# Permeability and porosity images based on NMR, sonic, and seismic reflectivity: Application to a carbonate aquifer

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Carbonate formations generally have a large distribution of pore sizes, ranging from microcrystalline to large vugs. Knowledge of these pore spaces and their connectivity is crucial to hydrocarbon reservoir characterization and to hydrogeological and near surface environmental applications. In this paper, we present permeability and porosity images based on crosswell seismic measurements integrated with well logs and petrography from a carbonate aquifer underlying Palm Beach County, Florida, U.S. Petrography and core analyses reveal relationships between the rock physical properties that control the compressional- and shear-wave velocities of the formation. In addition, core data and petrography characterized the matrix permeability and pore spaces as well as the lithology. The lithology integrated with well logs determined the hydraulic and rock properties of a 500-ft zone intercepted by a borehole. We delineated vuggy and permeable/impermeable zones at the borehole and interwell scales in the upper Floridan aquifer in south Florida by inverting reflection seismic data for impedance which, when correlated with borehole permeability and porosity logs, led to empirical relationships that are used to transform impedance images to permeability and porosity images. The images showed continuity between the major geologic units and lateral changes in the porosity image. 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. This was corroborated with P-wave and borehole data, which showed that, as P-wave velocity decreases, porosity increases. The images show that porous zones in the carbonate aquifer are laterally continuous up to 200 ft from the well and then become relatively discontinuous, and that these porous and permeable flow units are characterized by interconnected vugs.

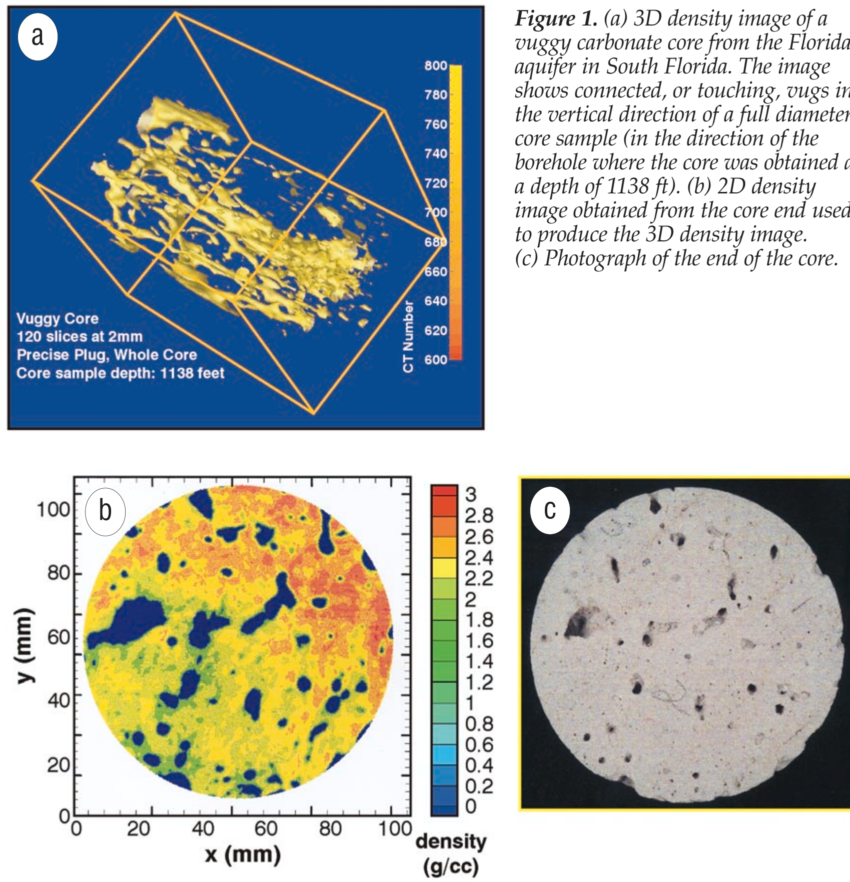


**Figure 1.** *(a) 3D density image of a vuggy carbonate core from the Floridan aquifer in South Florida. The image shows connected, or touching, vugs in the vertical direction of a full diameter core sample (in the direction of the borehole where the core was obtained at a depth of 1138 ft). (b) 2D density image obtained from the core end used to produce the 3D density image. (c) Photograph of the end of the core.*

**Figure 2.** *An optical microscope (OM) thin section image of the matrix of core shown in Figure 1. The magenta background is open pore space of the matrix (porosity).*

**Pore structure.** To analyze the pore structure of the carbonate rocks of the upper Floridan aquifer in South Florida, we processed x-ray CT and optical

