Sendji Formation reservoir delineation based on 2-D and 3-D inversion, Yombo Field, offshore Congo

JOHN VAN HORN, CMS Energy, Houston, Texas, U.S.

Seven fields with prolific Sendji Formation production have been discovered offshore Congo. These fields have ultimate recoveries of 100 million b/o or greater. Only the shallow waters (less than 200 m) of the play have been adequately explored. The inability to predict the amount of economically recoverable oil after initial discovery and delineation is a major production challenge. The Sendji Reservoir is a complex sequence of limestones, dolomites, and sandstones deposited as several distinct facies. These facies vary both laterally and vertically, and have vastly different reservoir characteristics. Predicting the configuration of these facies is the key to predicting reservoir performance and calculating the amount of oil that is economically recoverable. Predicting intra-Sendji facies distribution is a significant challenge to optimizing development drilling.

The largest oil field in the Congo is one example of this production challenge. N'Kossa Field, discovered by Elf in 1984, was estimated to have 900 million barrels of oil and condensate in place. Initial delineation drilling and testing supported a recovery factor assumption of 47%, meaning more than 400 million barrels could be economically produced. Yet N'Kossa has significantly underperformed and will probably produce only 300 million barrels, or 33% recovery. This shortfall is due to reservoir heterogeneity revealed only after producing several development wells.

CMS Oil and Gas operates Yombo Field within the Marine I Exploitation block, which is in the Lower Congo basin offshore the Republic of Congo (Figure 1). Sendji reservoir heterogeneity is experienced in Yombo Field. Amoco discovered Yombo in 1988. Five initial wells were drilled to delineate the field. Commercial pay was discovered in both the Cretaceous Cenomanian-age Tchala Formation and the Albian-age Sendji Formation. Yombo currently produces about 16 000 b/d. Production

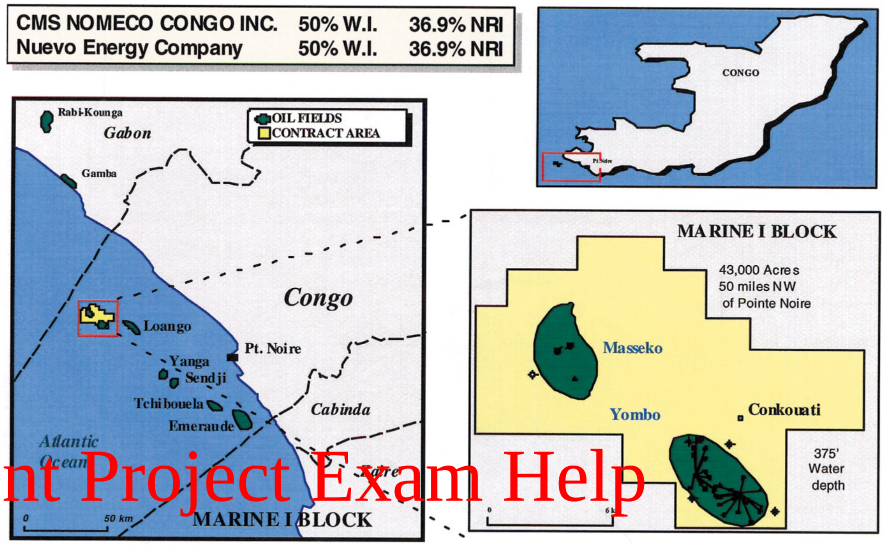


Figure 1. Yombo Field lies within the Marine I Exploitation block in the Lower Congo basin, offshore the Republic of Congo. Commercial pay was discovered in both the Cretaceous Cenomanian-age Tchala Formation and the Albian-age Sendji Formation. Yombo currently produces 16 000 b/d on average.

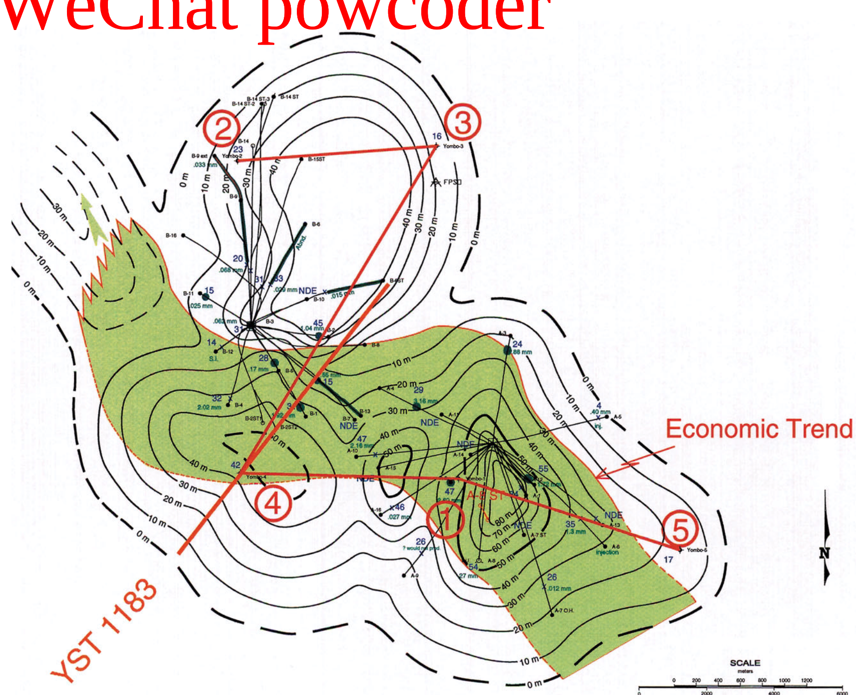


Figure 2. The Upper Sendji 1 reservoir net oil isopach demonstrates a large volume of oil in place in Yombo Field. A large portion of the field produces at a rate well below 500 b/d. The region of economic production is restricted to an elongate trend (green).

