High resolution P-wave surface seismic profiling to delineate flow units in carbonate aquifers of South Florida: a feasibility study

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Summary

High-resolution surface seismic, acquired at a south Florida aquifer, delineated flow units associated with permeability between 1- 4 Darcy and porosity between 30 to 45 percent. The impedance image determined by inversion from P-reflection data resolves most of the boundaries between facies. The facies properties are based on the integration of the lithology and the well logs, and they consist of vuggy carbonate units and sandstones. At this aquifer, the low permeability zones are sandstones and the permeable zones are carbonates with interconnected vuggy porosity. Porosity and permeability images determined from the impedance images and the well log information suggest that high-resolution surface seismic can delineate and map the stratigraphy as well as the rock physical properties of the south Florida aquifer.

Introduction

Carbonate formations generally have broad pore size distributions, from microcrystalline to large vugs (Choquette and Pray, 1970). These pore spaces and their geometries are crucial to an understanding of hydrocarbon reservoir characterization and hydrogeological and environmental issues. Pore structures are thus important aspects of a description of carbonate reservoir flow units and the hydraulic properties at the borehole and field scales. These properties have been evaluated at the core, borehole and crosswell seismic scales at the south Florida Water Management District's West Hillsboro aquifer storage and recovery (ASR) Pilot Project near Boca Raton in Florida (see Parra et al., 2001). High-resolution crosswell tomography and reflection images were used for petrophysical analysis in conjunction with core and logging data to evaluate lateral variations in the limestone aquifer to relate them to permeability and porosity variations. This work has provided information on the flow units of the aquifer at these three scales (core, borehole and crosswell) between wells at a separation of 330 ft.

Although these results provided good data at high resolution, the volume of earth covered is too small to be practical for geological mapping and for the delineation of regional flow units. In south Florida, the separation between water wells usually exceeds 1 mile, which makes the use of the crosswell technology impractical. This leads us to explore the use of high-resolution surface seismic as a possible technique to image the subsurface geology. The purpose of this paper is to evaluate the applicability of P-wave (compressional) reflection seismic for mapping subsurface features over a wide range of depths in a regional carbonate environment. The depth range of interest is generally from ground surface to 2000 feet. We use crosswell seismic images and well logs to evaluate the 2D surface seismic method to map the geology and flow units in the south Florida aquifer. This includes: (1) determine the shallowest and deepest range of subsurface imaging for the P-wave reflection method, (2) evaluate the horizontal and vertical resolution, and (3) relate the local geology and petrophysics through the use of P-wave sonic logs from observation well PBF10 located near the P-wave seismic survey line.

Data Acquisition

A 2D seismic P-wave line survey was conducted at a site located in southern Palm Beach County, Florida adjacent to the northern side of the Hillsboro Canal, where it enters the Florida Everglades. Bay Geophysical (a division of Blackhawk Geoservices) acquired two high-resolution reflection seismic test profiles along the Hillsboro Canal. The P-wave profile was collected along a two-track road running parallel to the canal and access was provided by the South Florida Water Management District. The topography of the test area was relatively flat except for a small drop in elevation near the beginning of the line. A total of 3,475 feet of high-resolution reflection P-wave seismic profile was acquired. Reflections containing frequencies of 300 Hz were recovered, which was the maximum frequency input by the seismic source. A seismic vibrator was used for P-wave data acquisition.

