# HIGH-RESOLUTION ACOUSTIC AND SEISMIC INVESTIGATION OF CARBONATE ROCK PROPERTIES

by

***Jorge O. Parra*** *and Chris* ***L. Hackert****, Southwest Research Institute, San Antonio, Texas*
***Michael Bennett****, South Florida Water Management District, West Palm Beach, Florida*
***Hughbert A. Collier****, Collier Consulting, Stephensville, Texas*

**Paper to be presented at the Society of Petroleum and Well Log Analyst (SPWLA), International Symposium to be held June 22-25, 2003, Galveston, Texas**

Southwest Research Institute,
6220 Culebra Rd.
San Antonio, Texas
Ph: (210) 522-3284
e-mail:jparra@swri.edu
http://www.reservoirgeophysics.swri.edu

# HIGH-RESOLUTION ACOUSTIC AND SEISMIC INVESTIGATION OF CARBONATE ROCK PROPERTIES

Jorge O. Parra and Chris L. Hackert, Southwest Research Institute, San Antonio, Texas
Michael Bennett, South Florida Water Management District, West Palm Beach, Florida
Hughbert A. Collier, Collier Consulting, Stephensville, Texas

## ABSTRACT

Understanding pore structures in carbonates is important for a characterization of lithology at the borehole and field scales. We delineate vuggy zones at the borehole and interwell scales in a carbonate aquifer in south Florida. Core data and petrography characterize the matrix and the vuggy porosity, as well as the lithology. The lithology, integrated with well logs, provide the rock properties of a 500-foot zone intercepted by a borehole. We predict flow units at the field scale with crosswell seismic imaging data, including velocity tomography and high-resolution reflection seismic data. We then produce synthetic seismograms based on the poroviscoelastic theory to model interwell seismic data, and we construct computer models with the rock physics parameters derived from well logs, including a Q log derived from monopole sonic data. Common-source observed and calculated seismograms show good agreement, and the observed and calculated amplitude-depth distribution curves suggest that the boundaries of the major geological units are connected between two wells, and the small differences in amplitudes are due to the presence of lateral heterogeneities. We invert the reflection seismic data for impedance to test the model results, and the impedance correlates with permeability and porosity logs at the borehole location, giving rise to empirical relationships. These expressions are used to transform impedance images to permeability and porosity images. The images show continuity between the major geological units and lateral changes in the porosity image, where a porosity of more than 40 percent correlates with a low-impedance zone. The high-resolution reflections observed at the field scale in the carbonate formation are associated with changes in porosity due to the presence of vugs. The images show that porous zones in the carbonate are continuous until 200 feet from the wells, and then relatively discontinuous, and that touching vugs form the porous and permeable discontinuous flow units.

## INTRODUCTION

Carbonate formations generally have broad pore size distributions, from microcrystalline to large vugs (Choquette and Pray, 1970). Information on pore spaces and their geometries is crucial to an understanding of hydrocarbon reservoir characterization and hydrogeological and environmental issues. Pore structures are important aspects of a description of carbonate reservoir flow units at the borehole and field scales. Understanding pore structures in carbonate rocks is important for the characterization of hydraulic properties at the borehole and field scales. At the borehole and interwell scales, wave attenuation is an important attribute that can be used as an indicator of lithology, pore structure, fractures, and clay and fluid content in a reservoir characterization program, especially when attenuation is well understood at the borehole. Because acoustic attributes from full waveform sonic logs can be easily related to petrophysics and core data in a single borehole, the intrinsic and scattering effects at the borehole can be determined. Since the early 1980s, various researchers have attempted to implement techniques to determine Q from single-hole full waveform acoustic log data. It is, however, commonly recognized that existing Q processing techniques have major limitations and pitfalls. In particular, these techniques have serious difficulties when the lithology and acoustic properties are highly heterogeneous in depth. In the south Florida aquifer studied, significant changes are often observed at the scale of one foot. The formation is carbonate rock with separated and interconnected vugs. It is desirable to obtain Q from the sonic log of this formation and determine if Q can be used to assess the pore structure of the aquifer. A preliminary study indicates that the difficulties due to the heterogeneity can, in principle, be overcome provided the associated scattering is taken into account.

In this paper, we present an application of acoustic inversion, seismic modeling, and processing techniques to map flow units in a South Florida aquifer. The aquifer is in the western Hillsboro Basin in Palm Beach County, Florida (Parra et al., 2001; and Bennett, et al. 2002). We analyze and interpret data from core, well log and field scales. The goal is to use model parameters based on lithology and well logs – permeability derived from the NMR well log (Parra et al., 2001) and Q derived from the full waveform sonic log. We use synthetic seismograms based on the model of a point source in a multi-layer poroelastic/viscoelastic medium (Parra 1991). Full waveform crosswell seismic data are used to verify the model and evaluate the degree of continuity of the different facies to determine the reliability of the porosity and permeability images derived from crosswell reflection data. We delineate vuggy zones at the borehole and interwell scales in the upper Floridan aquifer, between source well PBF13 and receiver well PBF10 at a separation of 330 feet. Lithology, integrated with well logs, provide the hydraulic and rock properties of a 500-foot zone intercepted by a borehole. We invert the reflection seismic data for impedance. Based on permeability and porosity logs, we transform impedance images to permeability and porosity images. The images show continuity between the major geological units and lateral changes in the porosity image. The images also show that porous zones in the carbonate aquifer are laterally continuous up to 200 feet from the well, then become relatively discontinuous, and that these porous and permeable flow units are characterized by interconnected vugs.

