Subsalt Exploration and Development: Imaging, Interpretation, and Drilling—What have we learned? 2006 SEG/EAGE Summer Research Workshop

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This year's Summer Research Workshop organized by SEG and EAGE under the title "Subsalt Exploration and Development: Imaging, Interpretation, and Drilling—What have we learned?" took place on 10–14 July 2006 in Snowbird, Utah, USA. The workshop was attended by approximately 150 geophysicists and geologists representing the whole spectrum of oil and gas companies, geophysical contractors, and academia. The workshop featured many presentations highlighting the current state-of-the-art in subsalt exploration. The large majority of the presentations focused on the use of surface seismic data to guide subsalt exploration and development. However, there were significant contributions that discussed the role of geology, geomechanics, and borehole data in constraining model building under salt bodies characterized by complex geometries (Figure 1).

The workshop organizing committee consisted of representatives from both the industry and academia and included Biondo Biondi (Stanford University), chairman; Henri Calandra (Total); Richard Cook (Shell); Colin Sayers (Schlumberger); Bob Tatham (University of Texas, Austin); Cung Vu (Chevron); and David Wilkinson (Chevron).

This year's workshop followed the successful "Workshop on Subsalt Imaging Problems: Practical problems seeking solutions" at the Colorado School of Mines in 2005. The CSM workshop focused exclusively on imaging problems facing subsalt exploration. The 2006 SEG/EAGE Summer Research Workshop covered a broader spectrum of issues, starting from data acquisition and ending with interpretation. It split its attention between highlighting problems and demonstrating new technology developed over recent years. In particular, many presentations at the workshop emphasized recent developments such as wide-azimuth and rich-azimuth marine acquisition, which provide new opportunities for subsalt imaging effectiveness, as well as challenges posed by larger volumes of unconventional data. Because of the workshop's success and the rapid progress of subsalt technology, at the end of the workshop the attendees voted almost unanimously to recommend that SEG support a subsalt workshop every two years.

The workshop presentations were divided into several sections addressing the main topics of interest for geoscientists involved in research and development for subsalt regions. See Table 1 for a list of speakers and their topics. Following a set of keynote addresses, the workshop addressed developments in wide-azimuth acquisition, imaging and interpretation, velocity estimation, and geologic model building.



(a) Biondo Biondi receiving an SEG Diploma of Appreciation from Arthur Cheng, chairman of the SEG Research Committee. (b) Bee Bednar (center) explaining the details of SEAM (SEG Advanced Modeling Project) to Paul Singer (right) and Ng Patrick (left). (c) From left to right, chairman Biondo Biondi with keynote speakers John Etgen, Anne Reeckmann, Jeb Blackwell, Fred Hoffman, and organizing committee member Cung Vu.

Subsalt exploration and production—keynote talks. The workshop opened with four keynote addresses given by representatives of oil and gas companies. Those addresses set the tone for the entire meeting by outlining many challenges and achievements of today's subsalt imaging.

Speakers emphasized the importance played by subsalt regions due to their large hydrocarbon potential coupled with high exploration and production risk. There are still very large opportunities for further exploration and production in the deep Gulf of Mexico subsalt play and in other subsalt basins around the world. However, the costs of drilling and development in the deep subsalt play are very high. A typical field developed subsalt can have net costs of many billions of dollars, especially if subsalt development occurs in deepwater. New technologies for acquisition, processing, and interpretation are being developed to overcome imaging difficulties subsalt. In addition, computer hardware improvements make processing and storage of large volumes of data affordable, thus enabling new approaches to acquisition and processing.

Recent advances in *acquisition* technology include wide-azimuth acquisition in marine environments, either using towed-cables or receivers installed on the ocean floor. Speakers emphasized that wide-azimuth acquisition includes acquisition of long-offset data. The combination of wide-azimuth/long-offset acquisition improves subsalt illumination and offers the potential for accuracy unachievable through com-

