved to better enhance the sonar resolution. The *dynamically focused* 230-kHz side-scan system (4500-DF) will provide image resolutions four times greater than conventional side-scan sonars of similar frequency. Resolution of 0.7 m at 250 m range is attainable with this sonar technology.

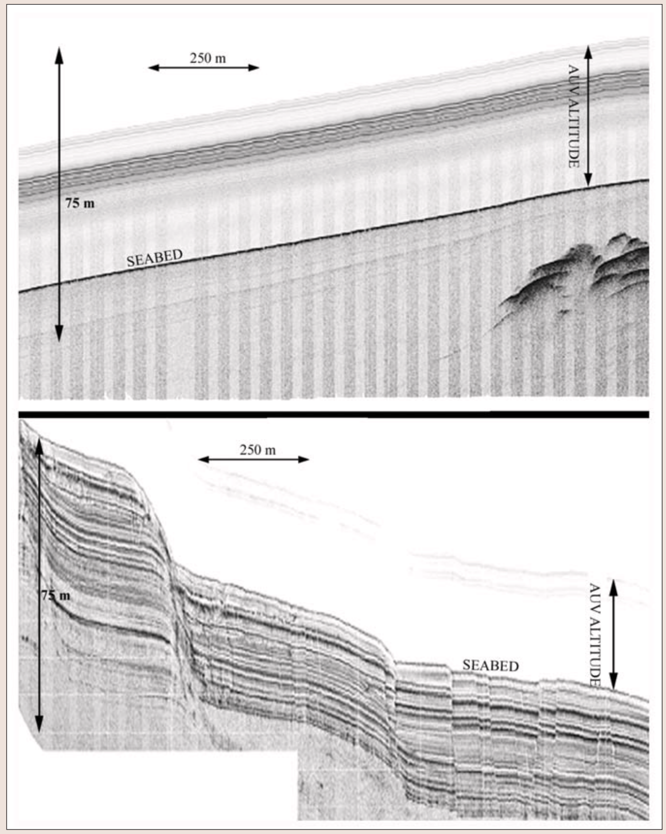

Figure 4. *AUV subbottom profile comparison of typical seismic stratigraphy recorded in West Africa (top) and Gulf of Mexico (bottom).*

Figure 5. *Subbottom profiler transducer upgrade (Edgetech DW106) undergoing lab testing. Increased source power levels and reduced beam widths should increase penetration depths to 150 m in clay-filled basins.*

Subbottom profiler upgrade. Two major areas for performance improvements for the subbottom profiler upgrade are increasing depth of penetration and improving resolution of reflecting horizons on the continental slope of West Africa.