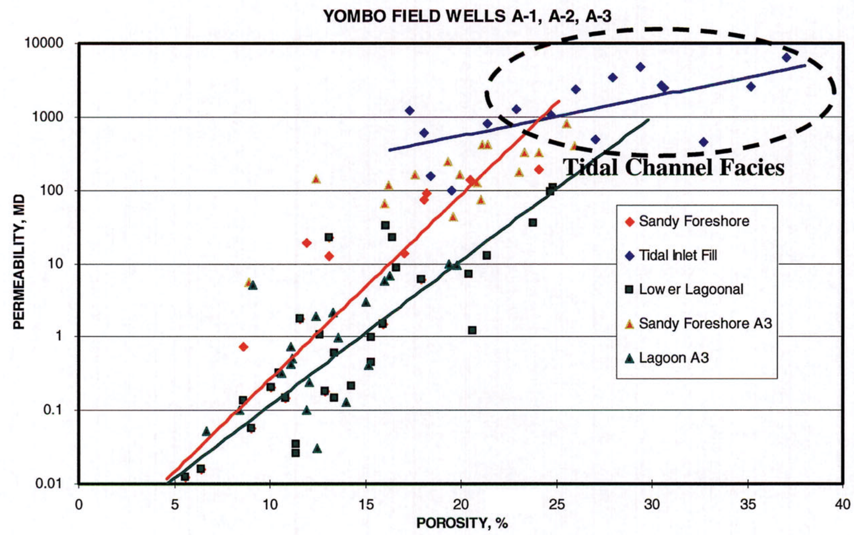


Figure 3. The Upper Sendji 1 porosity-permeability crossplot illustrates that the best reservoir permeability and best porosity lie in the stacked tidal channel facies.

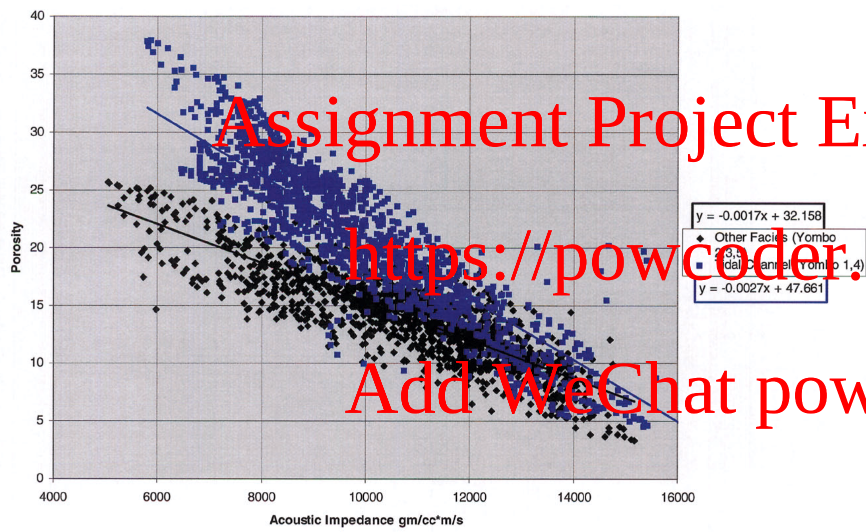


Figure 4. Porosity versus acoustic impedance within the Upper Sendji was crossplotted for the five delineation wells. Note the strong linear relationship between increasing porosity and decreasing acoustic impedance.

is almost evenly split between the two formations.

The Upper Sendji 1 reservoir net oil isopach map (Figure 2) illustrates the large volume of oil in place for the field. The five initial delineation wells are highlighted on the isopach map. A large portion of the field produces at the low rate of less than 500 b/d. The region of economic production—more than 600 b/d—is restricted to an elongate trend (green in Figure 2). Conventional core description and analysis show that this economic trend is confined to a limited facies of stacked tidal channels. Channels are predominantly porous, permeable quartz sandstone with varying amounts of dolomite as grains and cement. The uneconomic area to the north is dominated by tidal flat and lagoon facies. The area to the south is dominated by open marine facies. The tidal flat, lagoon, and open marine facies have poor reservoir characteristics, low permeability, and porosity.

Seismic inversion method to delineate economically productive facies. A seismic inversion method was recommended to accurately delineate the extent and distribution of the economically productive facies. If effective, seismic inversion was proposed to evaluate other Sendji Formation exploitation opportunities within the lease block. A stepwise approach allowed management to gain confidence in the technique before committing significant resources where the main expense is reprocessing the 3-D seismic volume. Given success, this method is cost-effective because inversion and interpretation can be completed in-house with commercially available software.

The stepwise approach employed the following sequence: (1) attribute cross-plotting and stratigraphic modeling; (2) inversion of current 3-D data; (3) analysis and review of results; (4) 2-D test reprocessing of selected 3-D sail lines and 2-D inversion; (5) analysis and review of results; (6) 3-D reprocessing of entire volume and inversion of volume; and (7) facies delineation using final inversion volume.

Attribute crossplotting and stratigraphic modeling. Amoco cored the Upper Sendji Formation in the field's first development and delineation wells. Core analysis has been vital to understanding the facies present and in developing a depositional model. We now understand that different facies have very different reservoir properties.

Core analysis clearly shows that permeability is facies dependent. Figure 3 illustrates that the best reservoir permeability and best porosity lie in the stacked tidal channel facies. This relationship suggests that seismic attributes would be appropriate in mapping the tidal channel facies. The technique of using acoustic impedance inversion on a 3-D seismic data set to delineate zones of relatively high porosity is well established. Inversion should theoretically be effective in detecting high-porosity, high-permeability tidal channel facies on seismic.