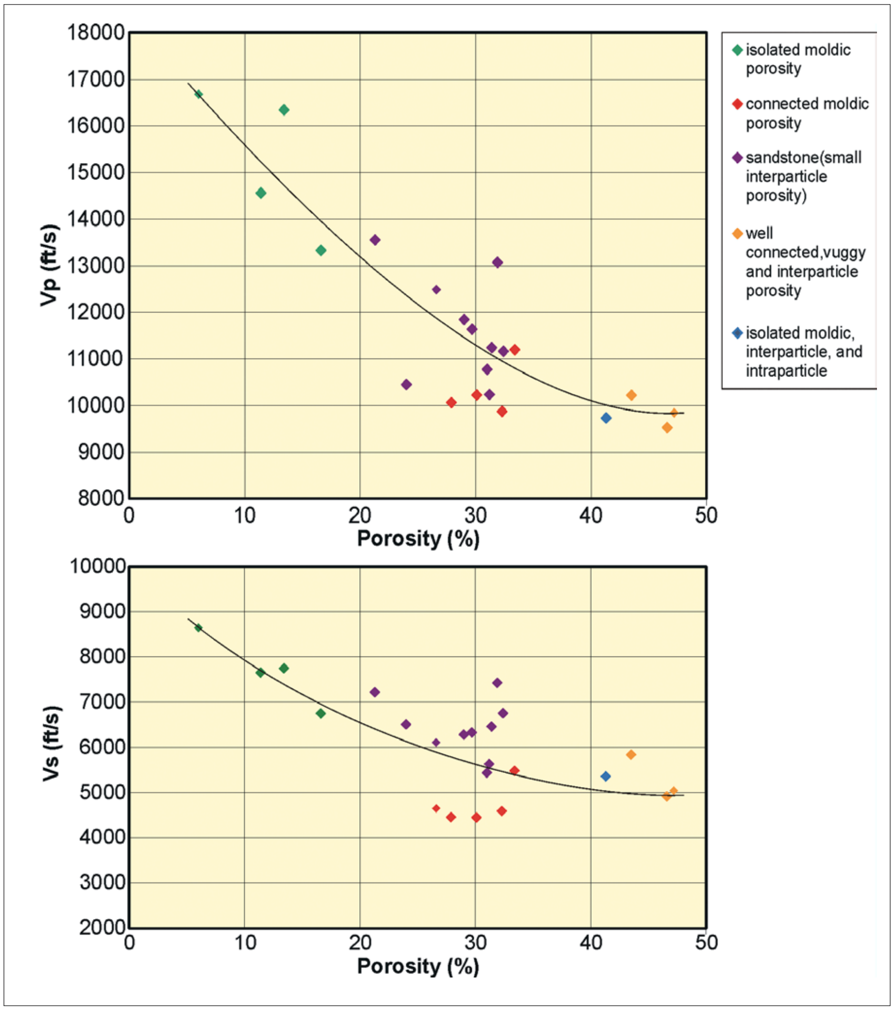


***Figure 3.*** $V_P$ *and* $V_S$ *plotted against porosity for five lithofacies.*

microscopic (OM) thin section images from core samples. Figure 1a shows, as an example, a 3D view of an x-ray CT image of a full diameter core sample from a depth of 1138 ft. The figure illustrates a typical interconnected vug system in the Eocene-aged Ocala Limestone. Vugs or vuggy porosity can be defined as pore spaces larger than or within the particles of rock and commonly present as leached particles, fractures, and large irregular cavities. A horizontal view of the end of the core was obtained from CT data. Figure 1b shows calculated density from the x-ray CT data of a core slice. Figure 1c shows a photograph of the end of the core for comparison. There is good agreement between the vuggy pores in the photograph and those visible in the CT cross-section. This sample has a vertical permeability of 4400 md and horizontal permeabilities of 904 and 3097 md. Differences between Figure 1b and 1c are ascribed to the lower resolution and inherent smoothing of the tomographic image. In addition, the CT slice is 2 mm behind the core end. Overall, the core exhibits high vug connectivity in the vertical direction. The matrix porosity of this carbonate rock sample is observed in a photomicrograph (Figure 2) which clearly shows the interconnected pores that correlate with high matrix permeability and porosity. The sample is best classified as a porous, calcareous packstone-to- grainstone, which denotes a texture that is grain-supported, but contains as much as 10% interstitial carbonate mud. The framework is dominated by skeletal grains, including abundant foraminifera tests. The internal structures of these skeletal grains are well preserved, as indicated by visible wall structures in coralline algae and forams.The pore structure and petrography help characterize the lithology and hydraulics properties of the rock units intercepted by the borehole. The lithology is subsequently related to field images to delineate the flow units in the interwell region.

**Velocity versus porosity and permeability: core scale.** To relate velocity to porosity and permeability images at the field scale, we examine first how the $V_P$ and $V_S$ velocities relate to porosity at the core scale. We selected 24 full-diameter core samples from different lithofacies intercepted by the borehole designated, well PBF-10, which was then used in concert with well PBF-13 to record sonic and crosswell seismic data. Several rock petrophysical measurements were made on these core samples. Figure 3 shows plots of $V_P$ and $V_S$ against porosity, including five facies. In general, P- and S-wave velocities decrease with increasing porosity in all facies. This velocity variation occurs because P- and S-wave velocities depend on the shear bulk moduli, or rigidity, of the rock matrix. The shear bulk moduli in turn correlates inversely to porosity, decreasing with increasing porosity. In effect, the pores reduce the structural integrity and hence the rigidity of the rock. Thus, flow units associated with connected moldic/vuggy-porosity are low-velocity zones. Figure 4 shows plots of $V_P$ and $V_S$ versus horizontal/vertical permeability. Although the P-wave velocity does not show a clear correlation between the rock samples, it does decrease as permeability increases. There are two major clusters: the high permeability samples in the region greater than 1000 md, which are uncorrelated with $V_P$, and the sandstones, which exhibit an increasing linear trend between $V_P$ and permeability. This trend is also observed at the borehole scale.

