Inversion and interpretation of multicomponent seismic data: Willesden Green, Alberta

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ABSTRACT

In this paper, 2D multicomponent seismic data and well logs from the Willesden Green, Alberta area are used to investigate potential oil reservoir intervals. The Upper Cretaceous (Turonian) Second White Speckled Shale (2WS) and Cardium formations are the zones of interest in this study. PP and PS synthetic seismograms generated from the well logs provide a reasonable correlation with the multicomponent surface seismic data. PP and PS inversion was applied to the vertical and radial components to yield P impedance and S impedance. The Vp/Vs estimate shows anomalous values over the zones of interest around the producing wells: 8-13-41-6W5; 8-26-41-6W5 and 6-15-41-6W5 and are helpful for productive zones and sand/shale discrimination.

INTRODUCTION

The Willesden Green oilfield is located in south-central Alberta, covers 50,827 hectares, and is the second largest Cardium field after Pembina (both in area and initial oil in place). Several productive horizons in this area (the Second White Speckled Shale, Cardium, Viking and Glauconitic sands) continue to produce significant quantities of oil and gas.

In the attempt to understand subsurface lithologies, it is useful to use not just P wave properties, but those of the S wave. Recent interest in the use of PS waves to help to characterize fractured reservoirs has lead to the acquisition of multicomponent surveys in the industry. The combination of pure P wave measurement with the converted waves can provide more information about the rock structure, state of fracturing, pore fluids, lithologic type and stratigraphy.

In 1992, two 3-C seismic lines were acquired: WG-1 an E-NE line crossed by WG-2 an N-NW seismic line. The location map is shown in Figures 1 and 2. The lines were oriented NNW and ENE, and were processed for PP and PS reflections, including anisotropic rotations. A first interpretation was done by Stewart et al. (1993). The overall goal was to see if 3-C seismic data could help find oil in the productive interval of the Second White Speckled Shale (2WS). VSP data acquired with vertical vibrator sources on line WG-2 was used for a more confident interpretation.

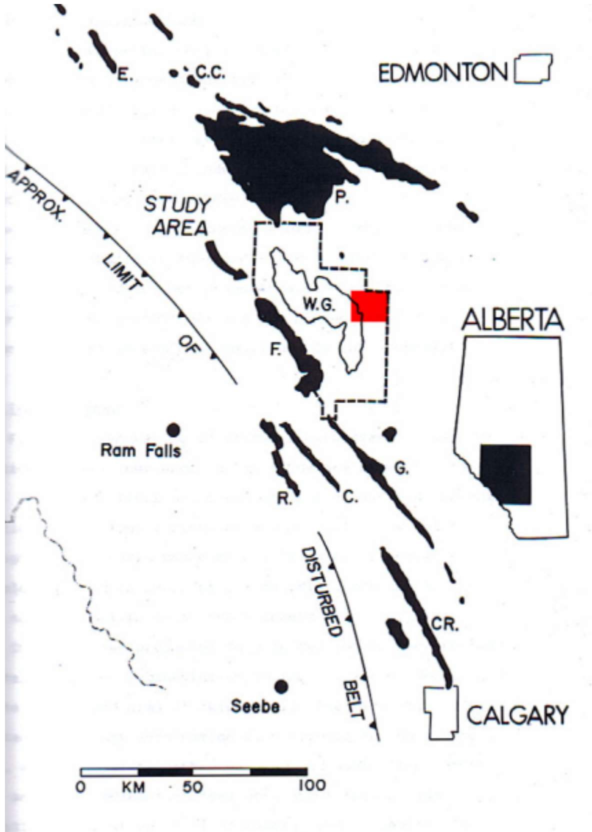


FIG. 1. Location of the Willesden Green area In West Central Alberta. The area in red contains our specific study area.