Porosity versus acoustic impedance within the Upper Sendji was crossplotted for the five delineation wells (Figure 4). A strong linear relationship exists between increasing porosity and decreasing acoustic impedance. Core analysis demonstrates that Yombo 1 and 4 wells penetrated the stacked tidal channel facies. Upper Sendji Formation in Yombo 2, 3, and 5 is dominated by less permeable and less porous facies. Within the good tidal channel facies, porosity varies from 18% to 35% at the low acoustic impedance range (6000-8000 gm/m^3/s). Outside the tidal channel facies, porosity is 15-25% at a low acoustic impedance range.

A well-log cross-section (Figure 5) using the five delineation wells was flattened on the Top of Upper

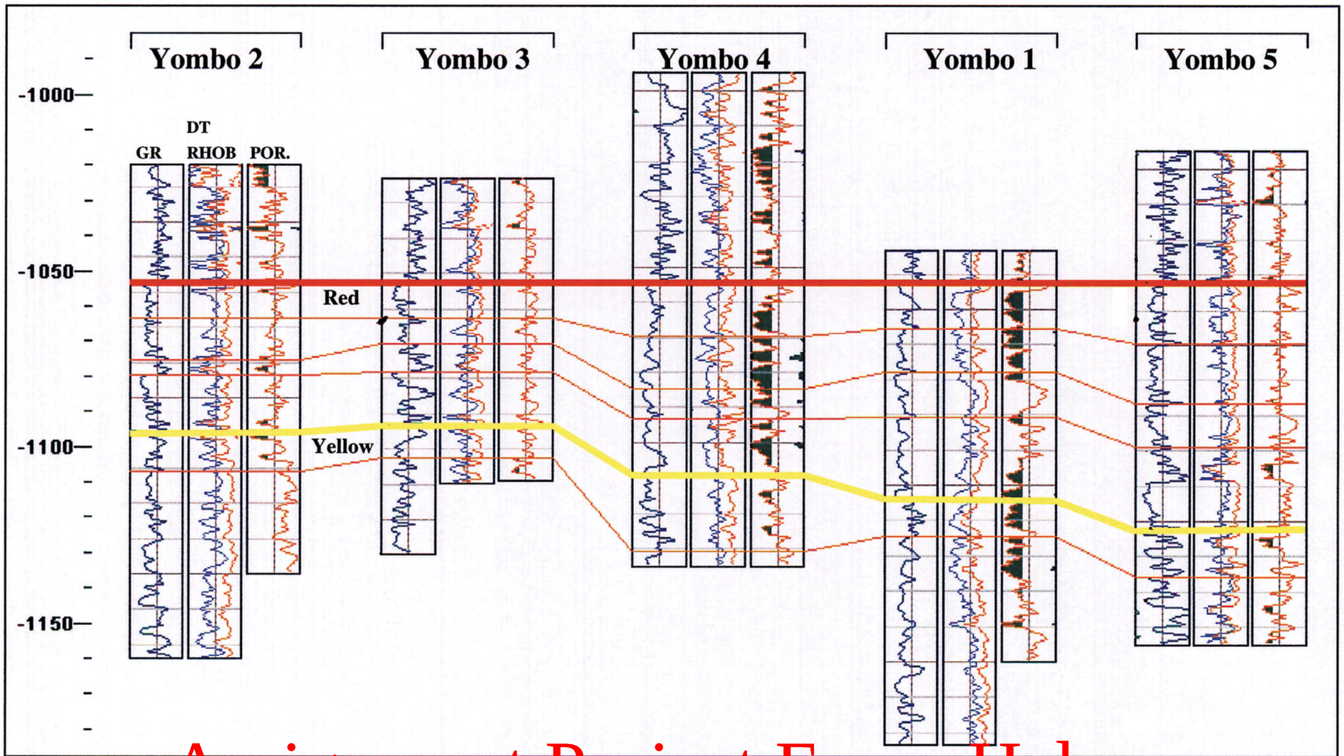


Figure 5. A well-log cross-section using the five delineation wells was flattened on the Top of Upper Sendji (red line). Porosity greater than 18% is black on the log curves. The zone of interest is between the red and yellow horizons. Yombo 1 and 4 have the highest average porosity and high permeability because they penetrated multiple, stacked tidal channels.

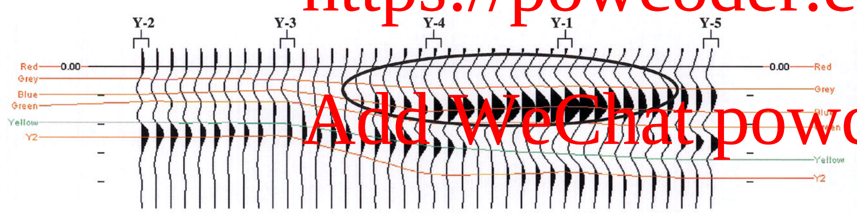


Figure 6. This log model was convolved with the wavelet extracted from the 3-D volume. The resulting vertical incidence response is shown. The area of stacked tidal channels is characterized by a strong trough/peak response.

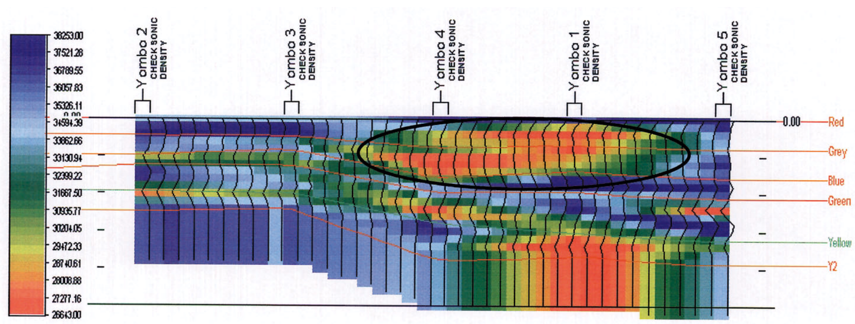


Figure 7. The acoustic impedance display exhibits a low impedance response as predicted from the attribute cross-plot (Figure 4). Cross-plots indicate that the high porosity zones of the Upper Sendji 1 have low acoustic impedance.