Table 1. *Speakers and presentations at the Summer Research Workshop.*

Subsalt exploration and production keynote talks	
Jeb Blackwell (Chevron)	The global scope of opportunities and challenges of subsalt exploration
Anne Reeckmann (ExxonMobil)	The role of a regional geologic framework for subsalt exploration
Fred Hoffman (Shell)	The role of geophysics in appraisal and development of subsalt discoveries
John Etgen (BP)	Innovative geophysical technology for meeting subsalt exploration
Wide-azimuth acquisition and imaging presentations	
King Sim Lee (Chevron)	High-quality 3D seismic data for subsalt field development in deepwater Gulf of Mexico
Richard Cook (Shell)	Wide-azimuth imaging in the SEG/EAGE salt model—multiples and shadows
Mark Willis (MIT)	Advances in imaging sediments beneath salt domes—VSP seismic interferometry and reverse-time depth migration
Gerard Beaudoin (BP)	Driving the design evolution of deepwater, wide-azimuth OBS node seismic survey for subsalt imaging
Carl Regone (BP)	A modeling approach to wide-azimuth design for subsalt imaging
Mike Howard (BHP Billiton)	Rich azimuth seismic using surface streamers
Jerry Kapoor (WesternGeco)	The challenge of rich azimuth (RAZ)—a processing opportunity
Scott Michell (BP)	Wide-azimuth imaging of a towed-streamer survey at Mad Dog and an OBS survey at Atlantis
Advanced imaging and interpretation presentations	
Carl Helsing (ExxonMobil)	A new approach to seismic interpretation in challenging imaging environments
Jennifer Lewis (Chevron)	The potential of mode-converted waves in salt interpretation
Antoine Guitton (Stanford University)	Illumination compensation with a robust imaging condition
Rob Wervelman (Shell)	Central North Sea subsalt imaging: Kirchhoff multivalued prestack depth migration
Robert Bloor (GXT Technology)	Subsalt imaging in VTI media with common-shot reverse-time migration
Antoine Guitton (Stanford University)	Attenuating imaging artifacts in reverse-time migration
Mike Thorton (Veritas DGC)	Imaging complex salt bodies with turning-wave one-way equation
Guojian Shan (Stanford University)	Imaging a complex salt body by plane-wave migration in tilted coordinates
Subsalt velocity presentations	
Junru Jiao (PGS)	An improved methodology for subsalt velocity analysis
Bin Wang (CGG)	Subsalt velocity model building using wave-equation-based imaging and modeling
Luc Ikelle (Texas A&M University)	Scattering diagrams in seismic imaging: an integration of velocity estimation and migration
Dan Ebrom (BP)	Kinematic V_P/V_S from Lockhead VSPs
Martin Albertin (BP)	Effective stress modeling techniques for estimating subsalt velocities
Colin Sayers (Schlumberger)	Subsalt geomechanics and pore-pressure prediction
Arthur Cheng (Cambridge GeoSciences)	LWD acoustics: what are we measuring?
Geologic and velocity model building presentations	
Greg Jorgensen (Bell Geospace)	Simultaneous 3D inversion of gravity, magnetic, and tensor gravity fields for imaging salt formations in the deepwater Gulf of Mexico
Scott Kraig (ConocoPhilips)	Salt model construction—a simple technique to preserve vertical edges on salt overhang
Jesse Lomask (Stanford University)	Parallel implementation of image segmentation for tracking 3D salt boundaries
Yves Le Stunff (Total)	Interpretation-based velocity model update taking advantage of fast wave-equation-migration algorithms
Dimitri Bevc (3DGeo Development)	3D tomography with automatic volume-based picking for subsalt imaging
Susan Lock-Williams (Veritas DGC)	Velocity model building through interactive interpretation
Steve Whitney (ConocoPhilips)	TI prestack depth migration—a practical approach for large areas