## PORE SCALE CHARACTERIZATION

To understand the pore structure of the carbonate rocks of the upper Floridan aquifer in South Florida, we analyze x-ray CT and optical microscopic (OM) thin section images from core samples (Hackert and Parra, 2002; Anselmetti at al.,1998). We select a full diameter core sample taken from a depth of 1138 feet. The core exhibits a typical interconnected vug system of Eocene-aged Ocala Limestone. Figure 1a shows calculated density from the x-ray CT data from a core slice. (Vugs or vuggy porosity are pore spaces larger than or within the particles of rock and commonly present as leached particles, fractures, and large irregular cavities.) In Figure 1b, a photograph of the end of the core is shown for comparison. There is good agreement between the vuggy pores seen in the photograph and those visible in the CT cross-section. Overall, the core exhibits high vug connectivity in the vertical direction. The matrix porosity of this carbonate rock sample is observed in photomicrographs, which clearly show the interconnected pore structure and petrography. This information helps to characterize the lithology and hydraulic properties of the rock units intercepted by the borehole. The lithology is subsequently related to field images to delineate flow units in the interwell region.

## BOREHOLE SCALE CHARACTERIZATION

***NMR well logs.*** To relate the geology with rock physical properties at the borehole scale, we used lithologic and geophysical well log, and petrographical data. Figure 2 presents a sample of the lithology intercepted by well PBF-10. The permeability log is derived from the nuclear magnetic resonance (NMR) well log. Also shown is Vp, Vs, bulk density, logging derived porosity, and the NMR-determined bound water volume. In this case we are interested in the region between 1000 and 1200 ft. because it has been identified as an aquifer storage and recovery (ASR) horizon. The lithology at this depth correlates with the permeability log. For example, the texture of the sandy carbonate facies is very coarse to granular with interconnected moldic porosity (based on cores and thin section analysis). Petrophysical core analyses indicate high porosity and permeability. The flow unit identified at 1020 to 1040 feet is part of the productive portion of the upper Floridan aquifer. Below this unit, a sandstone facies is observed that is fine-grained, slightly dolomitic, and well cemented. It has a predominately interparticle fabric and is characterized by low permeability but high porosity. This unit has a high bound volume of water, and it represents the boundary between the upper and lower productive horizons. A vuggy carbonate below the sandstone has a matrix with connected interparticle porosity and is characterized by very high permeability and porosity. The last zone in this region is a chalky carbonate of low permeability, which serves as the lower boundary of this targeted ASR horizon.

***Acoustic Well Logs***. We use full waveform sonic data measured with a source receiver configuration of 8 receivers to extract attenuation as a function of depth. Their offsets from the source ranges from 11 to 14.5 ft. The spacing between adjacent receivers is 0.5 ft. For our *Q* inversion algorithm we use spacing between receivers instead of spacing between source and receivers. Thus we can have a good spatial resolution, ranging from 0.5 to 3.5 instead of 11 to 14.5 ft., to capture variations in formation properties. For processing we use relatively long time windows to gate head waves, which leads to more stable results. Guided waves are separated from the full waveform with the aid of a guided wave model. In particular, we use a layered model to represent the vertical heterogeneity associated with lithological changes. As a result, the data measured at different depths are corrected and normalized for the regular use of the classic spectral ratio (SR) method. The correction for geometrical spreading of head waves also takes heterogeneity into account. Finally, the SR is calculated at properly defined peak areas of the spectrum of the corrected and normalized measured data to obtain *Q* for each specified depth.

To visualize the SR method we consider a plane wave or guided wave traveling from receiver 1 to receiver 2 in a uniform unbounded medium in the propagation direction. The measured wave amplitude at the first receiver is $A_1(T)$, and at the second receiver is $A_2(T)$**.** Assume that the wave speed is *V* and the distance is *l,* and after correcting for geometric spreading*,* the quality factor of attenuation, *Q*, is given by

$$Q^{-1}(\omega) = \frac{2V}{\omega l}\{ln[A_1(\omega)/A_2(\omega)] - ln[S_1(\omega)/S_2(\omega)]\}.$$

In this equation, $S_1(\omega)$ and $S_2(\omega)$ are the geometric spreading corrections obtained analytically for a point source in a fluid-filled borehole. We apply the inversion algorithm for the prediction of *Q* from the P-head waves of sonic logs in well PBF10 (see Figure 3). In general, *Q* correlates with the lithology and permeability. The interval between 1000 and 1070 feet is formed by sandstone, sandy carbonate, and carbonate with 15 to 20 percent sand. In this interval, *Q* correlates with the gamma ray log. In addition, in the zone between 1050 and 1065 feet, where permeability is very low, *Q* increases when permeability increases with a high level of correlation. Below 1070 feet, the well intercepts a carbonate zone with interparticle and vuggy porosity. In this interval, the gamma ray response is flat. Permeability is very high and increases when *Q* decreases. We observe zones with high permeability and low *Q* at depths of 1007.5, 1025, and 1040 feet. On the other hand, *Q* is apparently affected by the rock fabric and pore structure of the carbonate rock formation. These preliminary results are, in principle, consistent with findings in the literature (e.g., Sun et al., 2000; Dasios et al., 2001).