Sendji (red line). Porosity greater than 18% is black on the log curves. The zone of interest is between the red and yellow horizons. Yombo 1 and 4 have the highest average porosity and high permeability because they penetrated multiple, stacked tidal channels.

The stratigraphic model, derived from this cross-section, was convolved with the wavelet extracted from the 3-D volume. Figure 6 shows the resulting vertical incidence response. The area of stacked tidal channels is characterized by a strong trough/peak response. The acoustic impedance display (Figure 7) exhibits a low impedance response as predicted from the attribute cross-plot (Figure 4). Note that the acoustic impedance units for the cross-plot are in gm/m^3/s and the units for the model are in gm/ft^3/s. Cross-plots indicate that the high porosity zones of the Upper Sendji 1 have low acoustic impedance. Stratigraphic modeling demonstrated that this low acoustic response may detect the zone of stacked tidal channel facies in the reservoir. The next step was to extend the test to real seismic data.

Inversion of 3-D data over Yombo Field. Acoustic impedance inversion was applied to a subset of the 3-D seismic volume over Yombo Field. A very stable wavelet was extracted using the five delineation wells. The resulting correlation coefficients for the synthetic ties ranged from 0.55 to 0.76 (Figure 8).

An arbitrary line from the result-

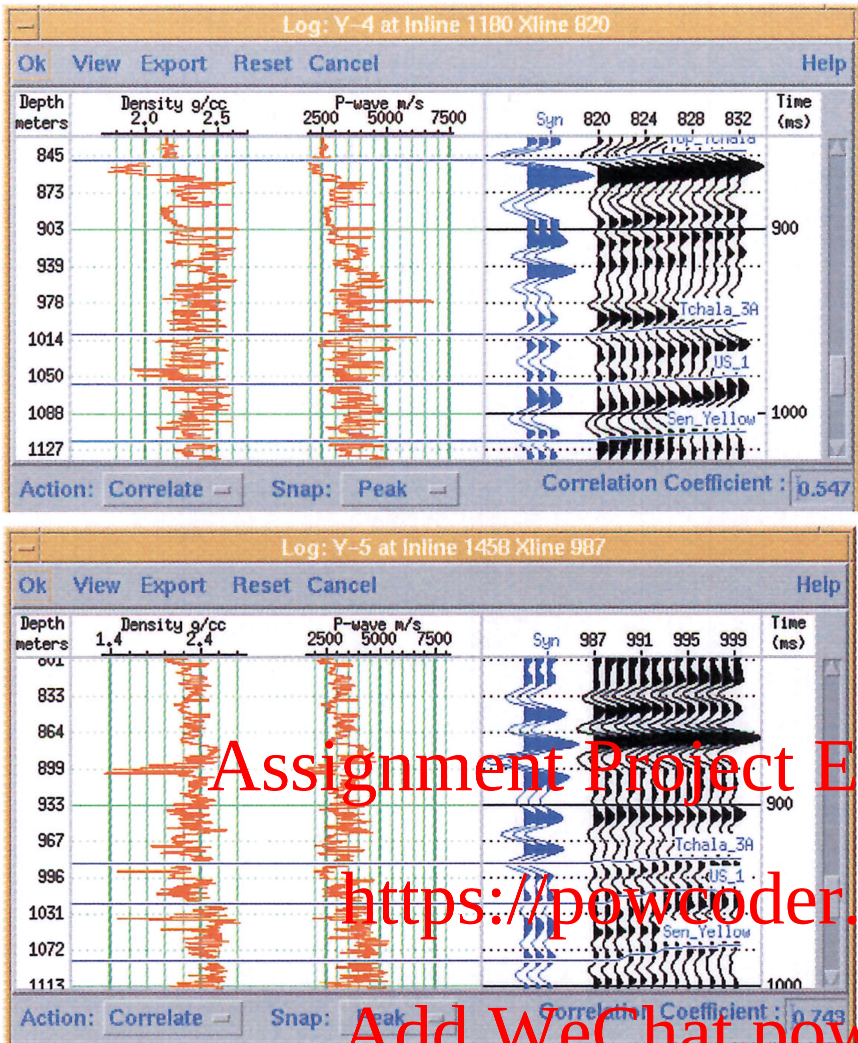
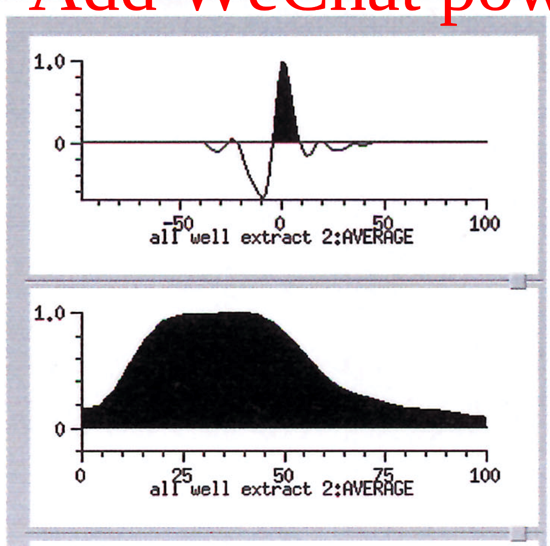


Figure 8. A very stable wavelet was extracted using the five delineation wells. The resulting correlation coefficients for the synthetic ties ranged from 0.55 to 0.76.



ing inversion 3-D volume was extracted across the area of the well log cross section and flattened on the Top Upper Sendji, red horizon, as done in the modeling. The resulting acoustic impedance section (Figure 9) matches the model. The thickest, most laterally continuous zone of low acoustic impedance lies within the zone of the stacked tidal channel facies. The inversion has detected the low acoustic impedance zone, outlined on Figure 9, which coincides with the economic production trend area shown on the net pay isopach map (Figure 2).