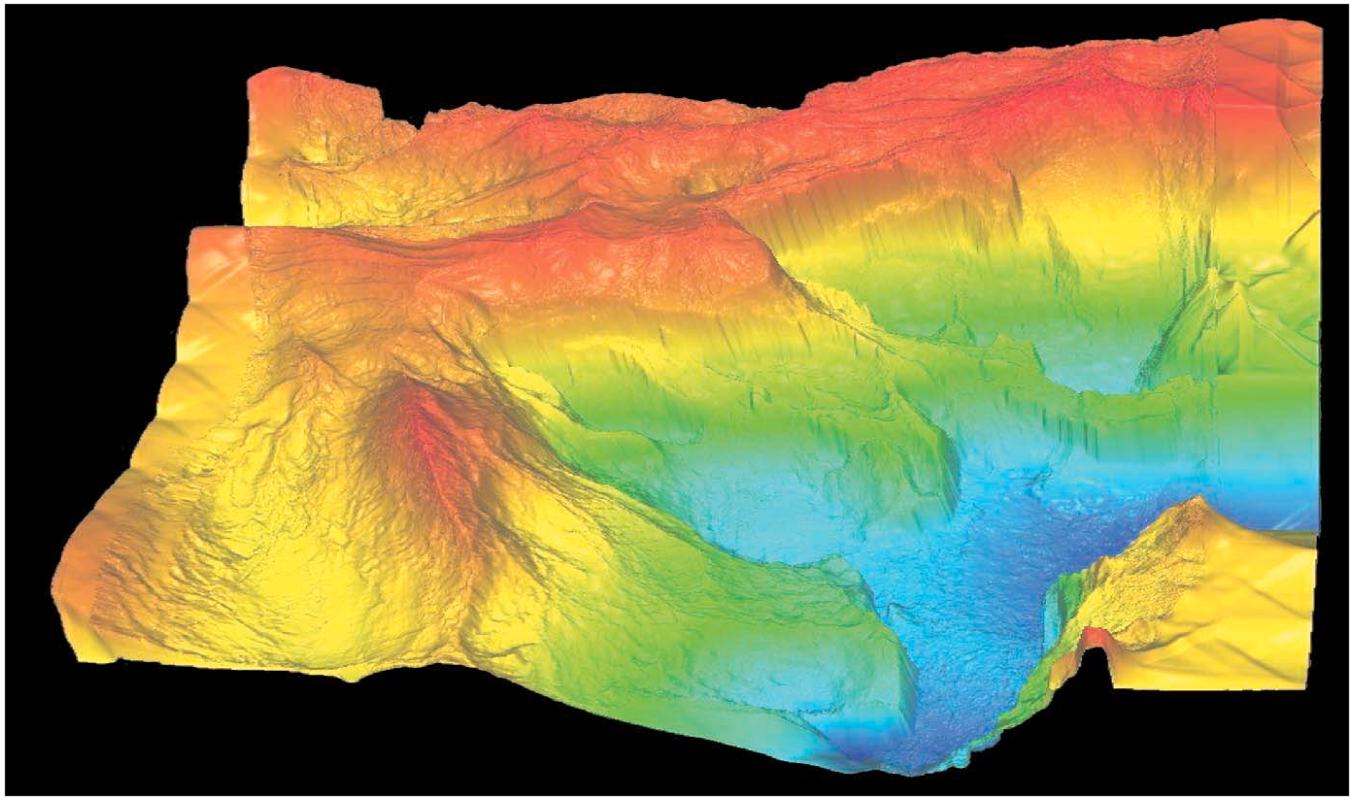


Figure 1. *Representation of a salt body along the Sigsbee escarpment. Depths below mud line range from just below the water bottom (red) to about 27 000 ft (dark blue). The rugged salt creates imaging challenges (Image courtesy of BP).*

plex processing of conventional narrow-azimuth data (Figure 2). In addition to wide-azimuth acquisition, other developments like over-under cable acquisition offer the prospect of noise reduction and increased bandwidth of seismic data.

Seismic data *processing* is also changing in sync with the changes in seismic acquisition technology. All keynote speakers emphasized that wave-equation-based algorithms correctly representing subsalt multipathing are essential for accurate imaging. This observation holds true for surface or ocean bottom data, but also for VSP or crosswell data. Virtual-source technology is also demonstrating potential for imaging of subsalt regions that are not illuminated from the surface. Multiple suppression involving 3D SRME technology is also progressing in synchronization with wide-azimuth acquisition technology, because fewer approximations are needed to generate data consistent with the SRME processing model.

Model building remains one of the biggest challenges of subsalt imaging. Geologic constraints are essential for constructing models that accurately represent subsalt geology. This observation is particularly true in relation to subsalt overpressure regions, because such information is often poorly constrained by surface seismic data. Another aspect of model building repeatedly emphasized by the speakers refers to anisotropy which can make a big difference in lateral positioning of important subsalt geologic features.

Seismic *interpretation* also poses challenges and opportunities subsalt. Among the technologies discussed in the keynote addresses, speakers emphasized the need for 3D interpretation tools (multiple volumes and integrated workflows), integrated interpretation of geology and geophysics, and large-scale basin modeling with emphasis of geomechanical rock characterization which provides bounds on material properties consistent with seismic data.

There were also discussions during the keynote session on the importance of a fundamentals-based regional framework to provide context for making predictions based on limited data, to deal with inherent geologic uncertainty, and to provide a predictive framework for incorporating new infor-

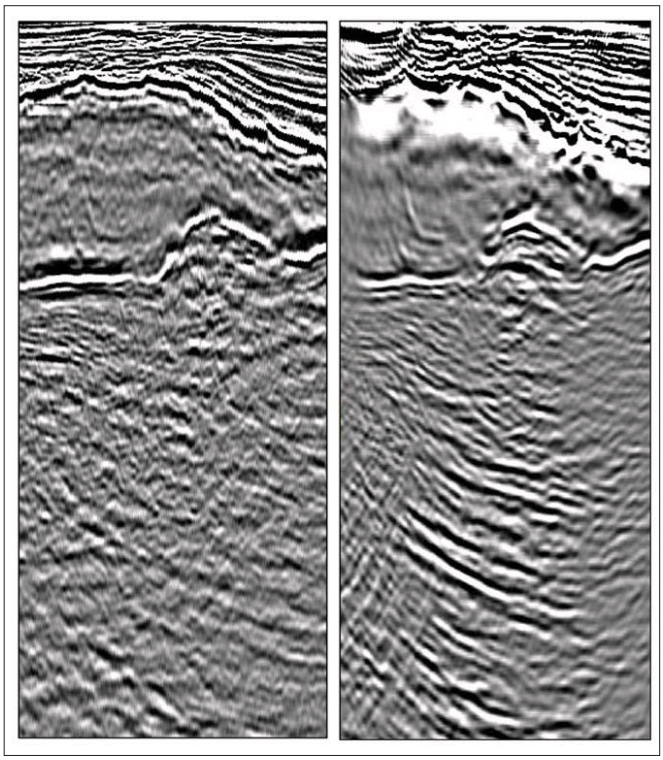


Figure 2. *Images constructed using narrow-azimuth towed-streamer technology (left) and wide-azimuth towed-streamer technology (right). The latter increased image accuracy, coherence, and signal-to-noise ratio (Image courtesy of BP).*