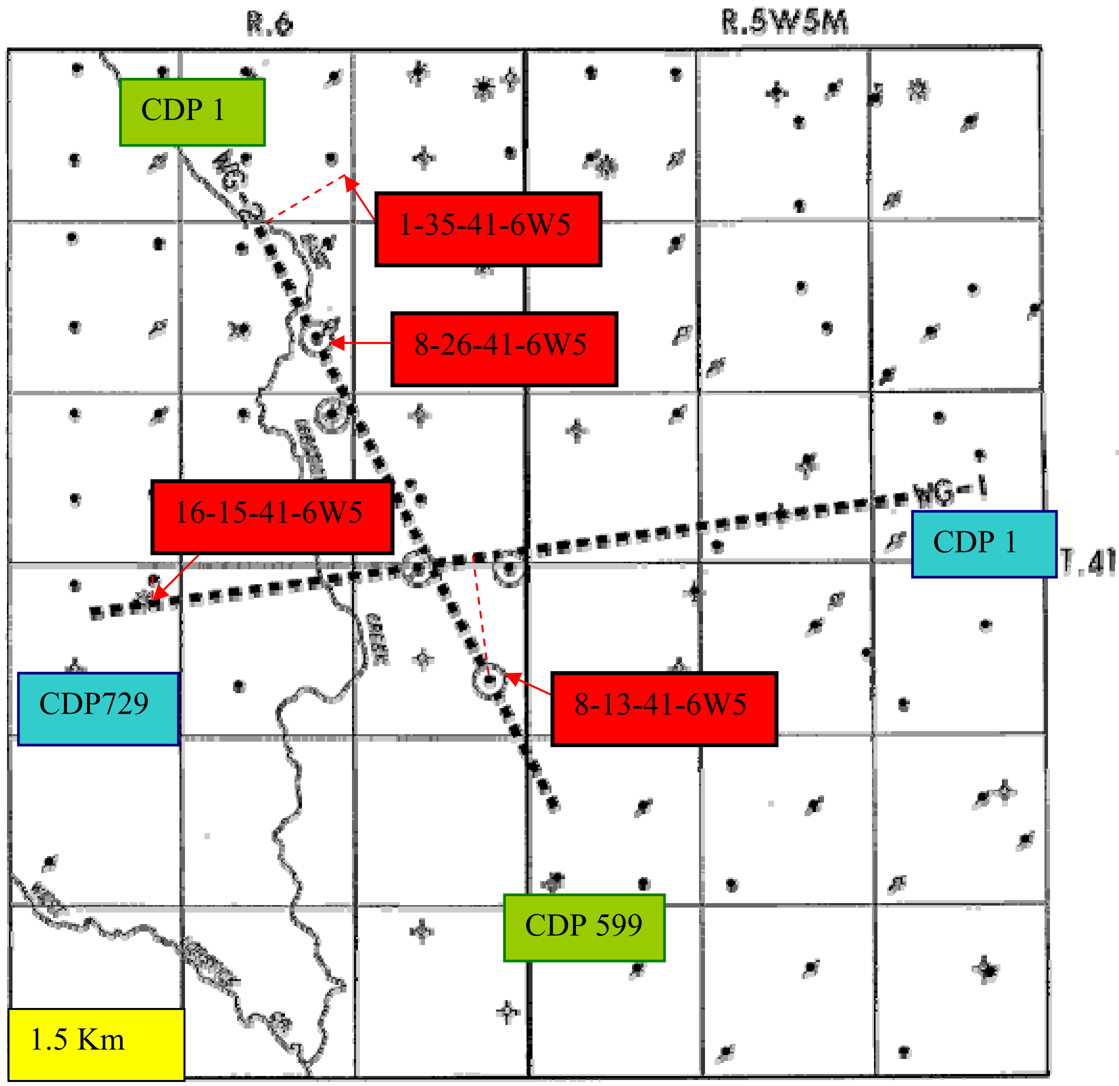


FIG. 2. Location of the two seismic lines used in this work with CDP numbers. The wells employed in the study are also annotated.

GEOLOGY AND STRATIGRAPHY

The Colorado Group was deposited during a period of global sea level high-stand, with the down flexing of the North American craton. This led to increased accommodation and thick, geographically continuous shale deposition (Leckie et al., 1994). Relative sea level fluctuations resulted in condensed sections and regressive siltstone and sandstone packages (Bloch et al., 1999).

Most studies of the Colorado Group have focused on investigations of the coarser grained reservoir units like Cardium formation. However, the shale-dominated sequences within the Colorado Group provide a much more complete record of deposition and a more comprehensive picture of Cretaceous paleogeography (Bloch, 1994). See Figure 3.