In the $V_S$ plot with permeability, a general increase occurs in permeability as S-wave velocity decreases. All pore-facies follow linear trends with a similar slope. The $V_S$ associated with the connected moldic and vuggy facies decreases from 5000 to 4000 ft/s as permeability increases from 700 to 6000 md. In the isolated moldic facies, $V_S$ decreases from about 9000 to 5000 ft/s, and permeability increases from 0.1-100 md. The S-wave velocity of the sandstones decreases from 7500 to 5000 ft/s as permeability increases from 12 to 700 md. This suggests that, as $V_S$ is reduced, the shear bulk moduli decreases and the pore structures change, with the pores being interconnected and more permeable.

**Well logs and lithology: borehole scale.** To relate geology with rock physical properties at the borehole scale, we used lithologic and geophysical well logs, and petrographical data. Figure 5 presents a sample of the lithology intercepted by well PBF-10. The permeability log is derived from the nuclear magnetic resonance (NMR) well log using a calibration method that requires a T2 cut off of 92 ms and cor-

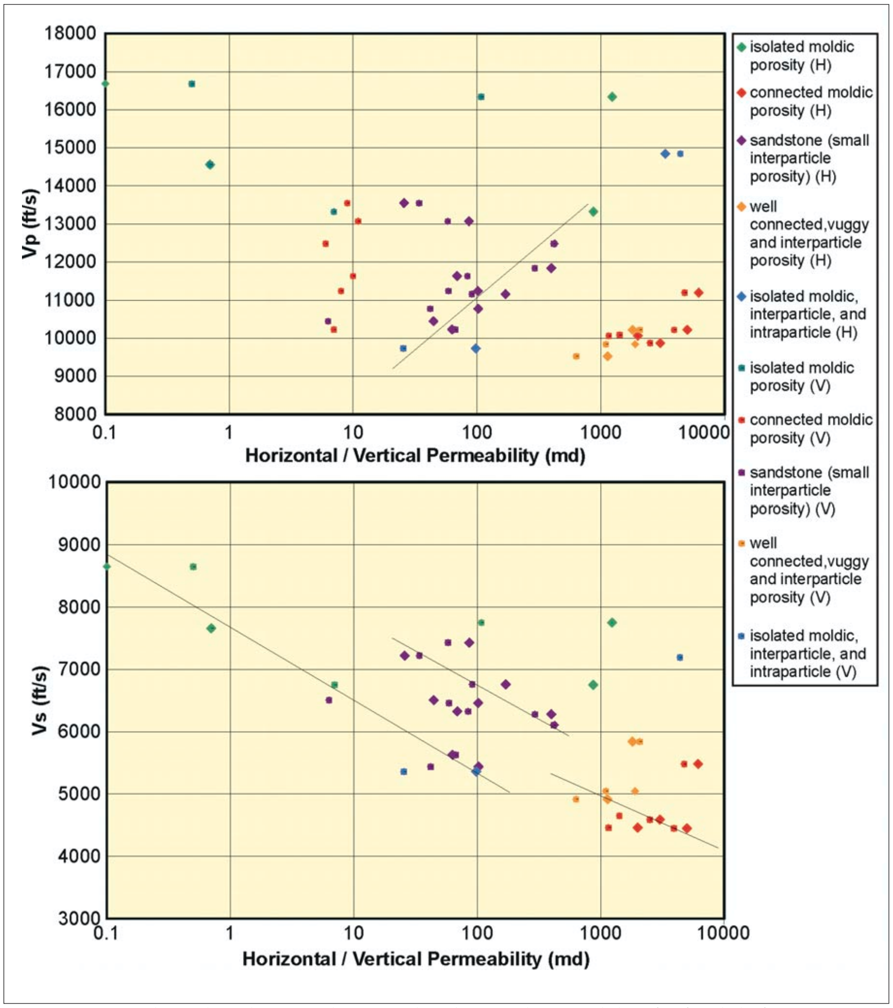


***Figure 4.*** *$V_P$ and $V_S$ plotted against horizontal and vertical permeability for five lithofacies.*

relations based on a data set containing carbonate core measurements from several reservoirs. Also shown are $V_P$, $V_S$, bulk density, log-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 1020-1040 ft 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.