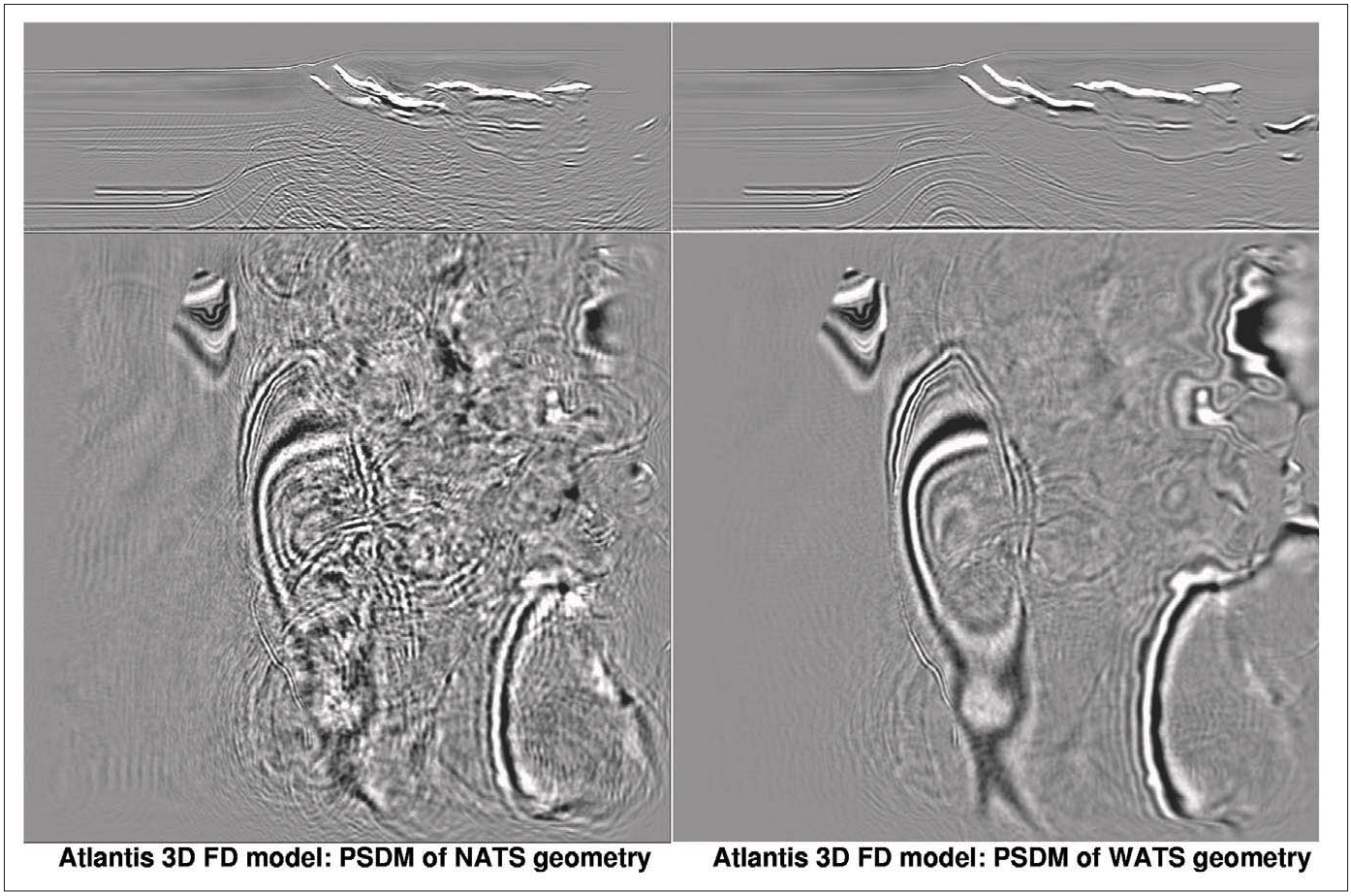


Figure 3. *Atlantis 3D FD synthetic data comparison of PreSDM results for NATS and WATS geometries (Image courtesy of BP).*

mation. Regional geologic scenarios and geophysical techniques play complementary roles in the subsalt exploration process. Improved imaging can assist in the reduction of uncertainty by eliminating geologic scenarios or by providing new ideas while a fundamentals-based regional geologic framework can assist in limiting the nonuniqueness inherent in many geophysical predictions.

Other opportunities suggested in the keynote addresses concern the need for more research focusing on imaging and interpretation at reservoir scale, fast turn-around processing time, and reservoir monitoring. Many technologies required for subsalt imaging are developed and tested in the Gulf of Mexico which, as suggested by one of the speakers, can be regarded as a "global subsalt center of excellence."

Wide-azimuth acquisition and imaging. Presentations in this session demonstrated recent advances in the acquisition technology, with special emphasis on wide-azimuth acquisition. Several speakers contrasted images obtained by state-of-the-art imaging algorithms of narrow-azimuth towed-streamer (NATS) data with same algorithms applied to wide-azimuth towed-streamer (WATS) data (Figure 3). Wide-azimuth data offer the potential for improved illumination, robustness in presence of velocity errors, and higher signal-to-noise ratio in migrated images. It was argued that these improvements originate from the larger data volume that increases signal-to-noise ratio at image locations. In addition, wide-azimuth data are more consistent with 3D geometries because they do not require wavefield truncation along narrow acquisition bands. This session emphasized the importance of 3D finite-difference (FD) modeling as a tool for survey design, imaging, and interpretation. Large-scale studies confirmed the deficiencies of narrow-azimuth towed-streamer surveys and predicted significant improvement in image quality with wide-azimuth methods.