Comparing 2-D and 3-D data for detailed inversion study. The result of the inversion on the 3-D seismic volume showed that the productive facies could be seismically delineated. The next question was: Can we increase the detail in the delineation by improving the seismic data and the resulting inversion? To answer this question in a cost-effective manner, we selected 12 sail lines for 2-D reprocessing. Each sail line ties at least one well.

The current 3-D volume, used in the inversion test presented above, is a poststack reprocessed version of the original 1990 processing. The original data were whitened to 160 Hz over the entire section. Data were acquired and processed at 2 ms to avoid aliasing these high frequencies. Filter testing showed that the signal/noise ratio deteriorated rapidly over 120 Hz in the zone of interest. The whitening, therefore, boosted high frequency noise. Upon completion of the poststack reprocessing, the whitening was removed. The resulting data were far less noisy, but the high frequency content of true signal was diminished. The 2-D reprocessed data are less noisy than the 3-D data. The high frequency content is preserved. Figure 10 compares extracted wavelets and frequency spectra of the 3-D and 2-D data. The dominant frequency content is 20-50 Hz in the 1998 poststack reprocessing. This has improved to 20-90 Hz in the 1999 2-D test reprocessing. The processing steps contributing most to the data improvement were prestack radon demultiple; offset DMO; prestack spectral balance (8-124 Hz); and one-pass Kirchhoff migration.

Most of these algorithms were not available when the data were originally processed in 1990. Only one-pass migration could be applied in the 1998 poststack reprocessing. The other algorithms are prestack processes.

2-D inversion defines the target facies. Inversion was applied to several of the 12 reprocessed sail lines. Figure 11 shows acoustic impedance inversion of sail line YST-1183 with the seismic data in wiggle trace overlay. The zone of interest is between the blue and light green horizons. The strong trough/peak response in the wiggle trace overlay is laterally continuous. This is the zone of lowest acoustic impedance in the Upper Sendji. The dashed line, enclosing the low acoustic impedance area, delineates the lateral extent of the stacked tidal channel facies. The acoustic impedance indicates that this facies is thinning updip, and this is confirmed

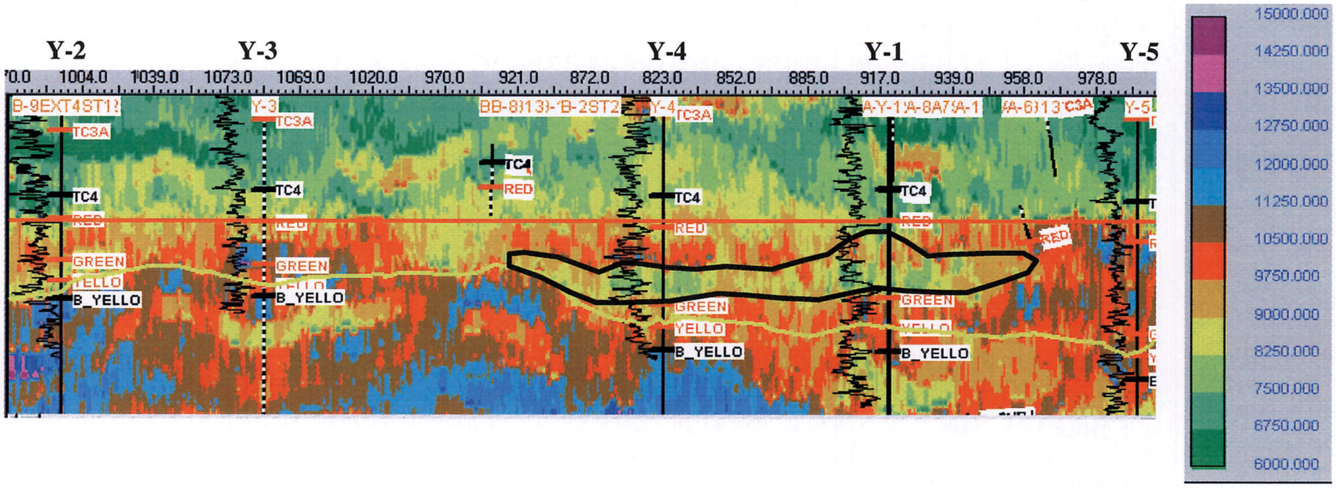


Figure 9. An arbitrary line from the resulting inversion 3-D volume was extracted across the area of the well log cross-section, and flattened on the Top Upper Sendji (red line) as done in the modeling. The resulting acoustic impedance section matches the model. The thickest, most laterally continuous zone of low acoustic impedance lies within the zone of the stacked tidal channel facies. The inversion has detected the low acoustic impedance zone (outlined in black) which coincides with the economic production trend area on the net pay isopach map (Figure 2).