## MODELING OF CROSS WELL SEISMIC DATA

To determine facies continuity in the aquifer we use a model-based processing approach. We require lithological information, P- and S wave velocity logs, density log, porosity, and permeability logs. The input parameters are used to calculate synthetic seismograms for the selected layered-earth structure using the model given in Figure 4. To include the fluid properties, permeability and porosity we use a code that simulates synthetic seismograms based on the solution of a point source in a poroelastic layered media (see Parra, 1991; Parra and Hackert, 2001).

Figure 4 also shows the layered model between two wells, a pressure source, and the array of hydrophones. The layered model is assumed to be sandwiched between two homogeneous half spaces. We simulate the region between 1000-1100 ft. using a multilayer medium of 100 layers; each layer has a thickness of one foot. The input parameters for this poroelastic model are obtained from the well logs given in Figure 2. To consider the effect of viscoelatic attenuation associated with the rock fabric, we use the *Q* well log data given in Figure 3. We calculate synthetic seismograms for a source at 1050 ft. that is placed in the sandy carbonate unit, and a second source of high permeability placed at 1085 ft. in the carbonate. The common source seismograms are calculated for an array of 41 detectors. To evaluate the results we compare the calculated and observed common source seismograms. In general there is good agreement between both seismograms. Most of the differences can be attributed to the post processing of the crosswell data.

To identify continuity, we extract amplitude-depth distribution curves directly from the interwell seismic data. The magnitude of the wave field along the line of detectors perpendicular to the layered medium is calculated for model parameters at several frequencies. These plots are easily compared with the lithology to locate boundaries. Thus, we produce amplitude-depth distribution curves from the two common sources, observed and synthetic seismograms. These curves are shown together with the P-wave and S-wave logs and the lithology. In Figures 5a and 5b, a strong correlation is observed between the experimental and synthetic amplitude-depth distribution curves in the region between 1000-1100. The small differences in amplitudes are due to the presence of lateral heterogeneities. The correlation between the observed and calculated curves demonstrates that the major facies are continuous between wells PBF10 and PBF13. This analysis supports the interpretation.

**INTERWELL PERMEABILITY AND POROSITY IMAGES**

Crosswell seismic measurements were conducted between wells PBF10 and PBF13 at an interwell spacing of 330 feet, using a TomoSeis advanced piezoceramic X-series source and a 10-level hydrophone system. The survey interval was from 550 to about 1225 ft. below the surface and covered a series of flat lying limestones with some interbedded sandstones. The sweep length was 1.2 seconds at a sampling rate of 125 microseconds from 200 to 2000 Hz. Source and receiver depth sampling spacing was 2.5 ft.; resulting in about 38,300 recorded seismic traces. Actual reflection coverage below the total depth for each well was limited by well spacing, as well as the deepest source and receiver locations in each well. The vertical resolution of the reflection data for this profile was about 2 ft. The reflection image was inverted for impedance using the band-limited method (a feature of the STRATA software, developed by the Hampson and Russell Company). Figure 6 shows the impedance image between the PBF10 and PBF13 wells at depths from 750 to 1550 feet. The Vp and density logs are overlain on the impedance image, and the image shows good correlation with the well logs. In particular, the impedance clearly shows the main boundaries of the upper and lower productive horizons that correspond to the high impedance zones identified in red. We analyze the impedance image in the region between 950 and 1250 ft. and cross-plot the permeability and porosity log data with the impedance at the borehole location. Cross plots of impedance with permeability and porosity were used to derive empirical relationships (or impedance cross plot fit equations) for permeability ($k$) and porosity ($\phi$) for depths of 950-1250 ft. These relationships were used to convert the impedance to produce the overlaying permeability and porosity images. These images are given in Figure 7, show continuous and discontinuous flow units. The lateral continuous flow unit observed in yellow, between 1020 to 1040 ft., has an average permeability of 2000 md, and an average porosity of 30 percent (observed in blue in the porosity image at a depth of about 1020 ft.). This flow unit was delineated as a continuous reflector in the reflection image.

The discontinuous flow unit shows lateral permeability and porosity changes in the region between the depths of 1070 to 1140 ft. In this zone it is difficult to estimate the contribution of macropores versus vugs to the overall permeability. Based on core data we know that P-wave velocity decreases as porosity increases, which suggests that at the field scale, seismic reflections observed below 1070 ft. are associated with a porosity change due to the vuggy carbonate. For example, the two porosity zones in the 1070-1140 foot interval (as shown in Figure 7) have been mapped with reflection images. These two zones are laterally continuous up to 200 ft. from the well, and then become relatively discontinuous. Based on core information, these two zones are vuggy in nature and correlate with high permeability, which suggests that their pore structure is formed by a network of interconnected vugs Therefore, these two zones (shown in black in Figure 7) are characterized by vuggy porosity, and matrix permeability in the gray zone surrounding the black unit is probably controlled by macropores in the rock matrix. These flow units carry most of the water flows in the interwell region of the upper Floridan aquifer at this site.