Another acquisition approach emphasized during this session refers to rich-azimuth (RAZ) acquisition technology where data are acquired by multiple passes along different directions, with each pass employing multiple (2–3) boats. (Figure 4). Subsets of RAZ data have wider azimuthal distribution than conventional narrow-azimuth data, but not as a complete set of azimuths as WATS data. Nevertheless, each acquisition direction provides complementary illumination of the subsurface (Figure 5) and overall increases the accuracy of subsalt imaging and interpretation. Speakers concluded that RAZ surveys provide improved illumination in complex subsalt geology, naturally attenuate multiples by stacking larger volumes of data, and improve velocity model building through more accurate imaging.

Alternative wide-azimuth acquisition can be carried out with ocean-bottom seismometers (Figure 6). An illustrative example is the Atlantis OBS node survey design evolved as the result of full 3D FD modeling over the Atlantis Field. It is the largest node survey with 1628 node deployments and recoveries over 247 km^2 in water depths ranging from 1280 to 2180 m. Node seismometer acquisition is characterized by flexible field operations and the possibility of acquiring multicomponent data, although data processing is less mature than the equivalent methodology for towed cable data.

Improved subsalt illumination can also be achieved by integrated analysis of different types of data, including VSP reservoir images, rock properties and AVO analysis, legacy 3D seismic noise analysis for multiples, and long-offset 2D seismic data. Low frequencies recorded in the field data have a critical impact in optimizing subsalt images due to their increased power of penetration subsalt. AVO modeling and

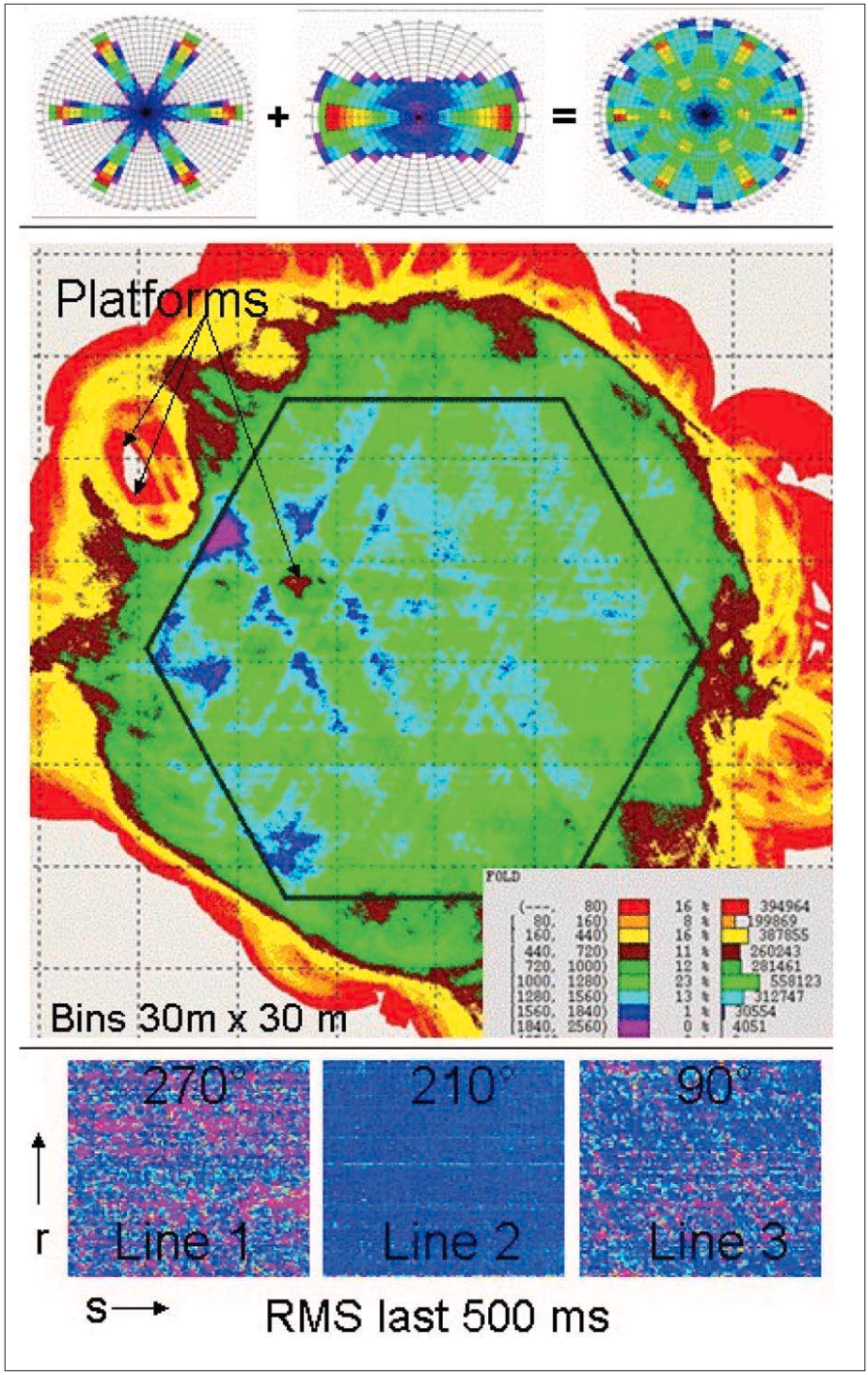


Figure 4. *Rich-azimuth survey designed for the development of the Shenzi discovery in deepwater Gulf of Mexico. The design has three vessels in a wide-azimuth configuration that is sailed in three acquisition directions to give rich-azimuth coverage as illustrated in the top panel. The center panel shows the fold of coverage for the survey. The lower panel shows rms amplitudes from three lines shot in different directions during rough weather. The seas were 4 m during the 270 line and then gradually improved during the line changes and the subsequent two lines at 210 and 90 (Image courtesy of BHP Billiton).*

high subsalt energy achieved using large air-gun arrays enhance subsalt data quality and lead to improved signal-to-noise and larger frequency bandwidth, enabling detailed subsalt fault and stratigraphic delineation (Figure 7).