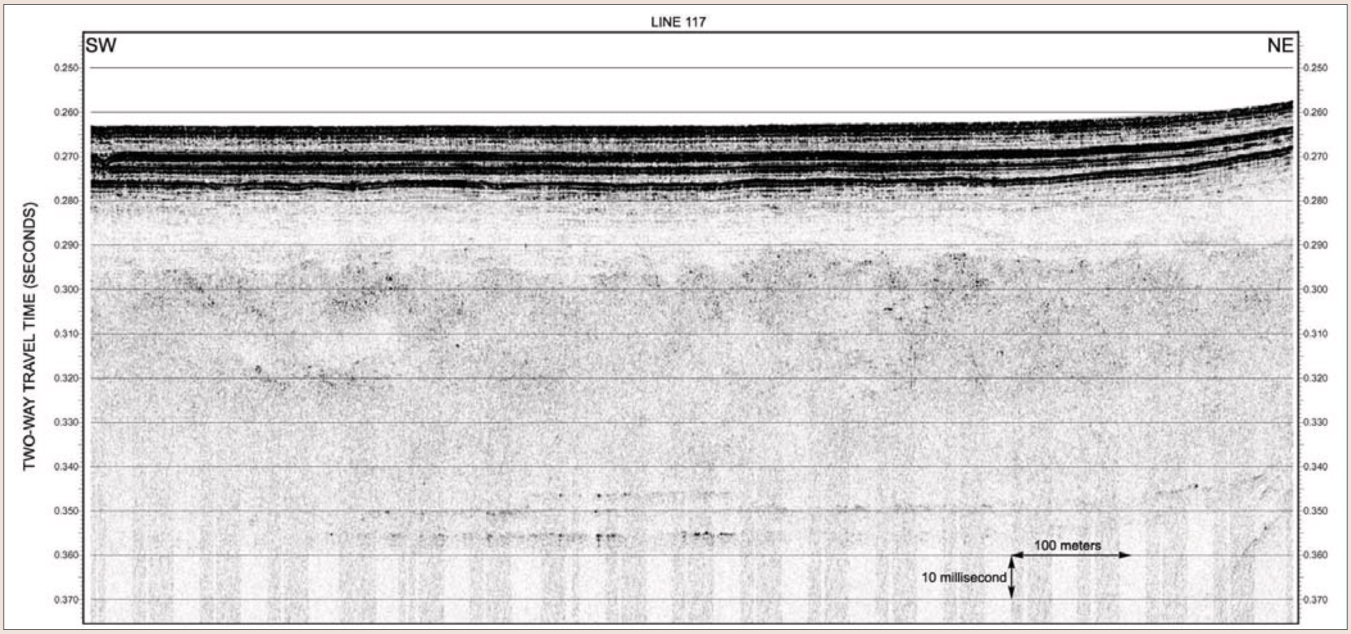

Figure 6. *Subbottom profiler test data (1–6 kHz) collected from an AUV in a Norwegian fjord. The faint reflectors at more than 80 ms below the seabed provide favorable evidence for the desired increased depth of penetration.*

The current AUV subbottom profiler resolves reflectors in clay-filled basins to an average depth of 75 m. Geotechnical engineers normally require 150-m soil borings at significant seabed infrastructure locations. The outgoing source pulse currently in use for the AUVs is frequency modulated between 2 and 8 kHz. A low-frequency signal at 1 kHz coupled with a significant increase in source level dB should allow penetration depths to 150 m below the seabed. Maintaining the high-frequency content, however, is desired for this specification. Seismic imaging to this 150-m depth allows correlation of the seismic interpretation to borehole logs. Assessing variability of seismic stratigraphy away from borehole locations could reduce the number of borings required at a development site.

A second major subbottom improvement concerns profiler data collected on the continental slopes of West Africa. Oil and gas companies have complained about resolution of the West Africa subbottom profiler data in comparison to those typically collected in the deepwater Gulf of Mexico (Figure 4). Reflections within the uppermost soil units from West Africa are generally very faint or altogether lacking. This seismic character is observed on data collected by hull-mounted and deep-tow subbottom profilers operating on the West Africa continental slopes because the acoustic impedance contrast is not great enough at these frequencies to create reflections on the seismic profiles. I proposed that synthetic seismograms from soil borings in the Gulf of Mexico and West Africa should be prepared and studied to better understand the differences in soil properties creating the observed differences in reflectivity.

Steven Schock of Florida Atlantic University investigated other possible sources for the poor West Africa performance other than low-acoustic impedance contrast. The power spectrum for the current Edgetech DW216 subbottom profiler indicated very low dB at 2 kHz across the 2–8 kHz frequency modulated source pulse. Internal noise feedback from other subsystems is an area of potential signal degradation, and so noise tests measuring the feedback were conducted to determine if additional isolation from other system electronics could be achieved. Decreasing the beam width of the transmit aperture can be achieved by increasing the diameter of the transducer face. AUV pitch and roll angles and inclined bedding planes represent sources of non-normal seismic wave incidence angles. Organic, silt, and sand pockets or other sediment inhomogeneities scatter high-frequency seismic waves.