## CONCLUSIONS

A new data analysis approach, from the pore to the field scale, allows us to characterize the hydraulic potential of a vuggy carbonate rock unit:

- Good agreement exists between observed and calculated interwell seismic data and amplitude-depth distribution curves. This suggests that the major geological facies are continuous in the interwell region.
- The poroelastic and viscoelastic layered earth model is appropriate for interpreting crosswell seismic data in the South Florida aquifer.
- The correlation between velocity and porosity at the core and borehole scales provides insight into how the high resolution (1000-2000 Hz) crosswell seismic data can capture changes in velocity, which are related to porosity changes in the formation vugs, which can be either separated or interconnected.
- The permeability, porosity, and impedance images delineate flow units that can be characterized as very permeable, and laterally heterogeneous discontinuous flow units directly related to vuggy porosity development. The images also delineate continuous, less permeable flow units related to the macropores (interpaticle porosity) of the rock matrix. These are the flow units that carry most of the flow in the interwell region of the upper Floridan.
- The reflection image-derived impedance provides the depth of the lower boundary of the targeted ASR horizon, as well as lateral continuity in the interwell region.

**ACKNOWLEDGMENTS:** The South Florida Water Management District provided the Florida aquifer data. Program work was supported by contract DE-FC26-02NT15343 from the U.S. Department of Energy, National Petroleum Technology Office. The assistance of P. Halder (DOE) is gratefully acknowledged. We also thank the Hampson and Russell Company.

## REFERENCES

Anselmetti, F.S., Luthi, S., and Eberli, G.P., 1998, Quantitative characterization of carbonate pore systems by digital image analysis: *AAPG Bulletin*, 82, 1815-1836.

Bennett, W.M., Linton, P.F., and Rectenwald, E.E. 2002, Hydrologic investigation of the Floridan aquifer system, western Hillsboro Basin, Palm Beach County, Florida, Technical Publication WS-8, South Florida Water Management District.

Choquette, P.W. and Pray, L.C., 1970, Geological nomenclature and classification of porosity in sedimentary carbonates: *AAPG Bulletin*, 54, 207-250.

Dasios, A., Astin, T.R., and McCann, C., 2001, Compressional-wave Q estimation from full-waveform sonic data: *Geophysical Prospecting*, 49, 353-373.

Hackert, C.L, and Parra, J.O., 2002, Simulating NMR magnetization diffusion in a real carbonate pore system: *Petrophysics*, 43, 425-433.

Parra, J.O., 1991, Analysis of elastic wave propagation in stratified fluid-filled porous media for interwell systemic applications: *The Journal of the Acoustic Society of America*, 90, 2557-2575.

Parra, J.O., and Hackert, C.L., 2001, A poroelastic model with azimuthal anisotropy to analyze flow unit responses at the Siberia Ridge Field, Greater Green River Basin: *Petrophysics*, 42, 93-106.

Parra, J.O., Hackert, C.L., Collier, H.A., and Bennett, M., 2001, A methodology to integrate magnetic resonance and acoustic measurements for reservoir characterization: Report DOE/BC/15203-3, National Petroleum Technology Office, Department of Energy, Tulsa, Oklahoma.

Sun, X., Tang, X., Cheng, C.H., and Frazer, L.N., 2000, P- and S-wave attenuation logs from monopole sonic data: *Geophysics*, 65, 755-765

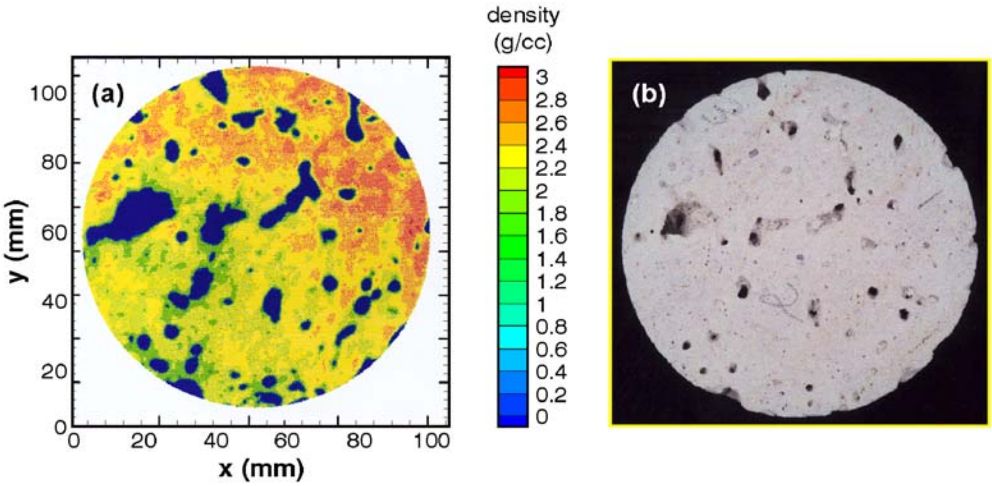



Figure 1. (a) Computed density from x-ray CT data, and (b) photograph of the end of the core.