Advanced imaging and interpretation. Speakers in this session emphasized advances in imaging methodology with implications for subsalt imaging. Among the techniques discussed, reverse time migration (RTM) was demonstrated as an effective methodology that can be used to image steeply dipping reflectors or prismatic waves. Anisotropy can be successfully incorporated in reverse-time imaging leading to better positioning and more accurate representation of reflection amplitudes. Alternative, and potentially more cost effective than RTM, approaches to imaging steeply dipping and overturned reflections are based on anisotropic wavefield extrapolation either in tilted coordinate systems or by two-pass migrations (e.g., downward continuation followed by upward continuation). The imaging condition is also a critical component of migration methodology, especially for reverse-time migration where spurious events are generated by cross-correlation of unrelated events.

This session also emphasized the importance of angle-domain imaging which is characterized by fewer artifacts than the alternative offset-domain imaging. It was pointed out, however, that even in this case, noise related to acquisition truncations and uneven illumination can be present in migrated images, thus hampering AVO interpretation and migration velocity analysis. A possible remedy for this situation comes from using 3D visualization tools to analyze combinations of migrated images. Another observation made during this session is that a large fraction of the seismic energy is transmitted in the subsalt regions as converted shear modes. Such data are usually discarded in seismic processing although they carry significant information about subsalt geologic structures. Proper acquisition and analysis of this complementary type of information can lead to better delineation of salt bottom.

Subsalt velocity. Subsalt velocity estimation remains the most important challenge facing subsalt imaging. This fact was repeatedly emphasized by the speakers in this session who discussed new methodology for subsalt velocity estimation. The limited angular coverage subsalt was cited as the rationale for using velocity scans for estimating accuracy of subsalt images. The difficulties of estimating velocity under salt make particularly important the use of all possible information to determine subsalt velocities, particularly when there is the possibility that overpressured zones are encountered during drilling. Geomechanical models can constrain seismic velocity when information from the data is insufficient. For example, sediment velocities evaluated outside salt and extrapolated subsalt are often too fast

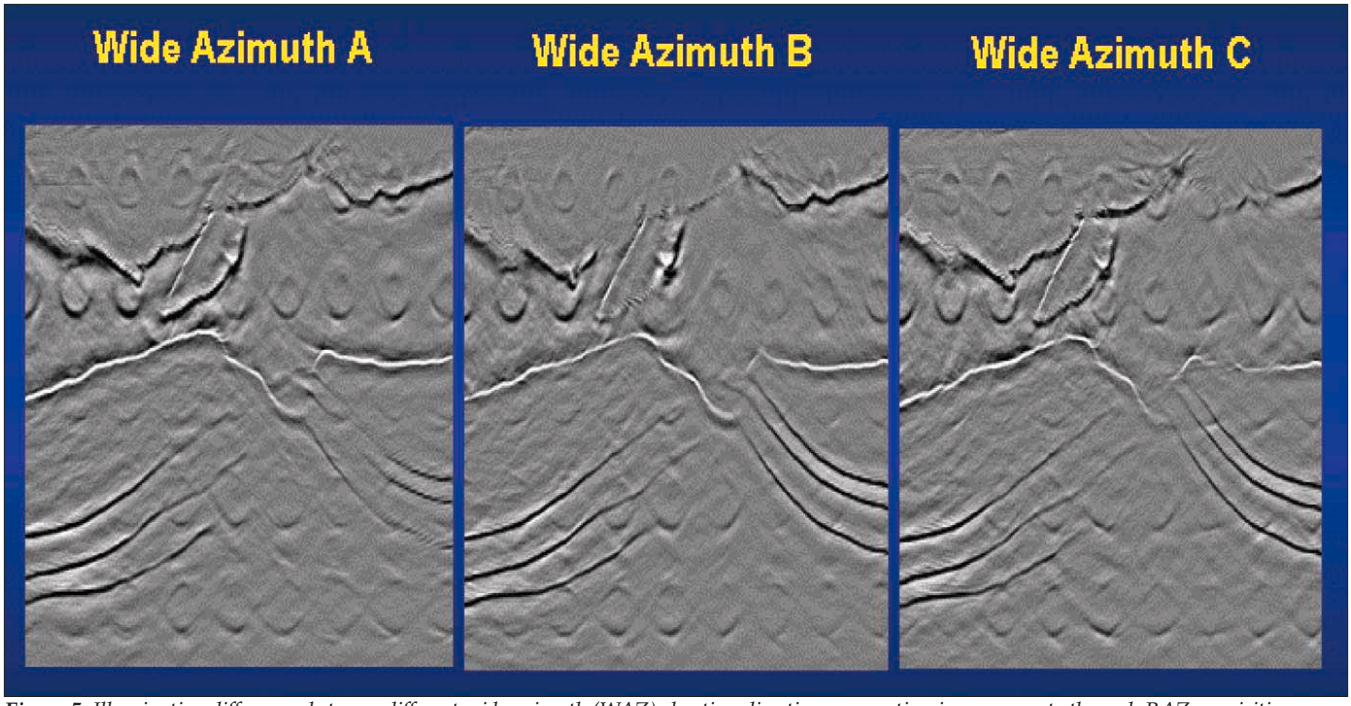


Figure 5. *Illumination differences between different wide-azimuth (WAZ) shooting directions suggesting improvements through RAZ acquisition (Image courtesy of WesternGeco).*

