Coordinated by Linda R. Sternbach

Subsalt success in the Republic of Yemen, using 3-D AVO and integrated exploration

Bill Towner, Vintage Petroleum Inc., Tulsa, Oklahoma, U.S.
Rick Lindsay, Diamond Geoscience Research Corp., Tulsa, Oklahoma, U.S.

The elusive Alif Formation sands are the primary exploration targets within and below a thick Jurassic salt section in Vintage Petroleum's Yemen Block S1 play. These meandering reservoirs, deposited underneath a series of large, laterally varying salt bodies are a difficult stratigraphic target to predict. Their elusive bounty is further complicated by extensional and listric faulting in this 1.1 million-acre wildcat tract. The story behind Vintage's Annaeem-1 well (Figure 1) is instructional because integrating good exploration fundamentals, geochemical analysis, and advanced seismic technologies mitigated risk. The result is a well that flowed hydrocarbons from porous, permeable sands in an area where Alif formation sands were thought to be completely absent.

Figure 1. Flow testing a well is always an awe-inspiring event. Adding to the enjoyment, Annaeem 1 flowed hydrocarbons from porous, permeable sands in an area where Alif sands were long thought not present.

The southernmost reach of the Arabian Peninsula is curiously labeled Rub Al Khali or the "Empty Quarter," an area so unexplored that surface maps are largely blank (Figure 2). The weathered desert floor is topped by sand dunes with relief of 100-200 ft. The mean annual temperature in the area is above 100°F, and rainfall rarely exceeds one inch per decade.

Block S1 roughly is composed of the eastern half of the east-west trending Shabwa-Al Jawf basin. The eastern part of the basin was believed by previous explorationists to be in the distal facies of the prolific Alif sands found productive under Hunt's western concessions. Block S1 area was first explored by a Russian exploration team during the late 1980s while South Yemen was still under Soviet influence.

The Russians shot about 3500 km of 2-D seismic data and drilled four wildcat dry holes. Shell took over Block S1 when the country was unified into a democracy in 1990.

Shell shot approximately 1500 km of 2-D seismic data and combined the data with older 2-D Russian data to form a single, useful data set. Shell also acquired 365 km^2 of 3-D seismic data. Despite this new information, Shell drilled another four dry wildcats.

Drilling efforts in the block prior to Vintage's involvement were primarily on the crest of structures. Most turned out to be salt features. Encouragingly, some shows of oil and gas were noted in the drilling reports. Shell exited the country after the civil disturbance of 1994. Eight exploration wells in total failed to find any significant Alif sand deposition. Four years later TransGlobe Energy studied the block and created a deal with the unified government of Yemen. Vintage joined the project with TransGlobe.

Figure 2. The Block S1 is located in the deserts of the southern-most reach of the Rub Al Khali or "Empty Quarter" as it is curiously named on the big empty maps of the Arabian Peninsula.

Vintage Petroleum believed that a new geologic model and a rigorous, integrated, geoscience analysis would prove the existence of excellent, hydrocarbon-filled reservoir rocks despite the problems of exploring below the seismically hard-to-image salt bodies in the eastern portion of the Shabwa Basin. A sound regional geologic framework combined with 3-D seismic workstation mapping techniques, geochemistry, and advanced seismic analyses were planned to unravel this intriguing geologic puzzle. The analytical strategy would