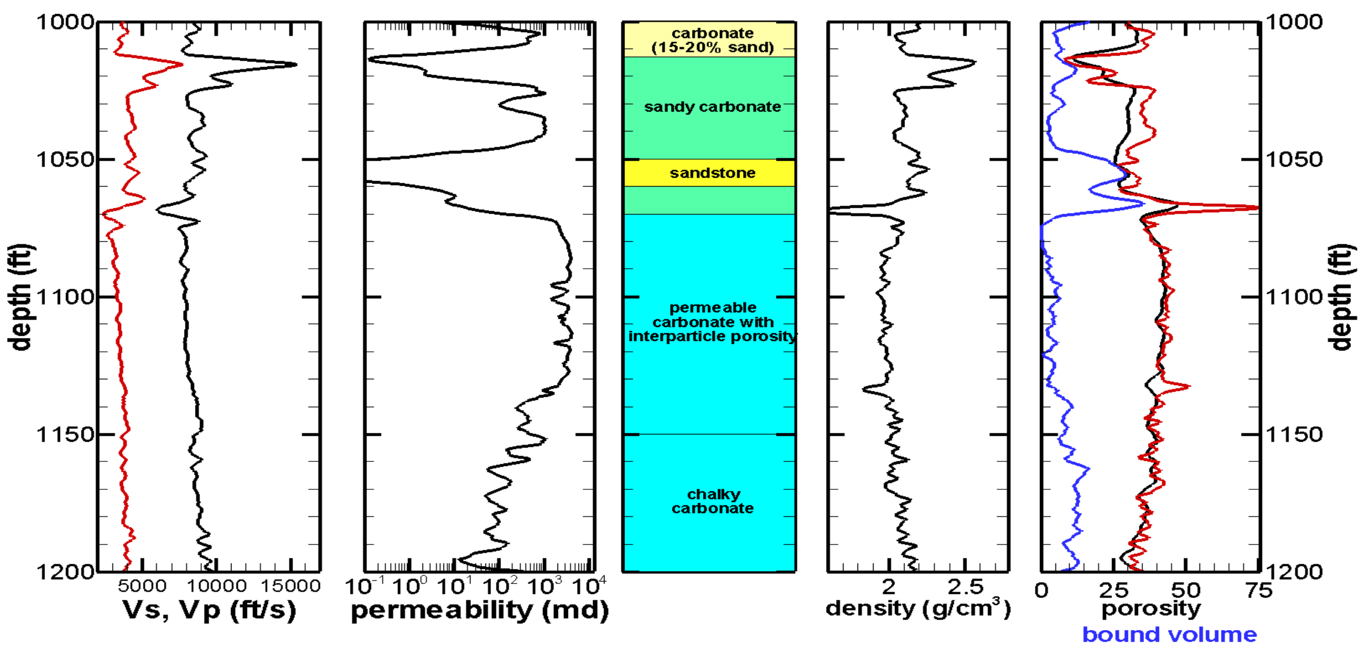



Figure 2. Well logs from well PBF10, South Florida.