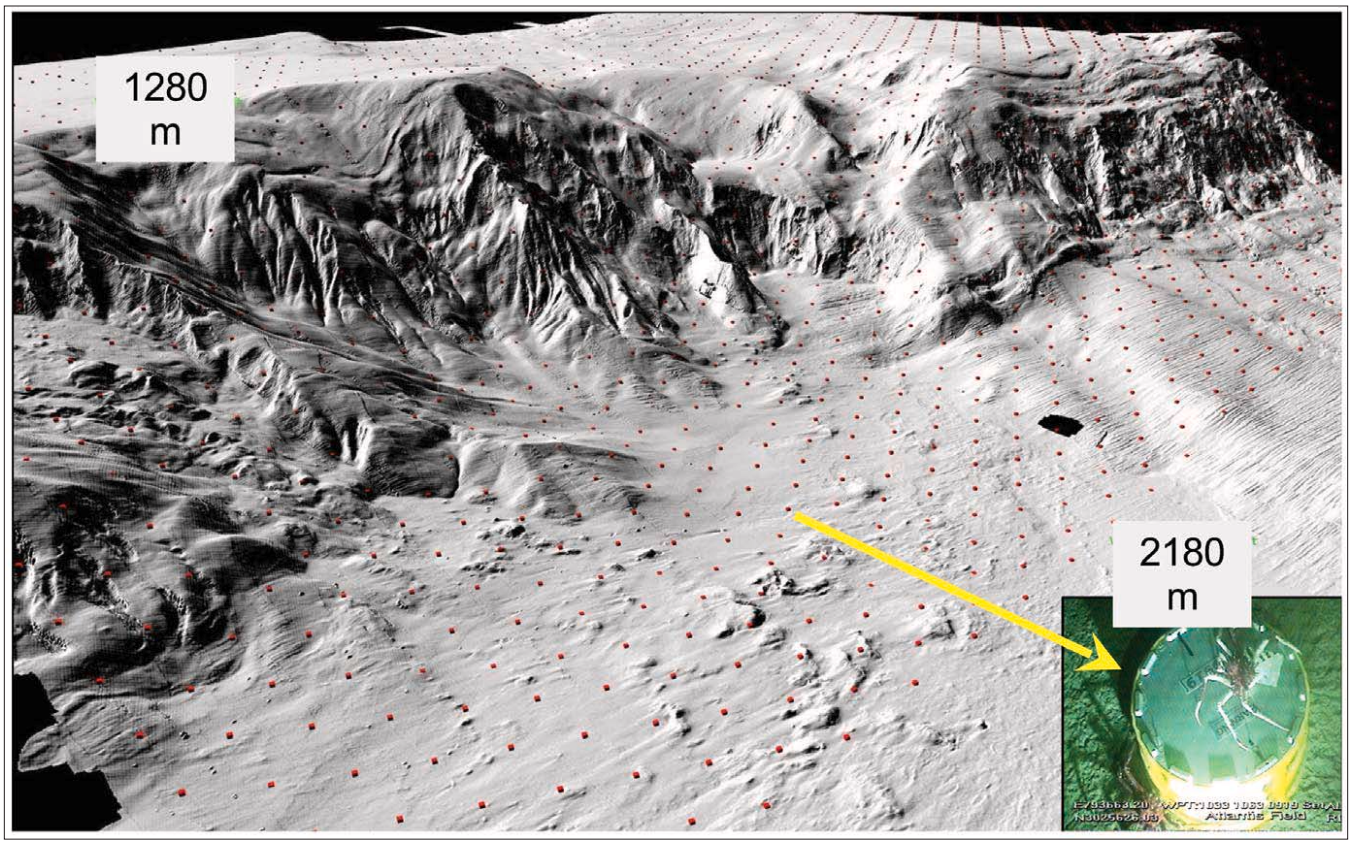


Figure 6. *Shaded relief bathymetry in the Atlantis area with node coverage overlay. Each dot represents an ocean bottom seismometer, pictured in the lower-right overlay. Water depths for the 1628 nodes range from 1280 to 2180 m. Each node was deployed and recovered from the seafloor by remotely operated vehicles (Image courtesy of BP).*

due to the presence of over-pressured fluids. VSP and LWD data also provide crucial information that can be used to detect overpressure zones ahead of the drillbit and avoid dangerous and costly mistakes.