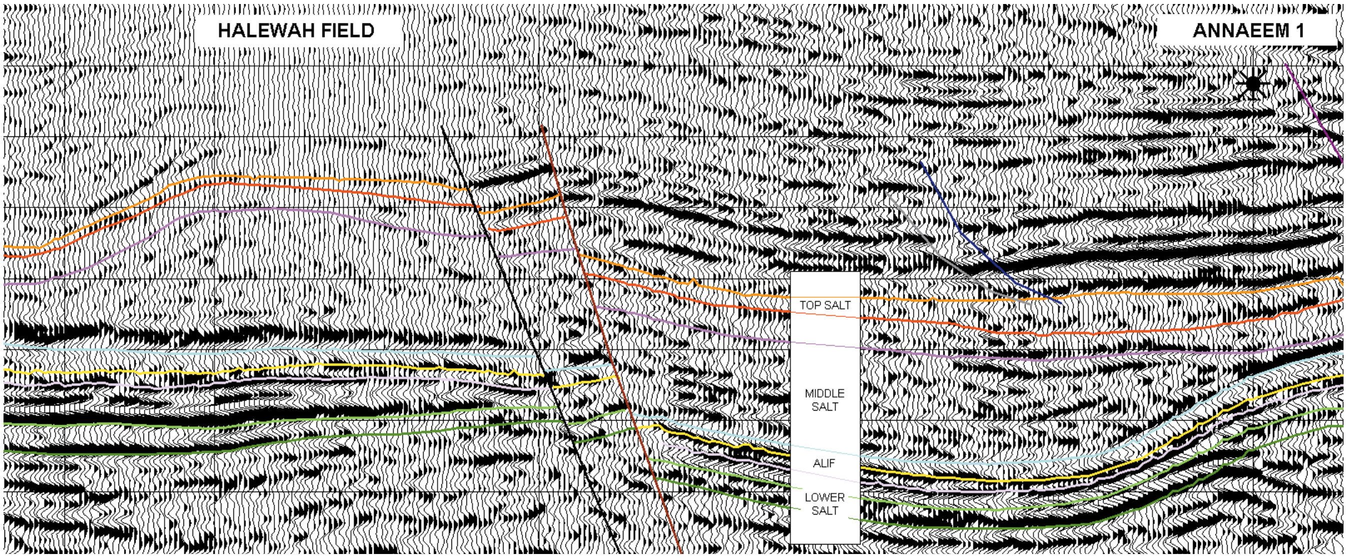

Figure 3. This regional, middle-angle band (15 to 30°) seismic profile ties the three main salts and and Alif Formation from the Halewah field in the west to Vintage's Annaeem 1 well location. Fault interpretations are diagrammatic only.

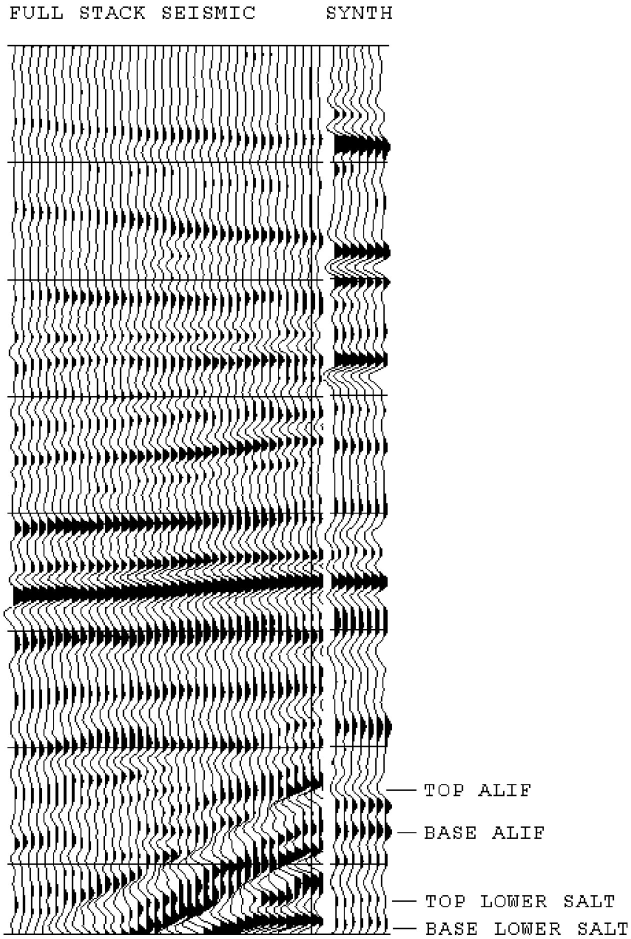

Figure 4. The normal-incidence synthetic seismogram ties the northwest-southeast full stack seismic profile at Annaeem 1.

involve creating rock property and reflectivity models that were used to calibrate and support AVO inversion and the subsequent analysis. State-of-the-art sand-thickness prediction algorithms, using neural networks, were to be used to map gross and net reservoir thickness.