Interpretation Methodology

Well logs from well PBF-10 and cores were used to create a lithological column between depths 700 – 1400 feet. The P-wave velocity well log was derived from full waveform sonic. The petrophysics and description of well logs are given in Parra et al. (2001). Since our main objective is to compare high-resolution interwell scale versus 2D surface seismic scale, we invert seismic data for impedance using the Vp and density logs. These data sets were inverted for impedance using the band-limited method (a feature of the STRATA software, developed by the Hampson and Russell Company). The permeability was derived from a NMR log calibrated with core data. In addition, we create cross plots between the impedance and the permeability and porosity

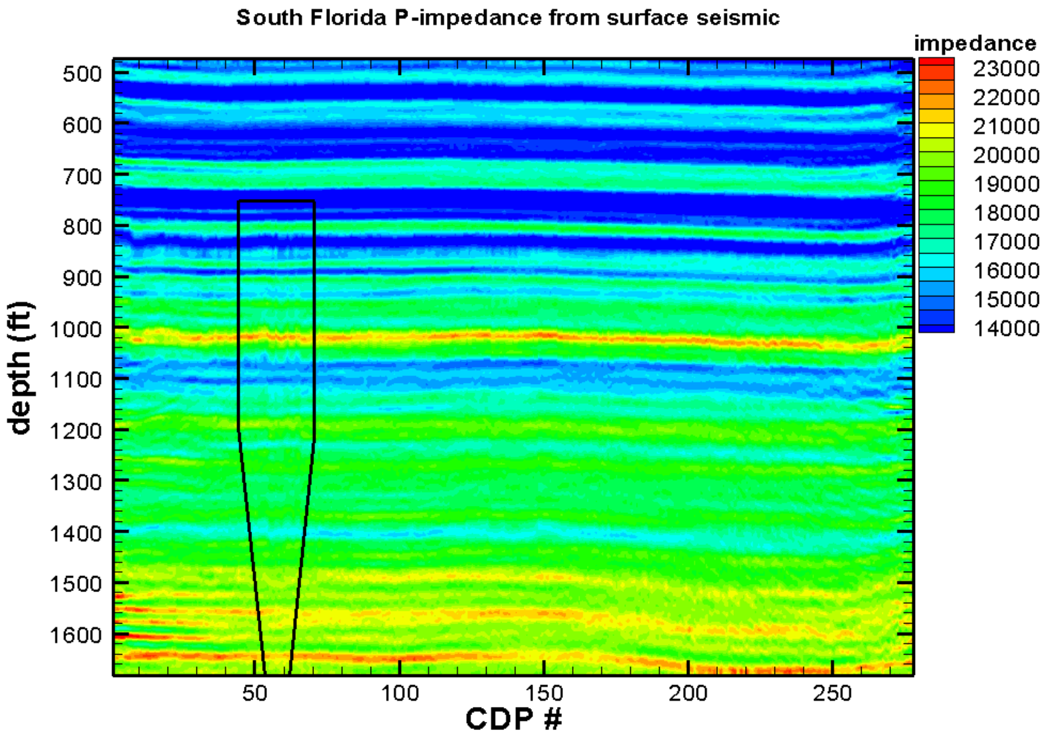

Figure 1: P-impedance from South Florida high-resolution surface seismic data. The heavy line indicates the approximate data coverage of a recent crosswell reflection survey.

well logs to derive regression equations at the borehole location. The resulting relationships are used to produce permeability and porosity images at the surface seismic scale. In addition, crosswell and 2D seismic synthetic seismograms are produced and compared with their corresponding observed seismograms to assess the quality of the data and the continuity of the major geological facies and boundaries.

The P-wave reflection data was converted to an impedance image using the PBF-10 well logs. The resulting impedance image shows the structure of this site more clearly than the reflection data alone (Figure 1). With the 12.5 ft spacing of the CDPs, the image covers almost 3500 ft in horizontal length. The seismic data shows many of the same features observed in the crosswell data, although at lower vertical resolution. The vertical resolution of the seismic data is much less than that of the well logs, as previously noted.

Figure 2 shows an expanded view of the P-impedance from the seismic line in the region where it overlaps with the crosswell reflection data. This figure also shows a comparison between the well log impedance parameters (P-wave velocity and density), and the impedance computed from the surface seismic section. The relationship is very good, partly because the well logs are used to help constrain the impedance values in the seismic section. Figure 3 shows the P-impedance derived from the crosswell reflection data. The crosswell data has roughly three times the bandwidth of the surface seismic data, with a corresponding increase in vertical resolution. The crosswell data also provides slightly better horizontal resolution, but of course is limited to the zone between the wells.