The Second White Speckled Shale (2WS of the Colorado Group) is an Upper Cretaceous fine-grained, laminated clay sediment, deposited in a shallow to open marine environment. It is a mainly calcareous shale and mudstone with intercalated chalk, calcarenite, bentonite, calcite and phosphorite and localized occurrences of sandstone and siltstone. It is a good stratigraphic marker and has thickness between 45m and 70m. It is overlain by the Colorado shale and underlain by the Belle Fourche shale. The 2WS is both, a source and a reservoir rock (in shales the hydrocarbon may remain trapped within the source rock), containing type II Kerogen (See Figure 4). It is suggested (Travis, 2002) that the 2WSPK may retain significant amounts of generated liquid hydrocarbons due to its fine-grained nature. At deeper burial depths, these hydrocarbons would be cracked to gas. For production of shale gas, a fracture system must be developed within the source rock to contribute storage capacity (porosity) and migration pathways (permeability) for the gas.

Sand lenses within the shale sequences are also common and would represent local zones of enhanced porosity and permeability within the overall shale reservoir (McKinstry, 2001). The 2WS formation represents a yet undeveloped unconventional gas play within the Western Canada Sedimentary Basin (Travis, 2002)

The 2WS is picked on geophysical logs due to its high gamma response. As calcite in the source rock increases toward pure limestone, the hydrocarbon potential decreases. A number of wells in the proximity have produced and still produce oil and gas from the 2WS. Because a number of penetrations of the 2WS have not produced oil, conventional P-wave prospecting was considered not enough.

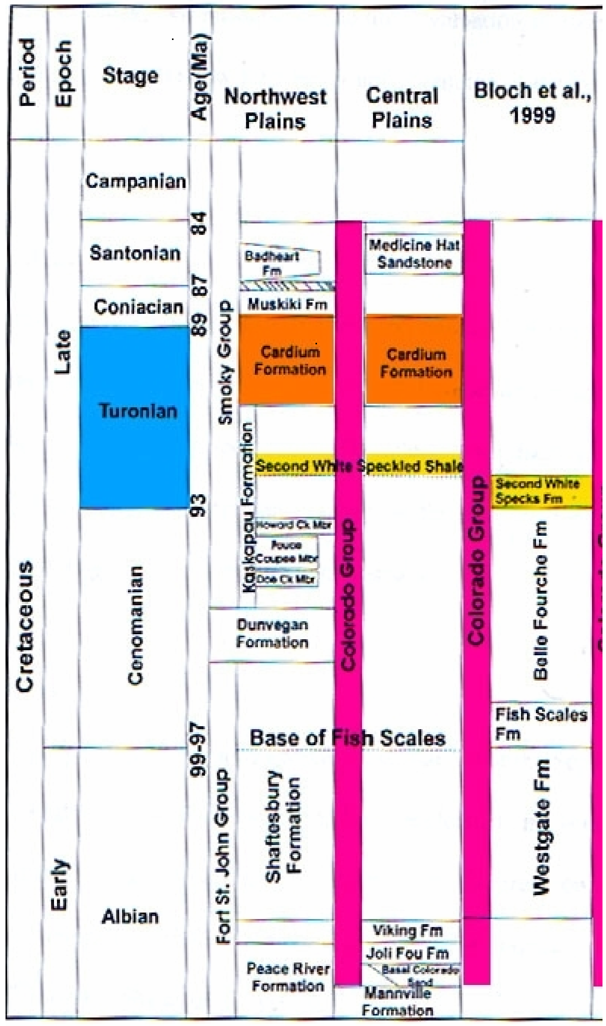


FIG. 3. Stratigraphic nomenclature of West Central Alberta (modified from Bloch et al., 1999).

The Cardium Formation was deposited along the western margin of the Cretaceous Interior Seaway within the Alberta Foreland basin of the Canadian Cordillera. The Cardium formation is the main sandstone unit within the Alberta (Colorado) group and contains about 100 m of interbedded sandstones and shales. It is overlain by the Wapiabi Formation which is about 600 m thick and consists mostly of shales. The top of the Cardium formation is recognized by the first appearance of a thin chert pebble bed, occurring below the First White Specks (a regionally recognizable well log marker) but above the main Cardium sandstones and conglomerates. The thickest Cardium conglomerates are preferentially accumulated in the East and Northeast of Willesden Green area. Some scouring of the Cardium sandstone by the conglomerates is probable within Willesden Green (Keith, 1985).

The Cardium zone is sometimes difficult to pick and, as shown by Griffith (1981), has frequently been incorrectly positioned. The markers with possible high resistivity kicks which can be identified on Gamma logs are: 1WS shale, Cardium and the 2WS shale.