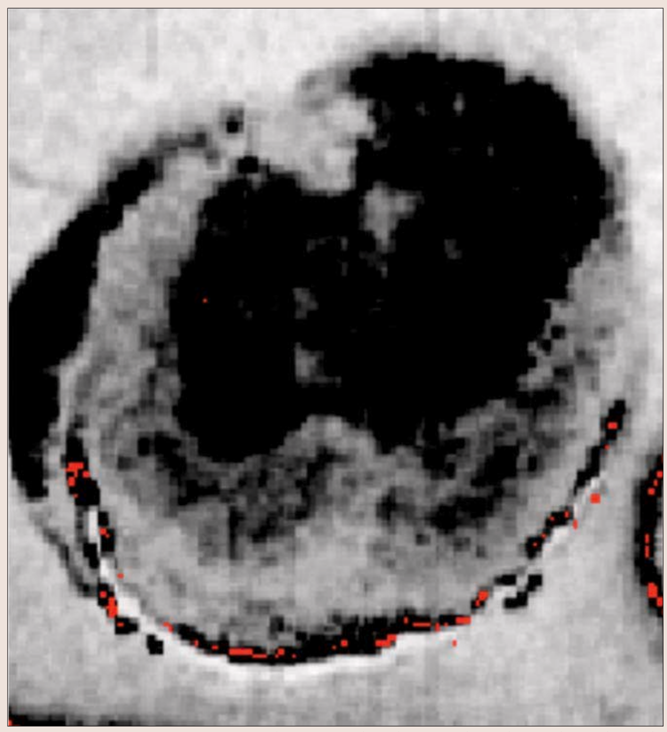

Figure 7. *AUV microseismic (4 × 4 m bins) time slice through pockmark offshore Nigeria. Image measures 700 × 500 m (Data courtesy of Total).*

The AUV subbottom upgrade (Edgetech DW106) planned for early in 2007 will provide significant improvements over the current system. Four transducers (Figure 5) replace the current one and will reduce the beam width from 94 to 38°. The frequency-modulated, well-tapered source pulse is in the bandwidth of 1–6 kHz. Power levels across the source pulse frequency will increase an average of 25 dB over the current AUV subbottom system. High signal dB at 1 kHz should provide the desired penetration depth of 150 m. The decreased transmitter and receiver apertures should increase the resolution of the subbottom signals significantly. Recently completed testing of the subbottom profiler from an AUV in a Norwegian fjord resulted in reflecting horizons being resolved to depths of 80 ms below the seabed through glacial till (Figure 6). These initial test results in this poor record area are very favorable.

3D AUV microseismic technique. Rugged and geologically complex deepwater exploration sites may require engineers to design seabed structures that cannot avoid all geohazards. Structural designs and interaction of near-seabed soils at these geologically complex sites may require detailed seismic imaging of the foundation zone. The maneuverability, speed, and navigational accuracy afforded by AUVs provide the ability to navigate closely spaced 2D seismic lines. These high-resolution 2D seismic data can be processed into a 3D seismic cube.

This technology was implemented at two investigation sites, a deepwater borehole location where stiff resistance to drilling was encountered and an active seafloor pockmark (~600 m diameter). A 4-m primary line spacing interval was used for two small 3D microseismic grids (< 1 km^2) in areas where detailed subbottom imaging was desired. The data acquisition time for these investigations took less than 24 hours.

The AUV subbottom system logs 300-ms record lengths at three times per second at a sampling interval of 63 ms, with average AUV speed of 0.66 m/s. The seismic traces are processed to 4-m bin centers, and the processing sequence options allow traces within the bins to be stacked or the trace nearest the bin center to be used for building the 3D cube.

The 3D microseismic cube enables the interpreter to take full advantage of the 3D workstation for geohazards analysis. Inlines, crosslines, arbitrary lines, seafloor amplitudes, and time slices (Figure 7) provide details not available with 2D interpretation techniques. This offers the seabed engineer the advantages of viewing the foundation design in combination with the 3D seismic data. A disadvantage of this technique is a loss of resolution with the inlines in comparison to the original 2D data recorded with trace separation of 0.66 m. Creating an irregular 4 × 2 m bin size increases resolution in the inline direction. Additional processing techniques for resolution enhancements need further investigation.

Conclusions. Third-generation AUV system upgrades to 4500-m water depths, and technological advances in sensor design will provide engineers the detailed information required for deepwater pipeline and subsea structure design. Implementation of a dynamically focused side-scan sonar system on the next generation AUVs will improve sonar target resolutions at longer ranges. A larger and more powerful subbottom profiling system will increase penetration depth and improve horizon resolution. 3D seismic cubes constructed from closely spaced, high-frequency 2D seismic profiles allow data manipulations not possible with 2D interpretation techniques.

Suggested reading. "Deepwater autonomous vehicle (AUV) logs 25 000 km under the sea" by George et al.(*Sea Technology*, 2003). "High-resolution AUV surveys of the Eastern Sigsbee Escarpment" by George et al. (Offshore Technology Conference *Proceedings*, 2002). "A high-resolution survey AUV" by Northcutt et al. (Offshore Technology Conference *Proceedings*, 2000). "High-resolution geological AUV survey results across a portion of the Eastern Sigsbee Escarpment" by Lee and George (AAPG *Bulletin*, 2004). TLE

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