In the carbonate region of the well logs there is a strong trend of porosity and permeability varying inversely with impedance. Crossplots of impedance versus permeability and porosity (all from the well logs) were produced for the depth range of 1000 to 1200 ft. Correlations can be fit to these crossplots, although with uncertainty of roughly an order of magnitude in permeability and about 5% in porosity. In spite of this relatively high uncertainty, the correlation equations were used to map the impedance images into permeability and porosity images with should reflect the trends in the formations at this depth. These images, shown in Figure 4 display the same high and low permeability units seen in the well logs and crosswell images (see Parra et al., 2001).

In particular, the bi-level structure of the high permeability flow unit from about 1050 to 1120 ft depth appears to be of wide extent. The large horizontal extent of this survey also appears to show a structural high near CDP #140. The lower part of this flow unit appears to be less continuous than the upper part over most of the horizontal distance, again consistent with the crosswell seismic image, shown for reference in Figure 5.

Conclusions

The P-wave data show coherent reflectors ranging in depth from approximately 100 feet to 2700 feet (estimated). Reflections containing frequencies of 300 Hz were recovered, which was the maximum frequency input by the seismic source. P–wave profiling can map major flow units and permeability barriers using wells located at large separation (exceeding 1 – 2 miles) in south Florida aquifers. The comparison between 2D surface seismic versus the crosswell seismic and sonic data demonstrate that high-resolution 2D seismic captures several flow units at comparable resolution to the crosswell data. The permeability and porosity well logs (overlain on the images) correlate with the permeability and porosity images based on the 2D seismic impedance. In particular, a vuggy carbonate zone was delineated by the permeability images between the depths of 1050 and 1120 ft. This suggests 2D seismic is the more practical method to use in south Florida for mapping flow units. The synthetic seismograms agreed very well with the observed seismograms, further suggesting that the major geological units are continuous in the south Florida aquifer.

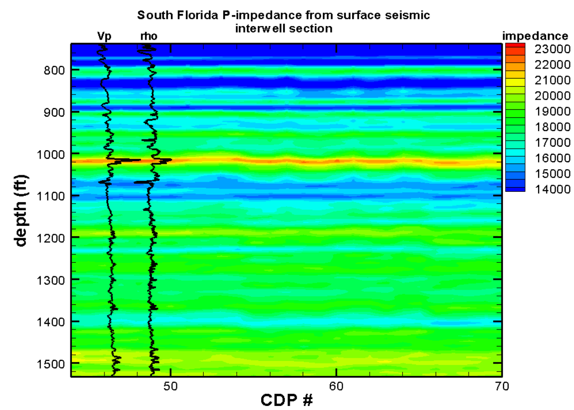

Figure 2: A section of the P-impedance from surface seismic data, which overlaps with the crosswell reflection data. Well logs of P-velocity and density are overlain near the well location of CDP #44.

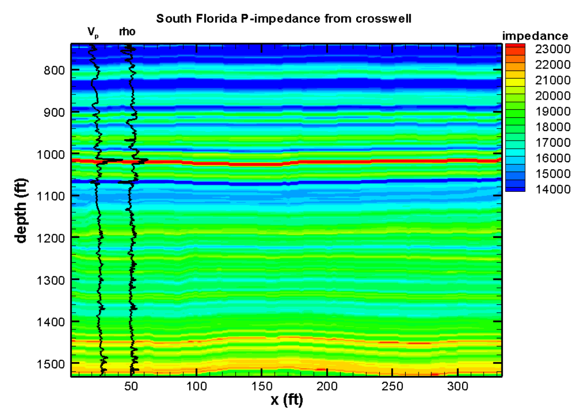

Figure 3: P-impedance computed from crosswell reflection data. Well logs of P-velocity and density are overlain near the well location of x = 0.