Figure 6 shows the correlation

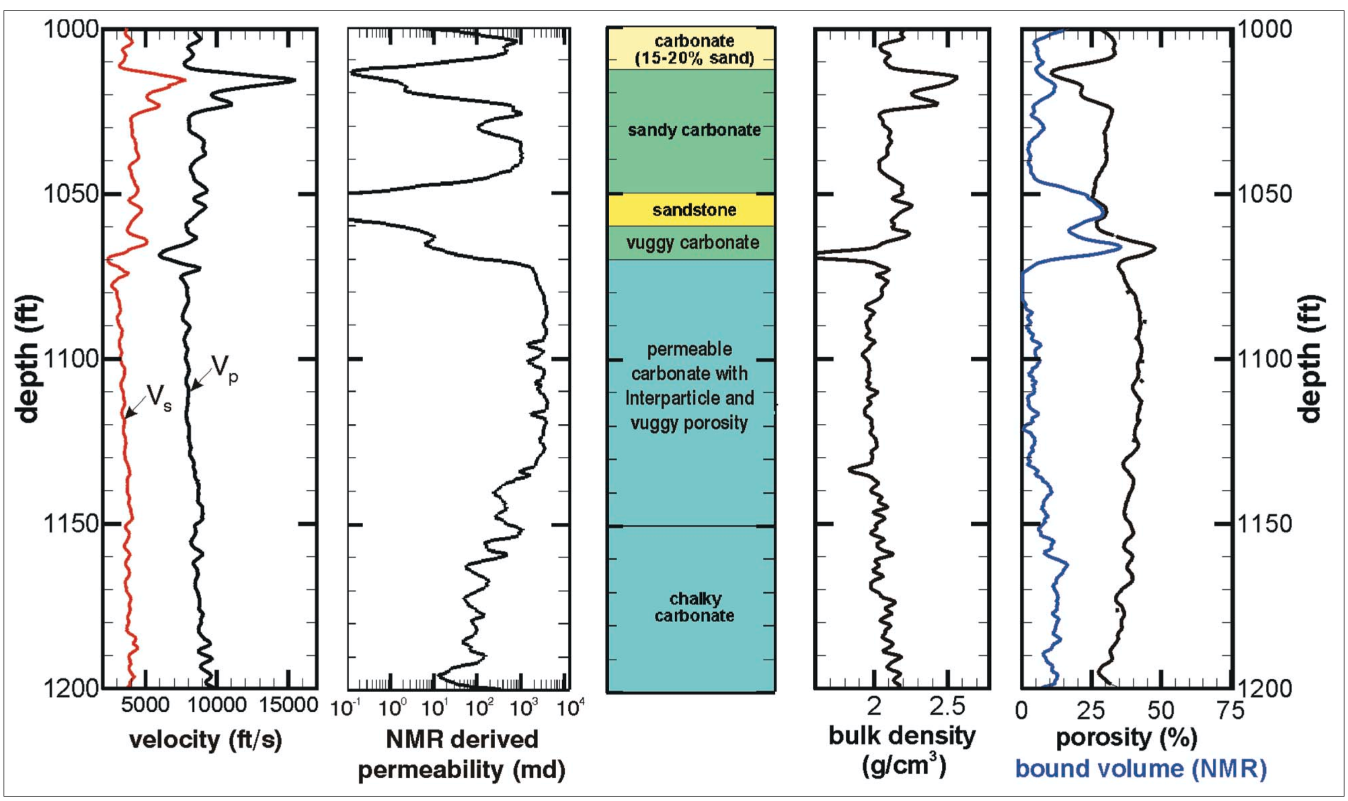


***Figure 5.*** *Lithology intercepted by well PBF-10 showing $V_P$, $V_S$, bulk density, log-derived porosity and NMR bound volume logs.*