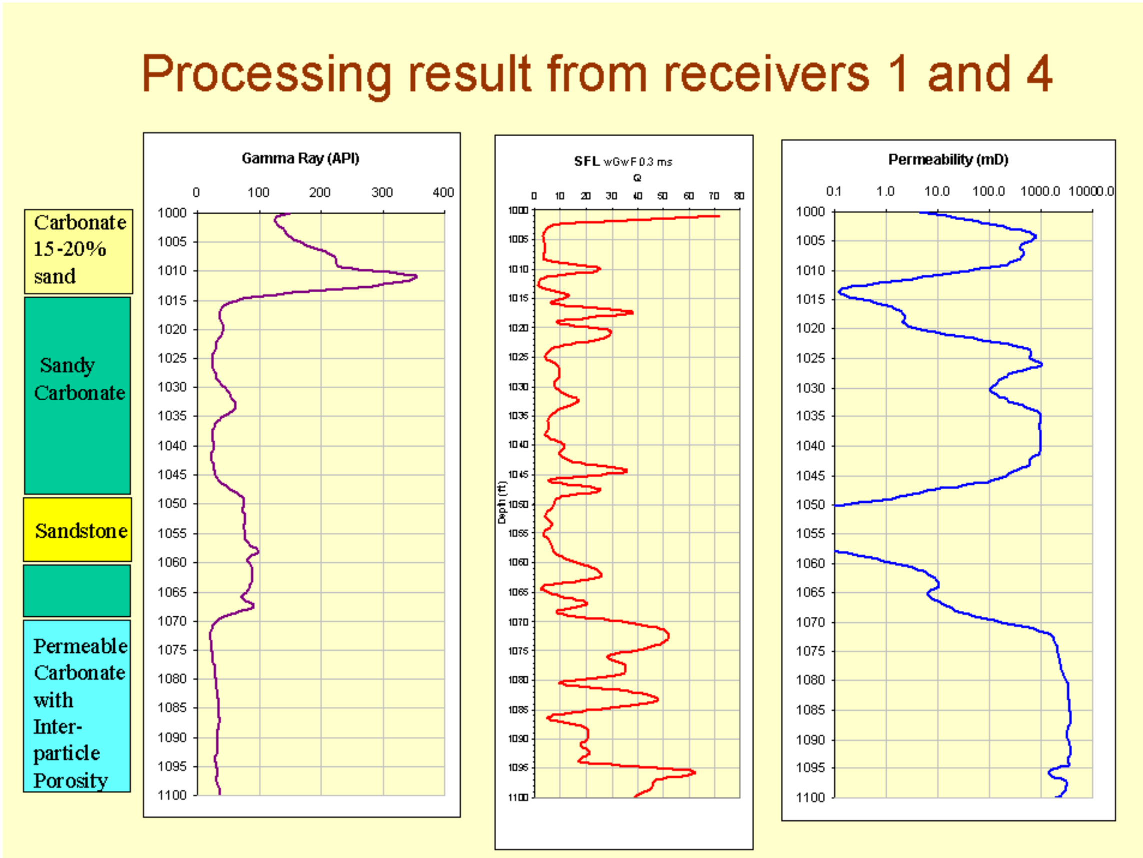



Figure 3. Comparison between estimated Q, lithology and permeability.

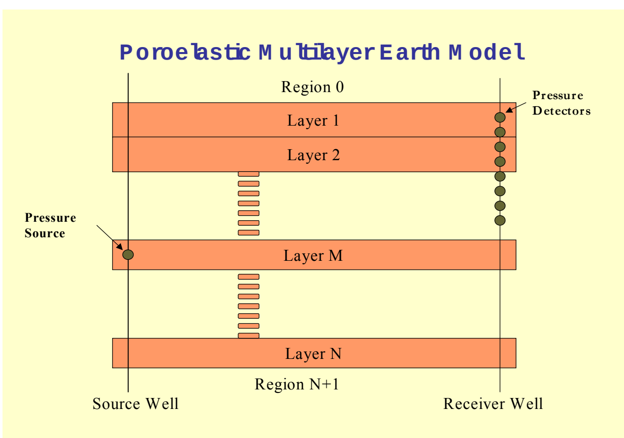
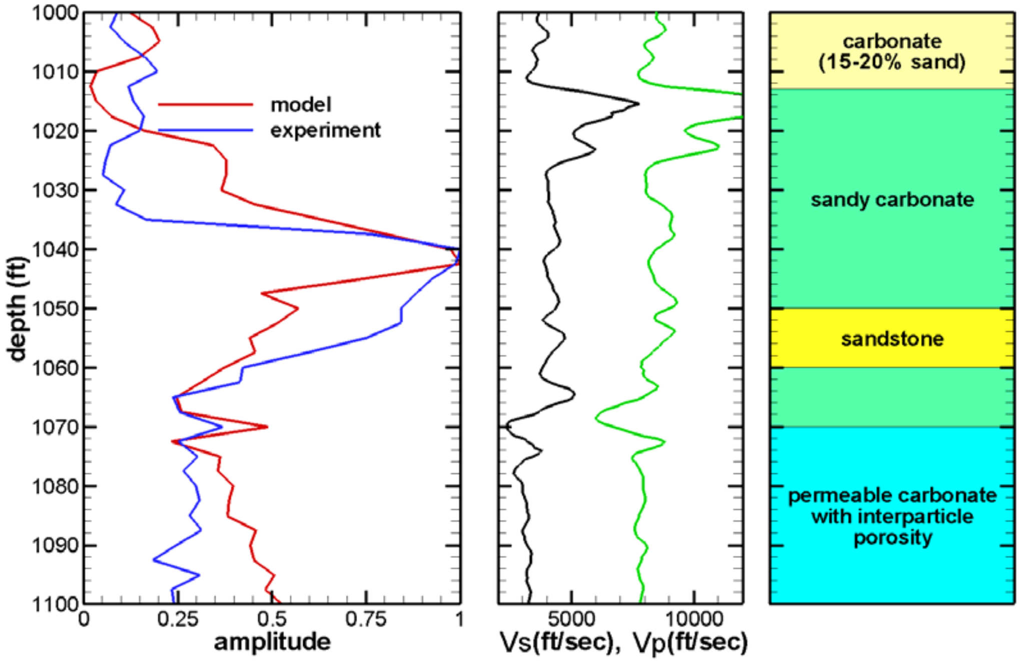



Figure 4. Layer model for calculating synthetic seismograms.