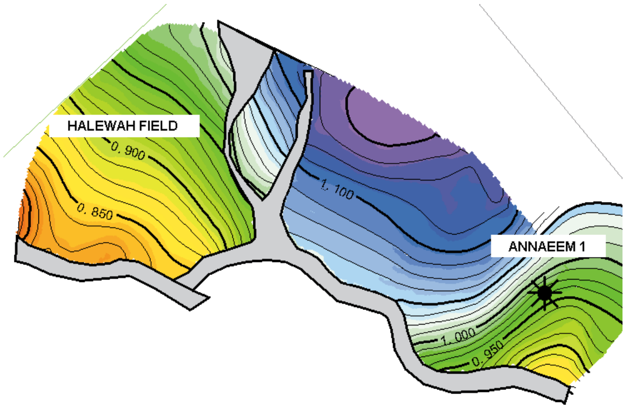

Figure 5. Northeast dip away from the regional high associated with basement rifting is evident on the Top-Alif time-structure map. While the Top Salt remains constant thickness locally, the Middle Salt thins considerably to the southeast, leaving the actual depth structure mildly shallower at Annaeem 1 than is indicated by the time-structure contours.

The first stage of the project was much needed data management. The process began by copying, cataloguing, and transcribing all available data. Subsequently, roughly 5000 km of previously acquired 2-D data was mapped to form the structural framework of the interpretation. Experienced Yemeni geoscientists, Abdulraqeeb Saeed and Ahmed Soleh, who had previously worked the area for the government, Hunt, Shell, and CGG assisted in the interpretation. The team's 2-D interpretations were integrated with the interpretation of Shell's 3-D data to produce a better understanding of the structural grain of the basin. The result was detailed structure maps on key horizons. Depositional models were overlain on the structural interpretations, and leads were outlined.

New data acquisition, processing, and interpretation. Vintage acquired a new 175 km^2 3-D seismic data set to better define key prospects recognized in the initial studies. The 3-D program was extended westward to provide 3-D data over the adjacent Halewah Field. This extension allowed for

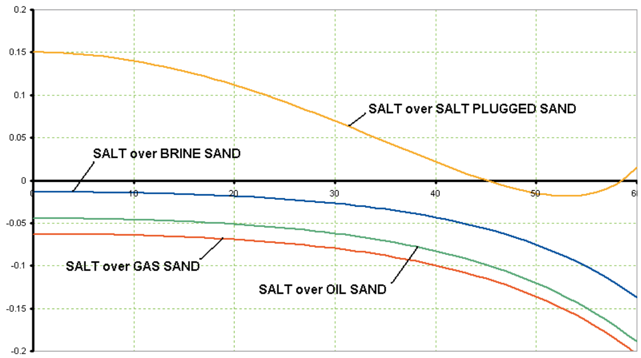

Figure 6. Half-space reflectivity models show the changes in amplitude of various interface reflections as a function of increasing incidence angle.