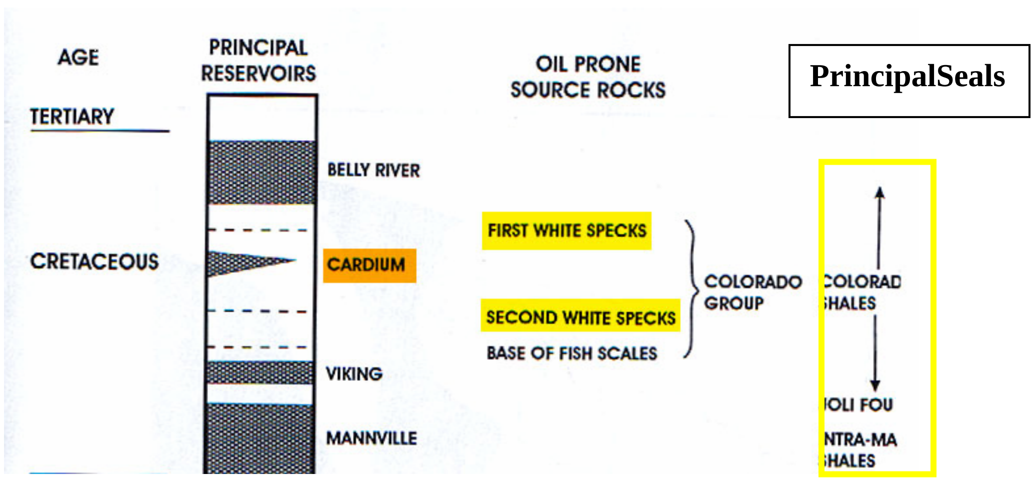
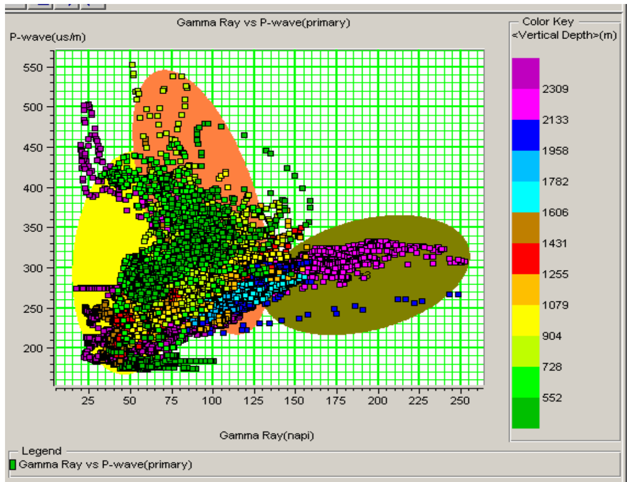


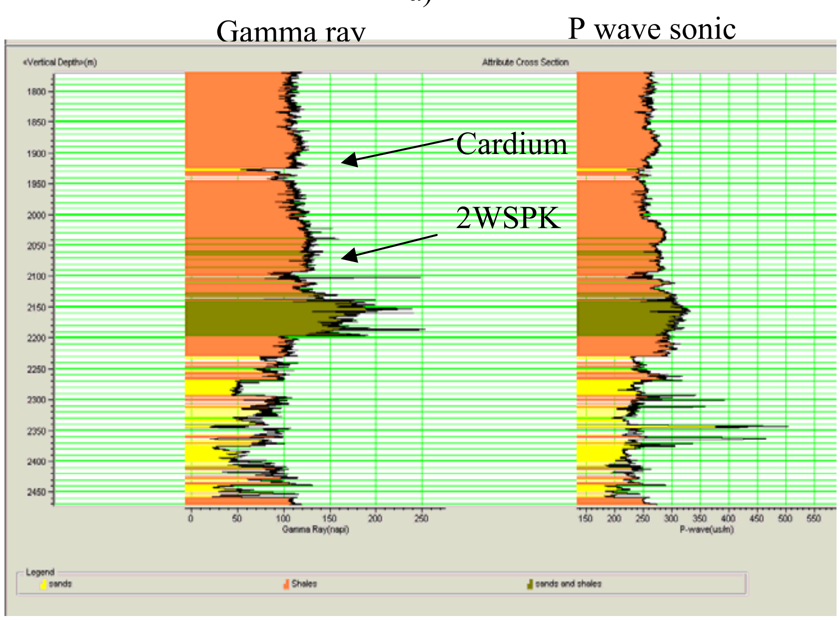
FIG. 4. Generalized stratigraphy of The Western Canada Sedimentary Basin (Creancy et al., 1992).