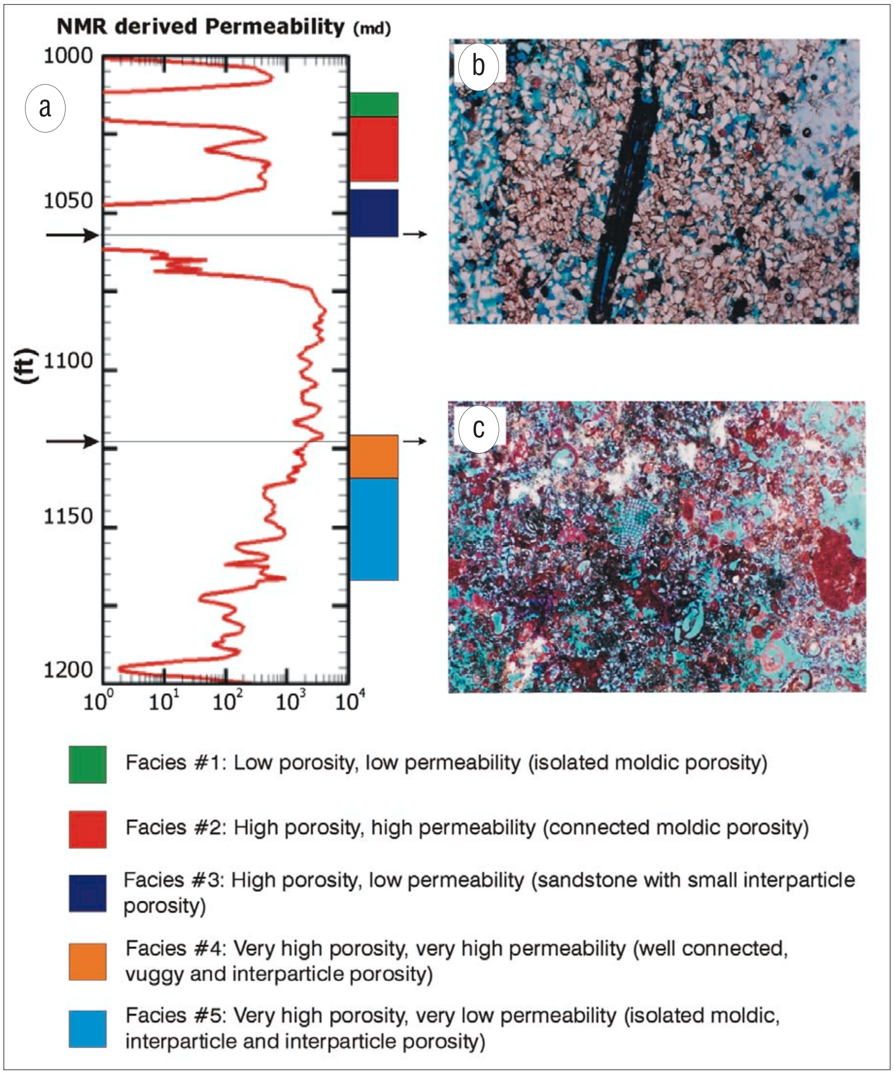


**Figure 6.** *(a) Correlation between the permeability log and the five petrophysical facies. (b) and (c) Two thin sections at 20× magnification which show the pore structure of facies 3 and 4, respectively.*

between the permeability log and the five facies. Two thin sections produced from core samples at 1060.5 and 1126.5 ft (20× magnification) show the pore structures of facies 3 and 4, respectively. The top thin section is representative of the very fine-grained, dolomitic, fossiliferous sandstone lithofacies. This facies has high, predominately interparticle porosity with low permeability. The bottom thin section shows a foram-pellet packstone with very good vuggy and interparticle porosity development responsible for the corresponding high permeability values.

**Crosswell seismic: field scale.** Crosswell seismic measurements were conducted at a site in southern Palm Beach County, Florida. The field measurements were conducted between wells PBF-10R and PBF-13 at an interwell spacing of 330 ft, 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 s at a sampling rate of 125 microseconds from 200-2000 Hz. Source and receiver depth sampling spacing was 2.5 ft, resulting in about 38 300 recorded seismic traces. Figure 7 shows the reflection image, velocity image, and well logs plotted in measured depth below land surface for well PBF-10, about 10 ft from well PBF-10R, (no velocity logs were available for well PBF-13). Actual reflection coverage below the total depth for each well was limited by well spacing. The vertical resolution of the reflection data for this profile was about 2 ft. There was no access to receiver locations below 1110 ft due to an obstruction in well PBF-10R. This limited access reduced reflection coverage in the deeper part of the section and thus the amount of reflection data available for mapping. The tomography image shows three flow units beginning at depths of 970, 1020, and 1070 ft, respectively. The flow unit at 970 ft is continuous between wells PBF-10R and PBF-13 and is about 10-ft thick. This flow unit has a low P-wave velocity with a moderate porosity averaging 28%. This flow unit coincides with high natural gamma-ray emissions present in the lower Arcadia Formation, which contains 15-20% phosphatic sands. The second flow unit, at 1020 feet, is a continuous bed less than 10-ft thick, with an average porosity of 20%. This unit, a sandy carbonate of the Arcadia Formation, is a high velocity zone associated with a low gamma-ray anomaly. Core samples from this unit are grainstones that contain separated vugs that may not contribute to its overall permeability. In this flow unit, permeability is controlled primarily by the matrix of the rock formation. The last flow unit is a 60-ft thick, low velocity region present within the Ocala Limestone at 1070 ft. It is a clean carbonate unit, as confirmed by the low natural gamma-ray emissions with interparticle porosity, which vary from 28 and 43% in the interwell region.

The reflection image in Figure 7 was inverted for impedance using the band-limited method. Figure 8 shows the impedance image between the PBF-10R and PBF-13 wells at depths from 750 to 1550 ft. The $V_P$ 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 (red). We analyzed the impedance image in the region between 950 and 1250 ft and plotted the permeability and porosity log data with the impedance at the borehole. Plots of impedance with permeability and porosity were used to derive empirical relationships (or impedance plot fit equations) for permeability ($k$) and porosity ($\phi$) for depths of 950-1250 ft. These expressions in terms of the Z impedance are given by

$$k=2\bullet 10^{14}\exp(-1.6\bullet{}^{a}10^{-3}Z) \qquad (1)$$

and permeability for depths of 1024-1045 feet is given by

$$k=10^{-24}Z^{6.28} \qquad (2)$$

Here, permeability is in md, porosity is in percent, and impedance is in $(g/cm^3)\bullet(ft/s)$. Equations 1 and 2 are used to convert the impedance to produce the overlaying permeability and porosity images. These images (Figure 9)