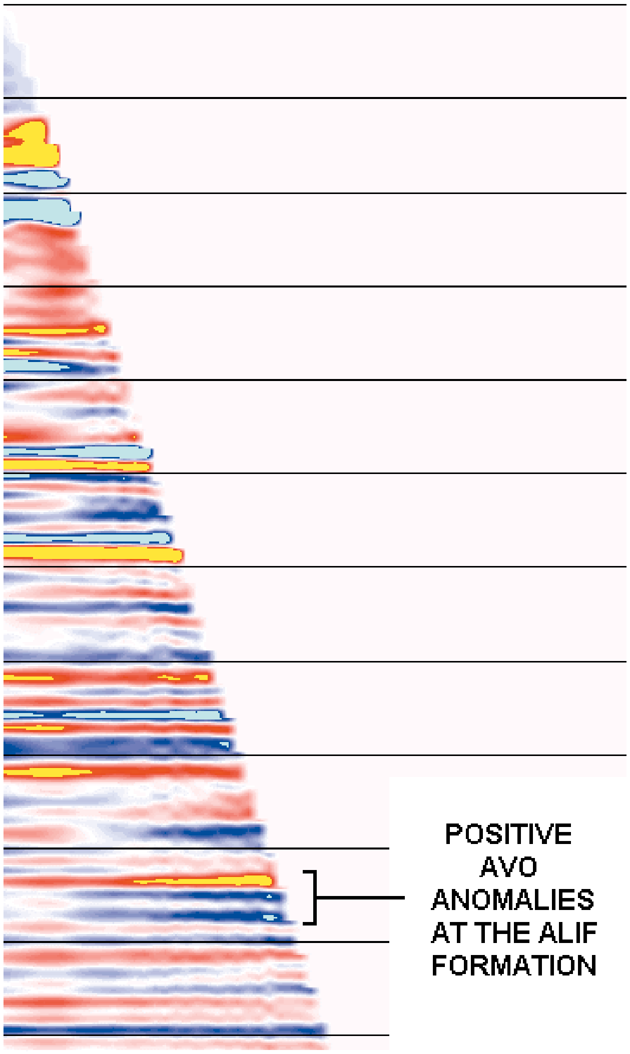

Figure 7. Offset synthetic seismogram.

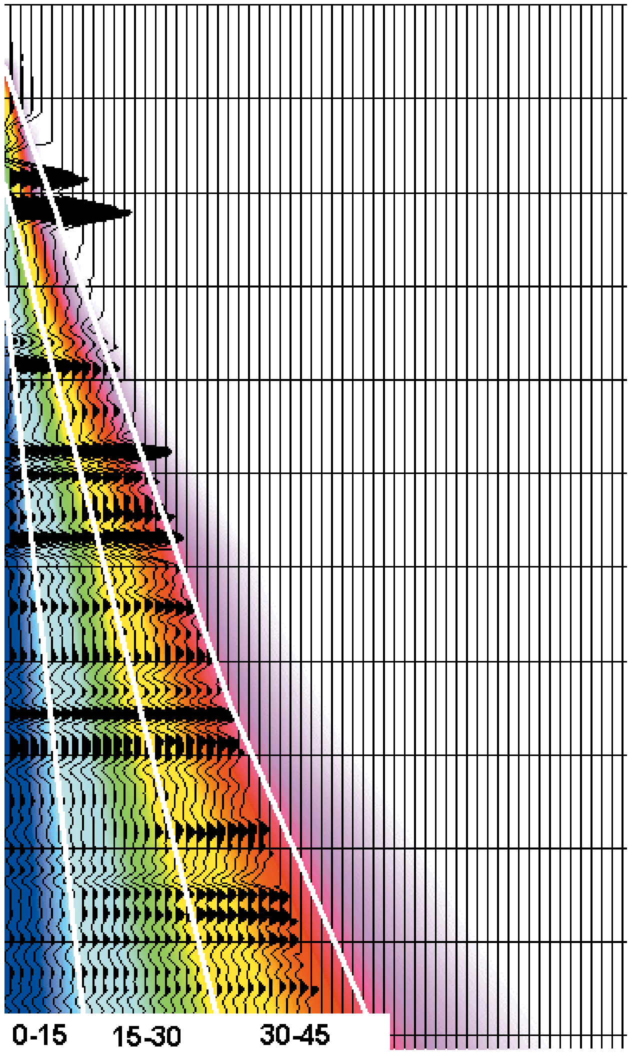

Figure 8. Offset synthetic seismogram superimposed over incidence angles, displayed as a color background, illustrate incidence angles associated with the various seismic events.

the creation of a seismic analog as well as a tie point for rock property and reflectivity modeling studies.

The seismic acquisition was designed to maximize field crew efficiency as well as to obtain the desired fold and long source-receiver offsets necessary for AVO inversion at the primary horizons. Large-scale geochemical reconnaissance was undertaken at the same time as the seismic party was deployed. The goal of this study was to identify significant hydrocarbon anomalies with "fingerprints" similar to those of the western area production. The geochem measurements were acquired as a 1 station per square kilometer grid over the 3-D seismic areas and 1 station per kilometer along key 2-D lines.

Shell and Vintage acquired uphole velocities from a series of shallow shotholes during their respective 3-D acquisitions. A static model was applied to the new Vintage 3-D data to compensate for the sand dunes and weathered layers present in that area. Shell's 3-D seismic data set was reprocessed to incorporate the new static model of the dune elevations. Significant static shifts were found between the reprocessed Shell data and the original effort. Subsequent ties between synthetic seismograms and the 3-D seismic data set verified the improvements in the seismic data.