Seals are generally formed by interbedded mudstones but may result from juxtaposition of low permeability rocks over reservoir rocks by thrusting.

To differentiate the lithologies, a crossplot of Vp versus gamma ray was created for the well 6-15-41-6W5 (Figure 5).



a)



b)

FIG. 5. Vp versus gamma ray for well 6-15-41-6W5. a) Three major types of lithology were selected: sands (yellow), shales (orange) and sand/shales (olive), b) Cross-section for well 8-26-41-6 delineating the three zones with different lithology. Low values in the gamma ray log usually indicates permeable sand interval with high porosities.

ACQUISITION AND PROCESSING FOR 3-C SURFACE SEISMIC AND VSP

The surface seismic surveys used two vertical vibrators, 3-C geophones and receivers with offsets up to 2520m. The two surface lines were shot at 70 degrees to one another with a 60m source interval and 20 m receiver interval. The source consisted of Mertz M18 vibrators sweeping for 12 s over an 8-70 Hz range. Records were vertically stacked twelve times. The geophones used were three component HGS 10 Hz receivers planted in a 45cm augured hole. There were 252 live stations in a split-spread configuration providing far offsets of 2520m. The VSP's were acquired with vertical vibrator sources and three component receiver at a depth interval between 400m and 2175m.

The two lines were reprocessed in 2004 by Peter Cary at Sensor Geophysical. Vertical and radial migrated stack were generated. The processing flow for the PP section was conventional and included surface consistent deconvolution, time-variant spectral whitening, refraction statics, trim statics, cdp stack and migration. The processing flow for the PS section included asymptotic cdp binning, surface consistent deconvolution, refraction statics, trim statics, cdp stack and migration.

SOFTWARE

Different software was used with the steps of multicomponent interpretation:

1) The correlation of well logs to the seismic data was accomplished using the eLog package. The tool to analyze PP and PS datasets simultaneously, and to create the Vp/Vs sections was the ProMC package.

2) Inversion was performed using Hampson-Russell's Strata package, where both PP and PS colored Impedance section were constructed and analyzed.

3) The Accumap System was used to retrieve the well logs and to get information for the well production and operation.

PP INTERPRETATION

As a first step for a more confident interpretation VSP data and corridor stack/VET from well 8-13-41-6 was stretched to tie the PP seismic data on line WG2 (Figures 6 and 7). Available log suites for most wells include P-wave sonic, density, gamma ray, resistivity and SP logs.

The next step was the correlation of the PP seismic data with the well logs, using the Hampson-Russel software eLog and ProMC package, as in Figure 9. By convolving the reflectivity and the wavelet at the well location, the synthetic traces (in blue) were generated. Then, each pick from the seismic data (in red) was correlated with a pick from the synthetic trace. The well log was stretched according to this correspondence (See Figure 8).