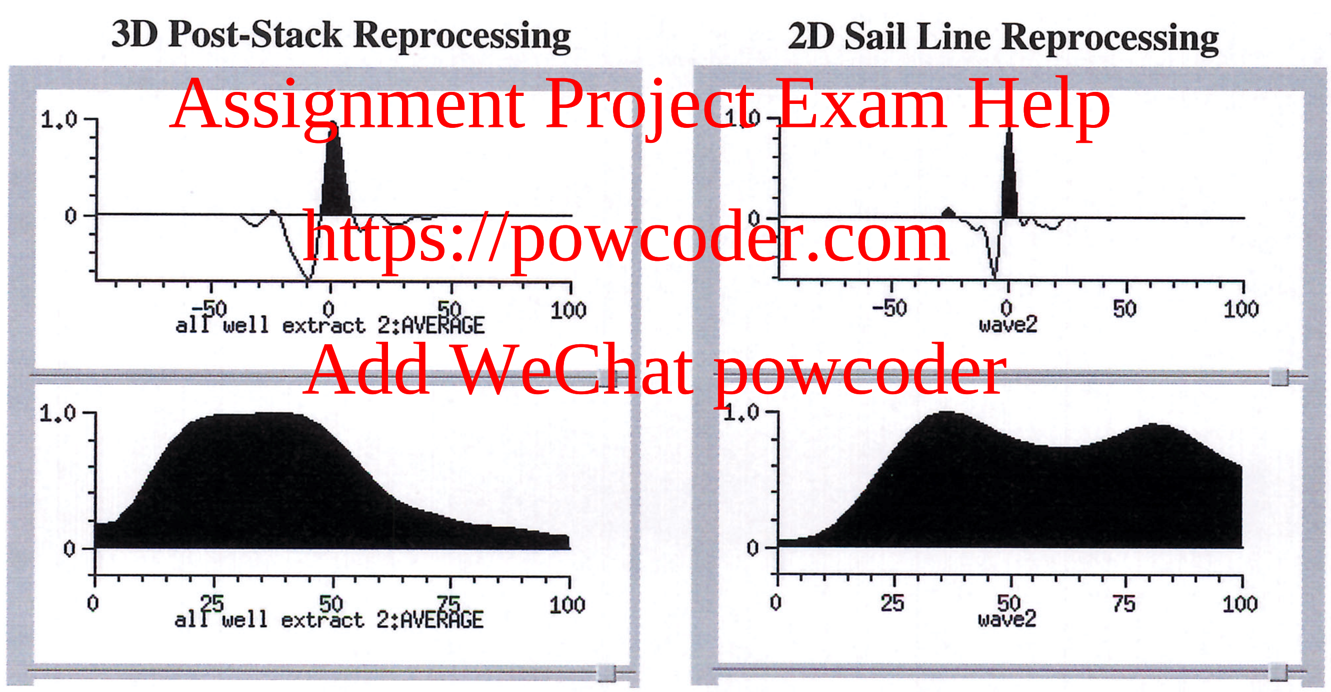


Figure 10. Comparison of extracted wavelets and frequency spectra of the 3-D and 2-D data. The dominant frequency content is 20-50 Hz in the 1998 poststack reprocessing. This has improved to 20-90 Hz in the 1999 2-D test reprocessing.

by well data. Well Y-4 encountered about 35 m of porous tidal channel facies, but B-13 only encountered about 7 m. The facies was absent in B-6St.

The location of sail line YST-1183 is highlighted on Figure 2. The low acoustic impedance outline matches the extent of Yombo Field's productive trend along YST-1183. Cumulative production from the wells is shown in Table 1.

Table 1. Cumulative production from wells

Well	Facies	Cumulative production
Y-4	Thick stacked tidal channel	not produced/delineation well
B-1	Thick stacked tidal channel	1.92 MMBO
B-13	Thin tidal channel	0.55 MMBO
B-6St	Lagoon/tidal flat	0.015 MMBO

3-D inversion, reprocessing, and reservoir facies delineation. The data improvement from the 2-D test reprocessing and the successful delineation from the 2-D and 3-D test inversions gave CMS management confidence in this technique and resulted in approval to reprocess the entire 3-D volume.

Inversion was applied to the reprocessed volume using the same five delineation wells. Volume

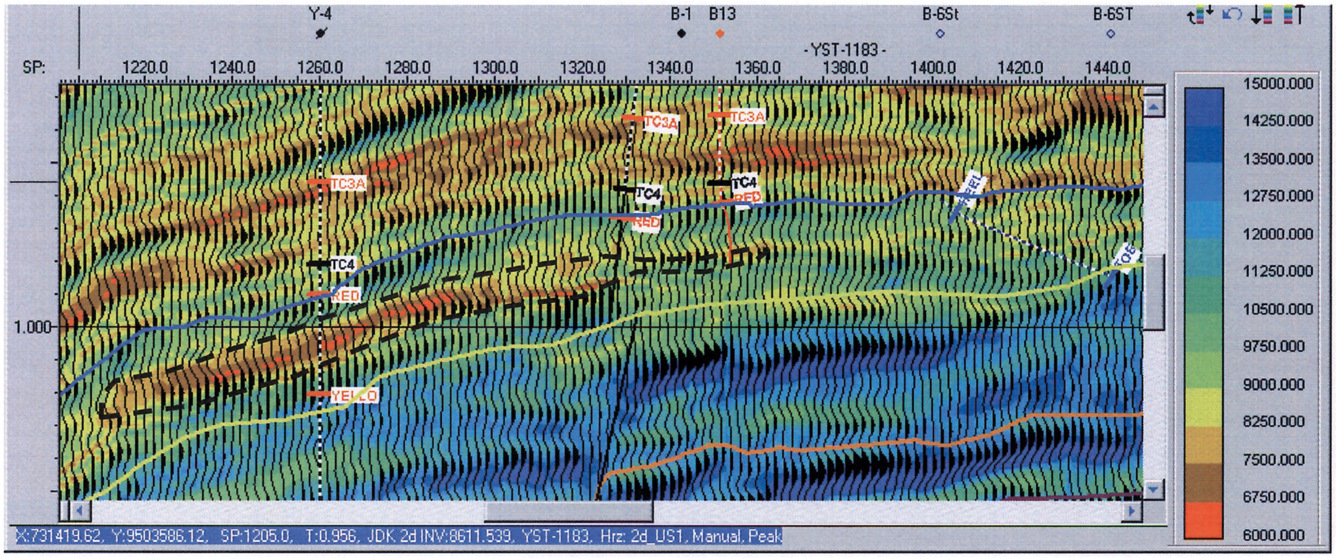


Figure 11. Inversion was applied to several of the 12 reprocessed sail lines. Acoustic impedance inversion of sail line YST-1183 is presented with the seismic data presented in wiggle trace overlay. The zone of interest is between the blue and light green horizons. The strong trough/peak response in the wiggle trace overlay is laterally continuous. This is the zone of lowest acoustic impedance in the Upper Sendji. The dashed line, enclosing the low acoustic impedance area, delineates the lateral extent of the stacked tidal channel facies.