(a)




(b)

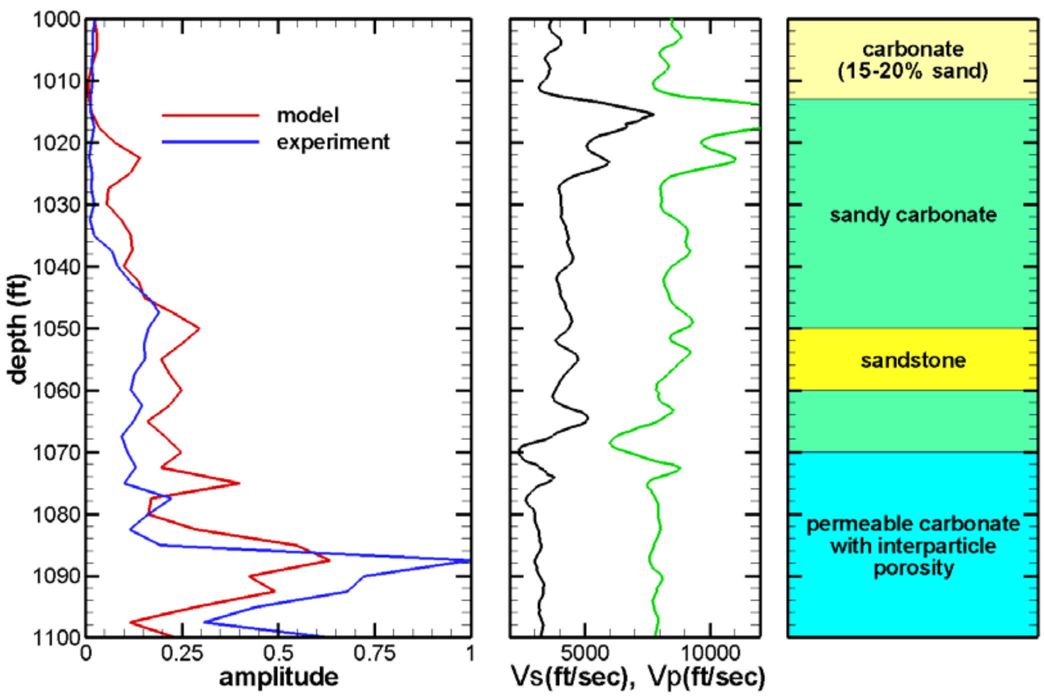



Figure 5. Amplitude-depth distribution curves based on observed and synthetic seismograms, (a) source at 1050 feet, and (b) source at 1085 feet.