Figure 4 shows the normal-incidence synthetic seismogram tie with the northwest-southeast full stack seismic profile at Annaeem 1. The top and base of the Lower Salt are picked immediately below the Lam shales that lie below and source the Alif. The top of the Alif Formation sands ties the seismic trace data set at the bottom of the trough created by the contrast between the base of the Middle Salt and the top of the Alif sands. The base of the Alif Formation sands ties

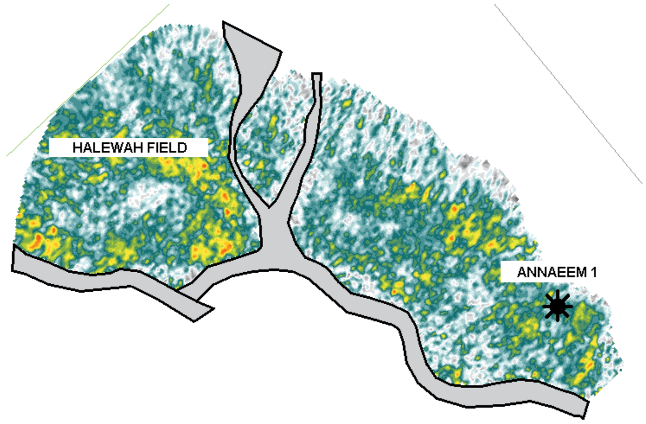

Figure 9. Seismic amplitude measurements across Alif Formation are mild, at best, in amplitude in this middle incidence-angle data set.

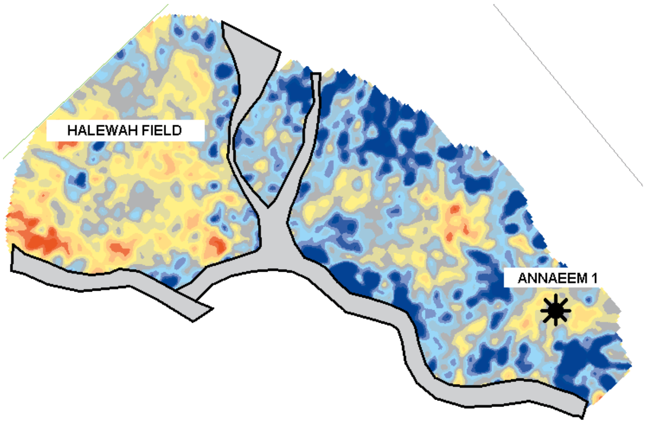

Figure 10. The AVO Strength Map is interpreted to indicate positive (warm color) anomalies associated with gaseous hydrocarbons. A slight roll off in magnitude is associated with oil-filled sands. The polarity of the AVO Strength Map switches to negative (cool colors) downdip in nonproductive salt-plugged sands.

the seismic trace near the center of the lower lobe of a peak-doublet roughly 32 ms below (at the Annaeem 1 well) the trough representing the top of the Alif interval.

Northeast dip away from the regional high associated with basement rifting was evident on the top-Alif time-structure map (Figure 5). While the Top Salt formation remains of constant thickness locally, the Middle Salt thins considerably to the southeast leaving the actual depth structure mildly shallower at Annaeem 1 than is implied by the time-structure contours.

After final structural interpretation of the 2-D and 3-D data, migrated full-stack raw amplitude values were studied as to how they might correlate with regional sand maps, the new structural understanding, and salt geometry.

The leads that Vintage decided to pursue were limited to those with the same key petroleum system elements that were found productive in the west half of the basin. Stratigraphic issues replaced structural highs as key lead factors. The geologic model required that the objective Alif reservoirs, to be charged, must be in contact with the primary source rock, the Lam Shale, and be sealed by the overlying salts and/or bounded by salt-filled listric faults.