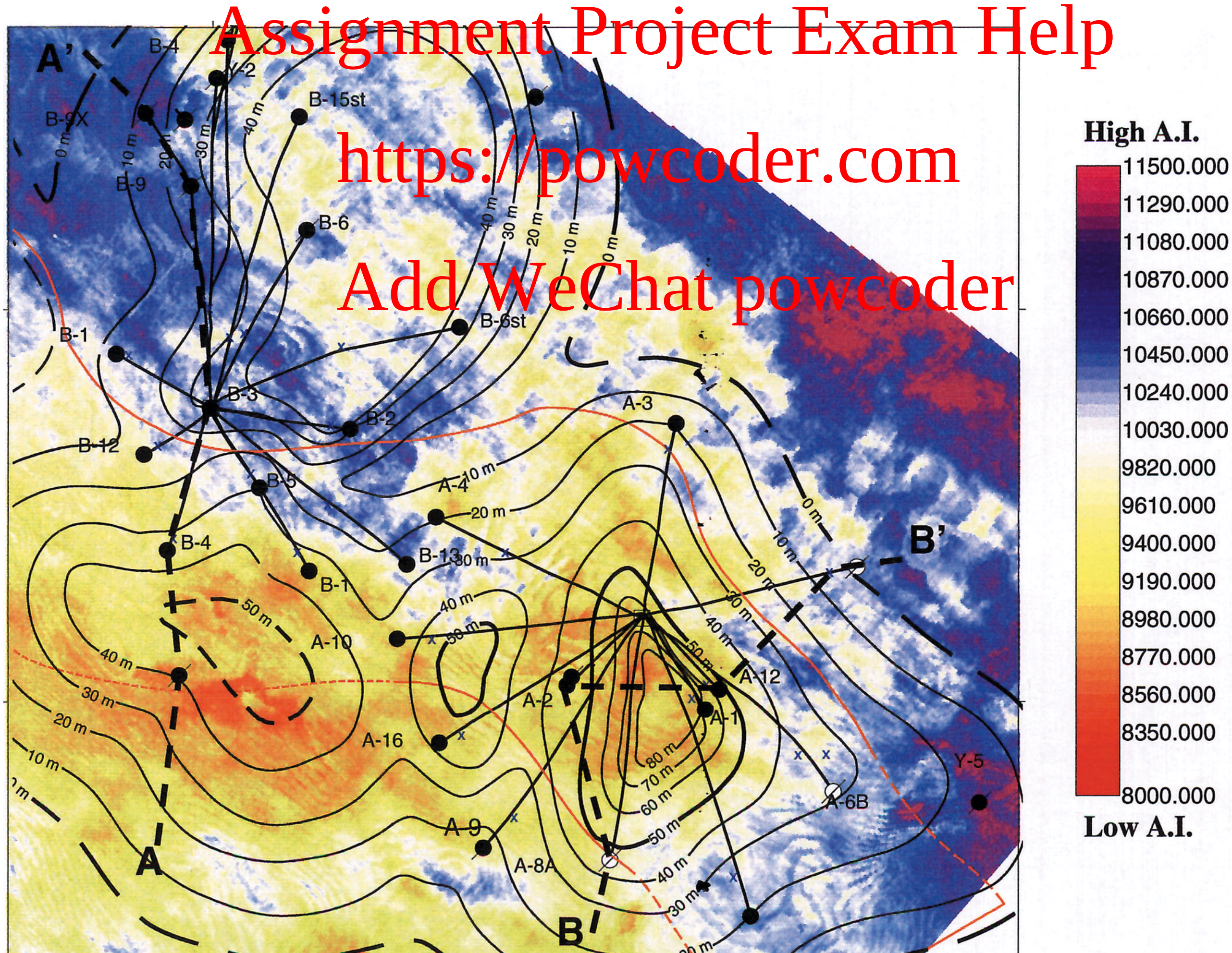


Figure 12. Mean acoustic impedance was the volume attribute that best delineated the extent of the productive facies. The contours of the net oil isopach map are overlain on the attribute map of mean acoustic impedance. The facies extent to the north and east is clearly mapped and matches the limits of the productive area.