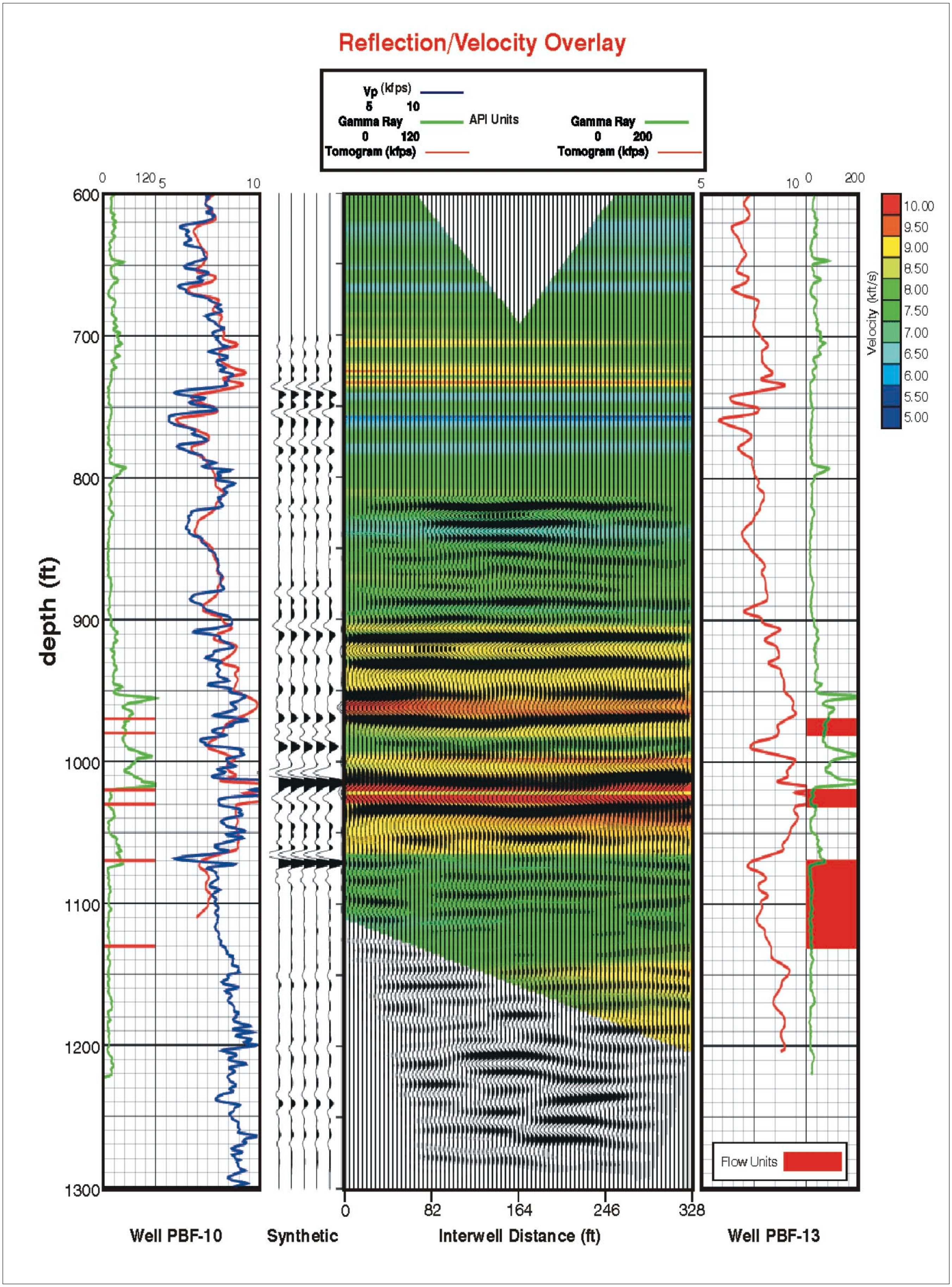


*Figure 7. Reflection and velocity images correlated with well logs from PBF-10 and plotted in measured depth below land surface (surveyed land surface elevation is 12.1 ft above sea level).*