Modeling and technical analysis. To better understand mapped amplitude anomalies, a series of rock property and

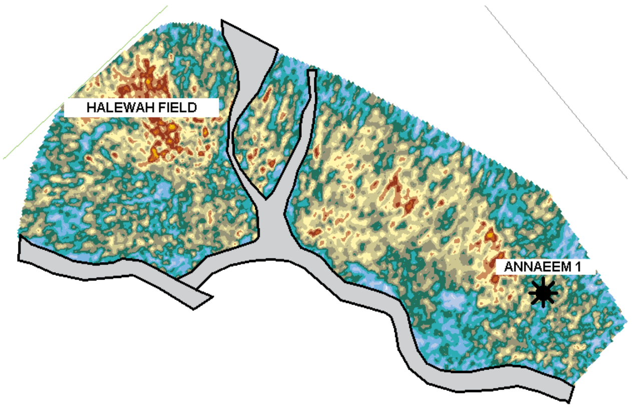

Figure 11. The Gross Reservoir Interval map shows thick sands in the Halewah as well as in Annaeem 1. This is the area where earlier geologic models indicated that no sands would be present.

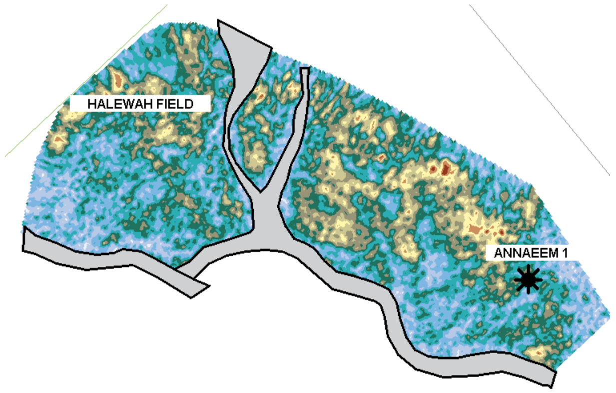

Figure 12. The Net Reservoir Sand map shows higher levels of net sand in Annaeem 1 than in Halewah Field. This map indicates the "character" of the sands more so than the actual net thickness. Alif sands found in Annaeem 1 are "cleaner" and less interbedded than Alif sands in Halewah Field. The Net Reservoir Sand map illustrates this improvement in reservoir quality.

reflectivity models were designed based upon in situ bulk density and compressional and shear wave velocities from open hole logs. A rock properties database that included wells that logged shale, gas, oil, and brine filled sand as well as sands with salt-filled porosity, was generated. Models were then designed using various fluid and porosity combinations that might be encountered pre-drill in the Alif Formation.

Amplitude-versus-angle models were generated for all likely lithology interfaces and pore fluid contrasts (Figure 5). Half-space reflectivity models show the changes in amplitude of various interface reflections as a function of increasing incidence angle. Salt over hydrocarbon-filled sands produced positive (slope) AVO curves with gas sands producing slightly stronger normal incidence reflections. Salt over salt-plugged sand, a likely downdip lithology to be encountered, produced strong normal incidence amplitude and negative AVO slope. A salt over porous brine-sand curve was included for completeness but was not expected to be a viable case as all instances of brine-filling have resulted in precipitation of salt into the pore spaces.

Offset synthetic seismograms (synthetic CMP gathers) furthered the understanding of the AVO response in the laminated Alif reservoir sands. The offset synthetic seismogram displayed in color for greater visual dynamic range, best showed the increase in amplitude with respect to seismic source-receiver offset, of Alif formation reflections (Figure 6). Another offset synthetic seismogram superimposed over incidence angles displayed as a color background, identified incidence angles associated with the various seismic events. The maximum incidence angles at the Alif Formation reached 45°. The traces representing these incidence angles overlay the red portion of the background in Figure 7. This display was used to transform and compare AVA models to AVO seismic measurements.

Vintage's 3-D seismic and portions of Shell's 3-D seismic were reprocessed at incremental incidence angle bands (0-15, 15-30, and 30-45°) and 3-D time migrated. The migrated angle stacks were then filtered and scaled deterministically based upon the rock property and reflectivity models. Amplitudes were extracted at the top and base of the Alif interval as well as at an inter-Alif seismic marker.