Geologic and velocity model building. The final session of the workshop brought together several presentations on the topic of model building, often in conjunction with interpretation of migrated seismic data. The presentations summarized

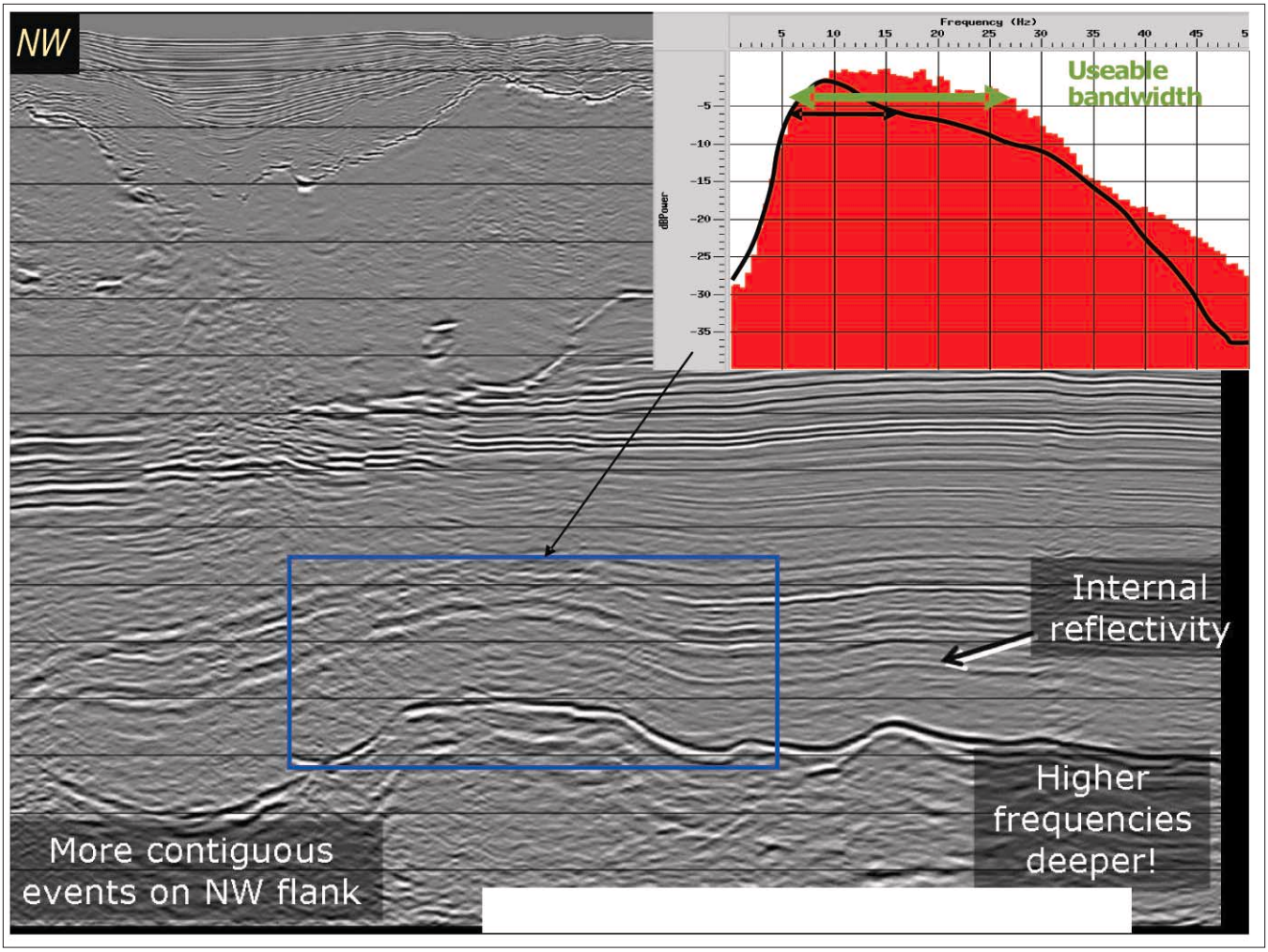


Figure 7. *High signal-to-noise and large frequency bandwidth, due to acquisition with large air-gun arrays, enabling more detailed subsalt fault and stratigraphic delineation. Image courtesy of Chevron (Data courtesy of WesternGeco/Q-Technology).*

conventional and new methodologies exploited in the context of subsalt imaging. Among discussed methods we find fast (re)migration using approximate wave equation or Kirchhoff techniques, conventional salt flooding, traveltime tomography with automatic picks, etc. It was also emphasized that improved interactive interpretation tools are needed in conjunction with velocity model building and imaging. A promising new approach to integrate interpretation with imaging in the model-building process takes advantage of the computational efficiency of new migration algorithms and computers. Several geologic scenarios can be effectively tested and compared with each other by running several migrations and automatically generating quantitative and objective measurement of migration accuracy. Additional constraints on the velocity model come from other geophysical techniques, as illustrated in the workshop by gravity and tensor-gravity techniques.

The workshop was well received by the attendees who expressed an interest in follow-up workshops in the coming years. Students who attended the workshop received travel support through grants from Shell and from the SEG Foundation through a donation from the Colorado School of Mines "Workshop on Subsalt Imaging Problems: Practical problems seeking solutions." More information about the 2006 SEG/EAGE Summer Research Workshop and presentation abstracts can be found online at *http://seg.org/meetings/srw2006*. TLE

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