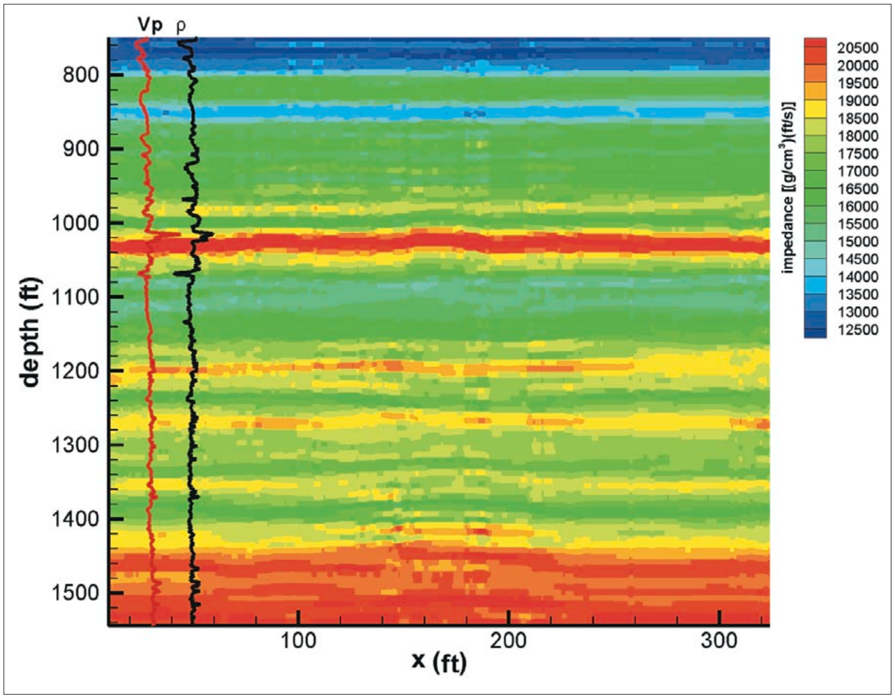


*Figure 8. Impedance image based on reflection data showing the* $V_P$ *and density logs.*

show continuous and discontinuous flow units. The lateral continuous flow unit (yellow) at 1020-1040 ft has an average permeability of 2000 md and an average porosity of 30% (blue in the porosity image at about 1020 ft). This flow unit was delineated as a continuous reflector in the reflection image in Figure 7.

The discontinuous flow unit shows lateral permeability and porosity changes in the region between the 1070 and 1140 ft. In this zone it is difficult to estimate the contribution of macropores versus vugs to the overall permeability. However, a rough estimate can be based on the relationship between $V_P$ and porosity as provided in Figure 3a and by observing the permeability and porosity images. We know that P-wave velocity decreases as porosity increases. This suggests that at the field scale (see Figure 7), seismic reflections below 1070 ft are associated with a porosity change due to the vuggy carbonate. For example, the two porosity