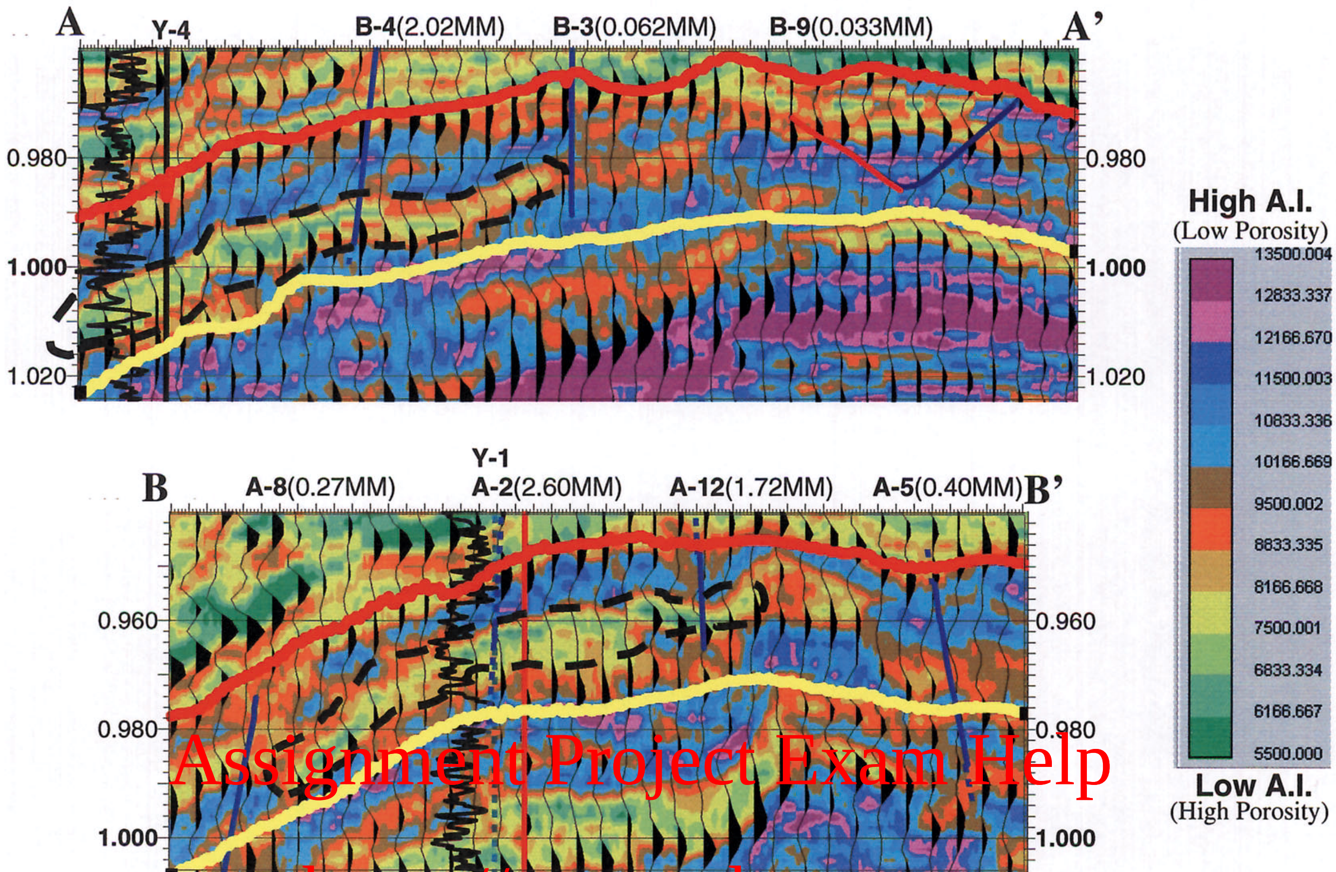


Figure 13. Two arbitrary lines through the 3-D inversion volume. Cumulative production for the Upper Sendji 1 reservoir is next to each well. Dashed lines indicate the interpreted extent of the stacked tidal channel facies. The inversion demonstrates that this facies developed off the southwest, the seaward-facing flank, of the structure.

attribute analysis was performed on the inversion data set. Mean acoustic impedance was found to be the volume attribute that best delineated the extent of the productive facies. The contours of the net oil isopach map are overlain on the attribute map of mean acoustic impedance (Figure 12). The facies extent to the north and east is clearly mapped and matches the limits of the productive area. A reasonable interpretation of the attribute map has the stacked tidal channel facies extending southwest of well Y-4, beyond the productive trend. Wells have not been drilled in this area because the oil-water contact has begun to rise and new wells would likely produce too much water.

Figure 13 shows two arbitrary lines through the 3-D inversion volume. Cumulative production for the Upper Sendji 1 reservoir is next to each well. Dashed lines indicate the interpreted extent of the stacked tidal channel facies. The inversion demonstrates that this facies developed off the southwest, the seaward-facing flank of the structure. The northern portion of the net oil isopach is attractive because it is high above the water contact, with potential undeveloped oil in place. The facies transition from tidal channel, to tidal flat and lagoon dramatically decreases the permeability and lowers the average porosity, which results in low oil production rates. The inversion volume is assisting in delineation of the extent of the productive tidal channel facies and optimizing the location of future Upper Sendji development wells.

Conclusions. A strong linear relationship between increasing porosity and decreasing acoustic impedance is observed in Yombo Field, offshore Congo. Crossplotting indicated that the high-porosity zones of the Upper Sendji 1 would have low acoustic impedance. Stratigraphic modeling demonstrated that this low acoustic response detected the zone of the stacked tidal channel facies in the formation.

A seismic inversion method was recommended to accurately delineate the extent and distribution of the economically productive facies. The thickest, most laterally continuous zone of low acoustic impedance lies within the zone of the stacked tidal channel facies. The acoustic impedance indicates that this facies is thinning updip, and this is confirmed by well data. The inversion detected the low acoustic impedance zone that coincides with the economic production trend area shown on the net pay isopach map. E

Acknowledgments: The author thanks CMS Oil and Gas Company, Nuevo Energy Company, Societe Nationale Des Petroles du Congo. and the Ministry of Hydrocarbons, Republic of Congo, for permission to publish this paper. I thank Allen Brown, Barry Faulkner, and Doug Jordan for key contributions. I thank the management of CMS and Nuevo for supporting the publication of this article.

Corresponding author: J. Van Horn, jvanhorn@cmsenergy.com

John Van Horn received a bachelor's degree in geology from the State University of New York at Binghamton and a master's degree in geophysics from Michigan Technological University. He joined Mobil in 1980 and worked on a series of exploration and production projects in a variety of domestic and international locations. In 1996, he joined Texaco international exploration, working on the China exploration team. In 1998, he joined CMS Oil and Gas.