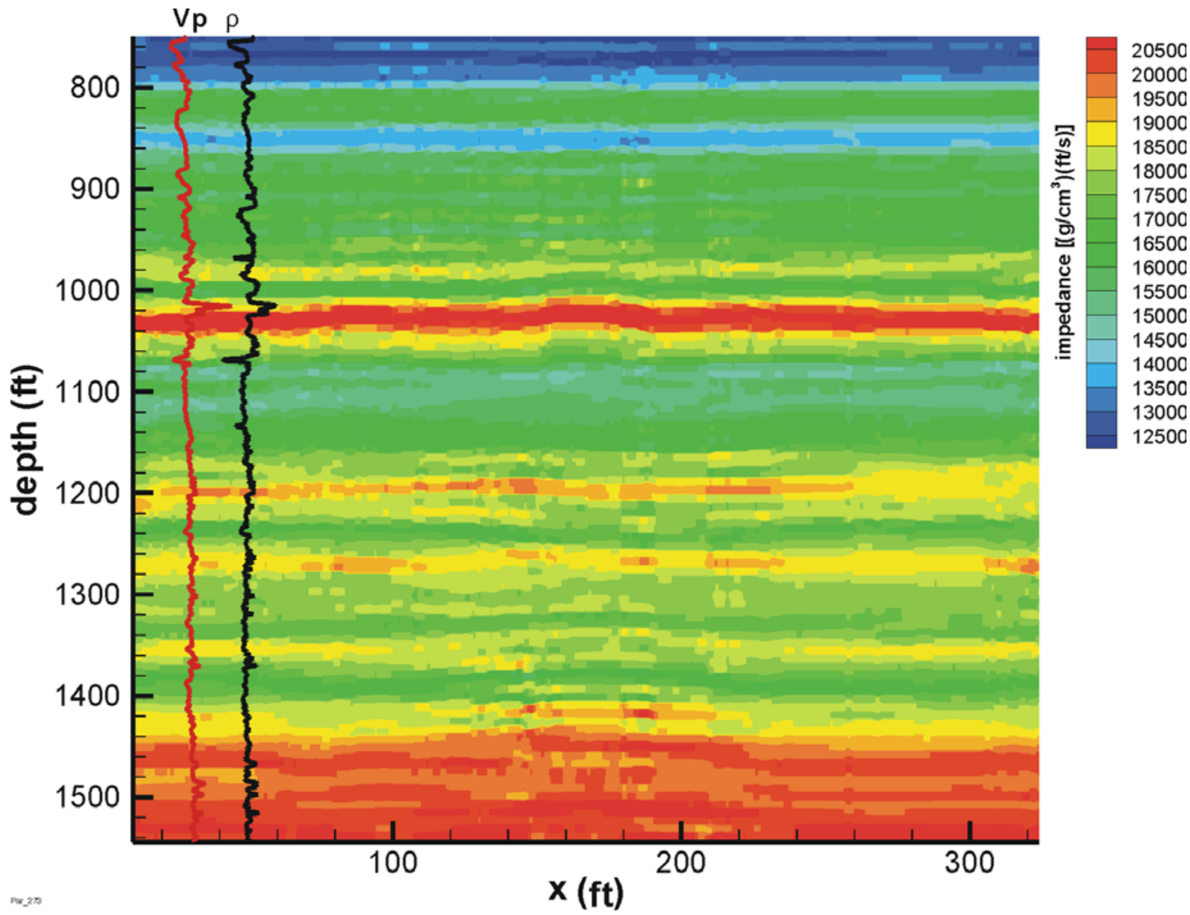



Figure 6. Impedance image from crosswell reflection data. Vp and density logs are overlain on the impedance image. The image shows the boundaries of upper and lower aquifers.

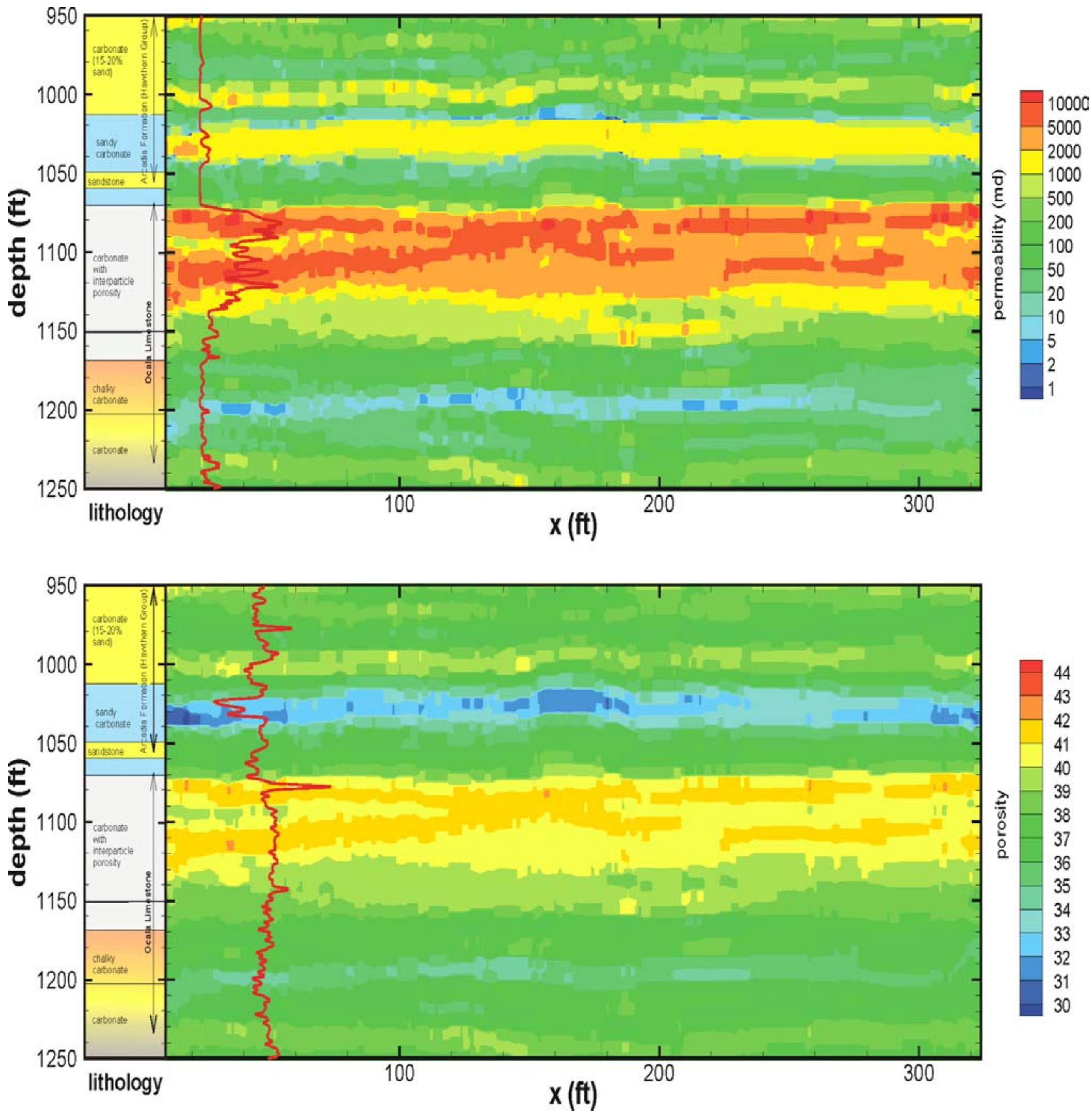



Figure 7. Permeability and porosity images in the interwell region. The images are computed by correlating the permeability and porosity well logs with crosswell impedance at the same location. The overlain lines show the corresponding well log profile.