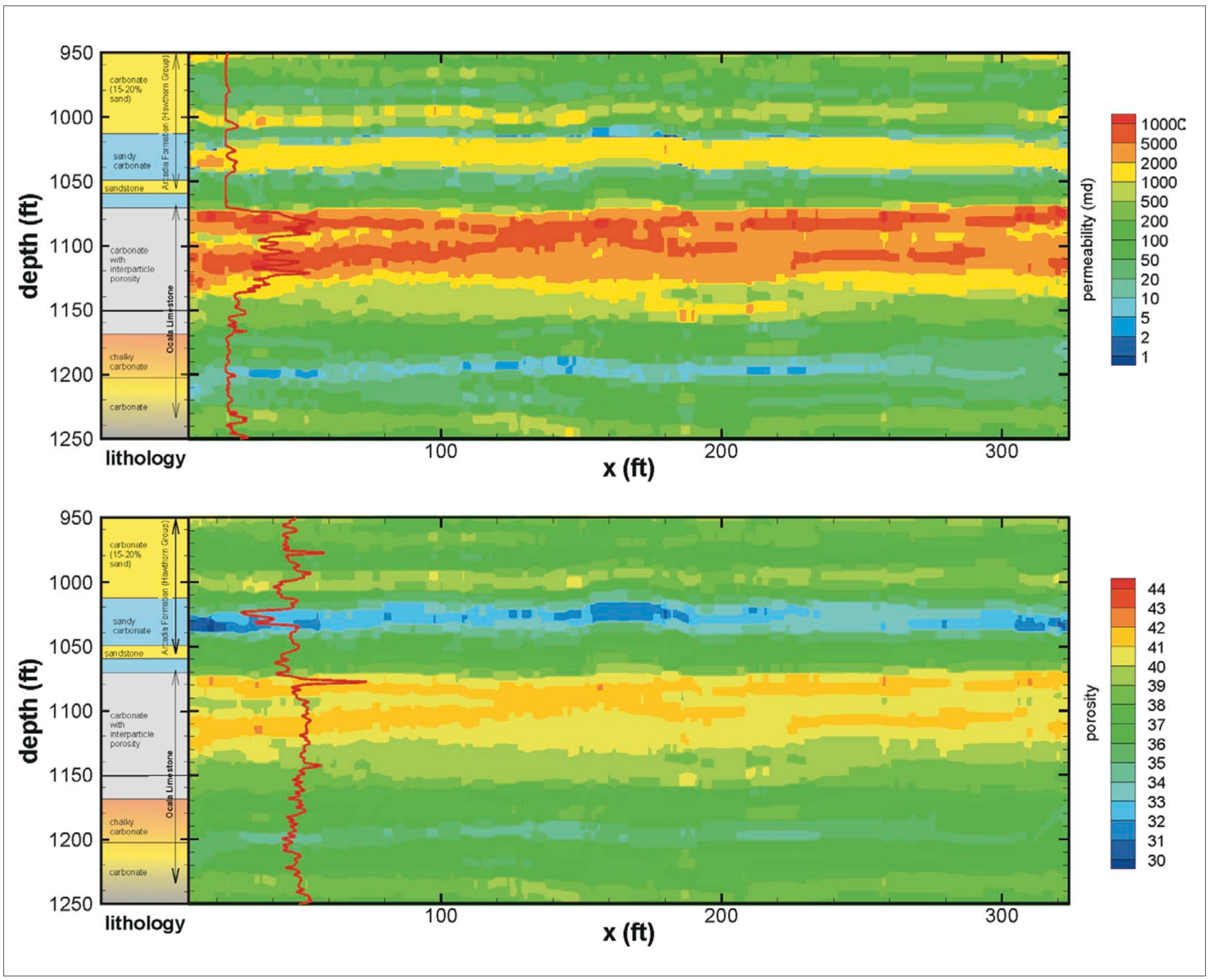


*Figure 9. Permeability and porosity images compared with lithology.*

zones in the 1070-1140 ft interval in Figure 9 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 (see the core image in Figure 1). Therefore, these two zones (red in Figure 9) are characterized by vuggy porosity, and permeability in the orange, yellow, and light green zones is probably controlled by macropores of the rock matrix. These flow units carry most of the water flow in the interwell region of the upper Floridan aquifer at this site.

**Discussion.** Lithologic and geophysical log data indicated a high flow zone between 1060 and 1070 ft at a lithologic or formational contact where a moderately indurated limestone is overlain by poorly indurated sandy limestone unit. This is seen on the geophysical logs by a enlarged borehole (caliper log), high log-derived porosity (60%), and low bulk density. Generally, within the Floridan aquifer, the majority of upward flow is produced by a 5-15 ft section of the borehole at lithologic boundaries (possibly due to sea level changes that control primary and secondary porosity development-sequence stratigraphy concepts). Flowmeter log data have shown two points of increased flow (planar feature), one at 1065 and the other at 1050 ft (another change in lithology), which dominate the contribution to upward flow. The water density in this flow zone and above are higher than below and the resulting water column (0-1065 ft) may act to suppress the upward flow from the lower unit by acting as a water stop or plunger effect. These flows may also overshadow any water production below this point. Although, the overall NMR permeability distribution is accurate, it does not necessarily quantify the point flow sources. A good approach would be to integrate or relate derived transmissivity data (in gallons per day/ft) to derived-NMR permeability and crosswell reflection data.

**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:

- Using a suitable calibration procedure, the NMR well log gives information on porosity, pore structure, and permeability.
- Plots between P-wave velocity and porosity core measurements demonstrate that velocity variation in the carbonate formation is inversely proportional to porosity. This relationship is also observed at the borehole scale.
- 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.
- Based on the pore scale analysis, the high porosity zones are formed by large 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 that are directly related to vuggy porosity development. The images also delineate continuous, less permeable flow units related to the macropores (interparticle porosity) of the rock matrix. These are the flow units that carry most of the flow in the interwell region of the upper Floridan.
- This study delineated a high-permeability region that is consistent with the hydrogeologic data collected from wells PBF-10 and PBF-13. The reflection image-derived impedance provides the depth of the lower boundary of the targeted ASR horizon as well as the lateral continuity within interwell region.

**Suggested reading.** "Quantitative characterization of carbonate pore systems by digital image analysis," by Anselmetti et al. (*AAPG Bulletin*, 1998). "Sonic velocity in carbonate sediments and rocks," by Anselmetti and Ebertli (in *Carbonate Seismology*, SEG 1997). "Hydrologic investigation of the Floridan aquifer system western Hillsboro Basin  Palm Beach County, Florida, by Bennett and Linton (Technical Publication WS-8, South Florida Water Management District, 2002). "Geological nomenclature and classification of porosity in sedimentary carbonates," by Choquette and Pray (*AAPG Bulletin*, 1970). "Simulating NMR magnetization in real carbonate pore systems," by Hackert and Parra (*Petrophysics*, 2002). "Estimating scattering attenuation from vugs and karsts," by Hackert and Parra (paper accepted for publication, GEOPHYSICS). "Petrophysical parameters estimated from visual description of carbonate rocks: a field classification of carbonate pore space," by Lucia (*Journal of Petroleum Technology*, 1983). "An integrated approach based on NMR/acoustic techniques to map permeability in carbonate aquifers: from the pore to field scales," by Parra et al. (paper accepted for publication, *NSG, Volume II*, SEG); "Wave attenuation attributes as flow unit indicators," by Parra and Hackert (*TLE*, 2002). "A methodology to integrate magnetic resonance and acoustic measurements for reservoir characterization," by Parra et al. (DOE/BC/ 15203-3 Report, 2001). "Seismic properties of carbonate rocks" by Wang (in *Carbonate Seismology*, SEG, 1997). TLE

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