Seismic amplitude measurements across Alif Formation were mild, at best, in amplitude in the middle incidence-angle data set (Figure 8). The oblique incidence angle rays produced the AVO anomalies associated with porous hydrocarbon-filled Alif sand. In the Halewah Field, amplitudes in the oil-filled sands were slightly dimmer than in the gas cap. Discrimination based upon amplitude alone was problematic. However, mild reductions in amplitude were observed concordant with structure at the gas-oil contact.

The AVO Strength map (Figure 9) had a positive, warm color when anomalies were associated with gas hydrocarbons. A slight roll off in AVO magnitude was associated with oil-filled sands. The polarity of the AVO Strength map switched to negative (cool colors) downdip in nonproductive salt-plugged sands. Variations in AVO measurements were less ambiguous than amplitude measurements alone and further agreed with the fluid state change.

Diamond Research used its processing and mapping techniques to invert the seismic trace and velocity information into mapped values of reservoir thickness. Gross and net sand maps were produced and calibrated to the thicknesses found in Halewah Field. The Gross Reservoir Interval map (Figure 10) showed thick sands in the Halewah Field as well as at Annaeem 1. The Net Reservoir Sand map (Figure 11) showed higher levels of net sand in Annaeem 1 than in Halewah Field. The net map indicates the "character" of the sands more so than the actual net thickness. Recall this is the area where earlier geologic models indicated that no sands would be present.

Diamond's 3-D pore pressure prediction algorithm, developed in Gulf of Mexico subsalt studies, was recalibrated for the Yemen Block S1 environment and used to create a 3-D pore pressure data set. Structural horizons at the Alif reservoir interval were used to extract values and create reasonably precise pore pressure maps (Figure 12). The pore pressure maps showed variation in pore pressure from fault block-to-fault block and laterally within the Halewah Field. This phenomenon was observed in the pressure measurements taken in various wells within Halewah Field. Pore pressure predictions were used to improve the precision of rock property and reflectivity models as well as to provide a loose guide to well design.

Drilling results and conclusions. Vintage committed with the Yemen government to drill three wildcat tests in Block S1 during the first exploration phase. The first well, Annaeem 1, was drilled earlier this year. Pre-drill geophysical prognosis predicted that porous, hydrocarbon-filled Alif sands would be encountered at 1300 m. The predicted thickness from the gross sand map was 32 m at the chosen well location.

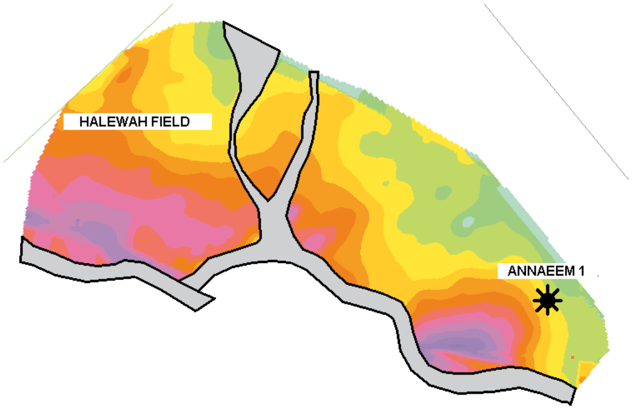

Figure 13. The pore pressure (gradient) map shows variation in pore pressure laterally. Pore pressure variation is indicated by changes in color.

The actual top of the Alif sand in Annaeem 1 was 1298 meters below which 34 meters of porous and hydrocarbon-filled sand was measured (Figure 13). Alif sands that were found in Annaeem 1 were "cleaner" and less interbedded than Alif sands in Halewah Field. The Net Reservoir Sand map illustrated this improvement in reservoir quality.

As is the case with most exploration projects, the data gathering/ manipulation/study leading up to the final decisions represents a great portion of the effort. By definition, then, a lot of time and work goes into these ideas before we get to have the fun of contouring and picking a location. However, we can reduce our risks by integrating good exploration fundamentals, related geoscience technologies such as geochemical analysis, and advanced seismic technologies. E

Acknowledgments: The authors thank Vintage Petroleum, Diamond Geoscience Research, TransGlobe Energy, The Yemen Oil and Gas Company, and Rasheed S. Baraba and the Ministry of Oil and Mineral Resources for the Republic of Yemen for permission to present this paper.

Corresponding author: R. Lindsay, ROLindsay@aol.com