References

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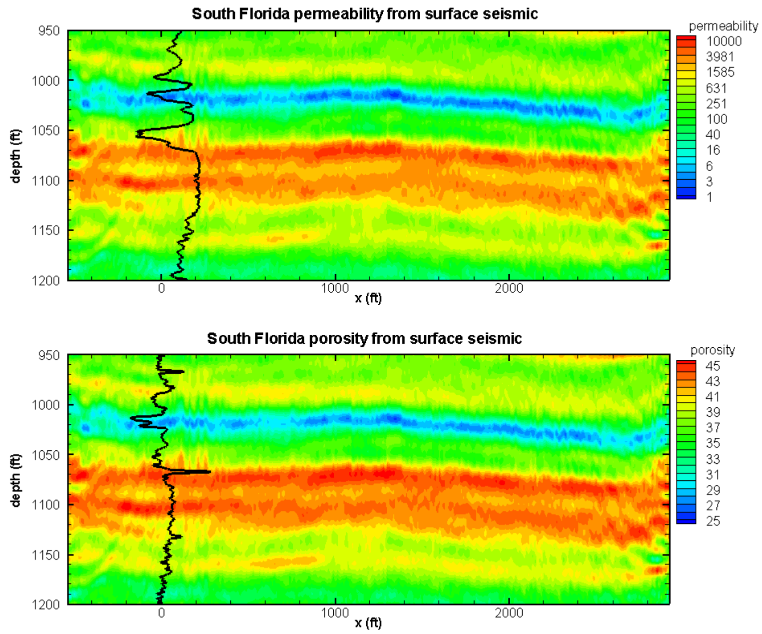

Figure 4: Permeability and porosity inferred from surface seismic P-impedance and correlations with the well logs. Logarithm of permeability and porosity well logs are overlain near the well location of x = 0 (CDP #44).

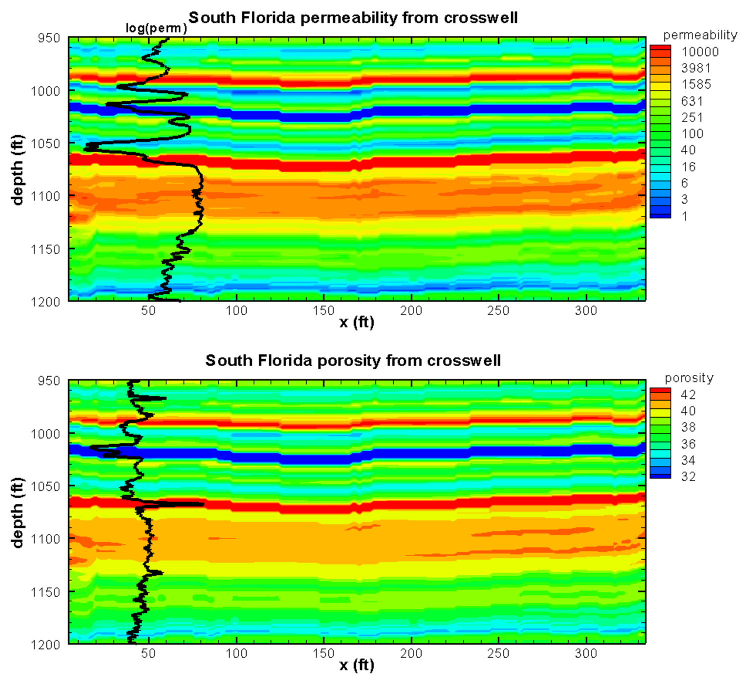

Figure 5: Permeability and porosity computed from crosswell P-impedance and correlations with the well logs. Logarithm of permeability and porosity well logs are overlain near the well location of x = 0. The crosswell data provides higher resolution, but limited horizontal extent.