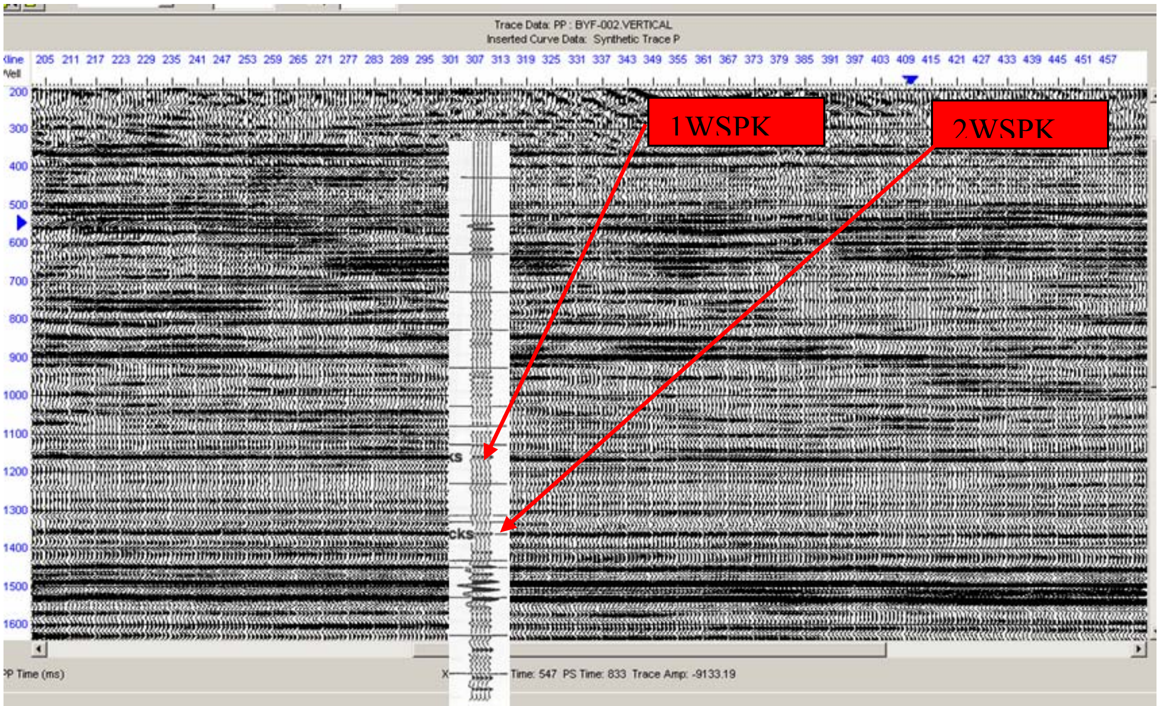


FIG. 6. WG2 seismic line correlated with the corridor stack/VET (Stewart et al., 1993) from well 8-13-41-6W5.

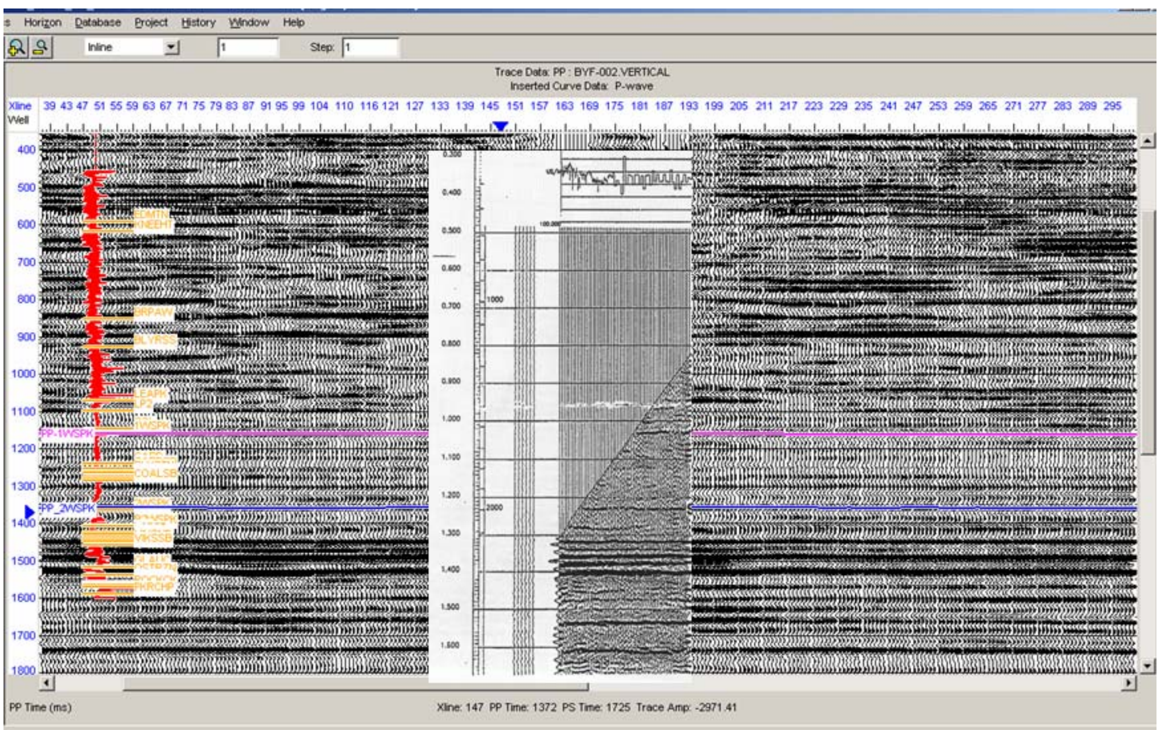


FIG. 7. WG2 seismic line correlated with the zero-offset VSP (Stewart et al., 1993) stretched two way time at the well 8-13-41-6W5.

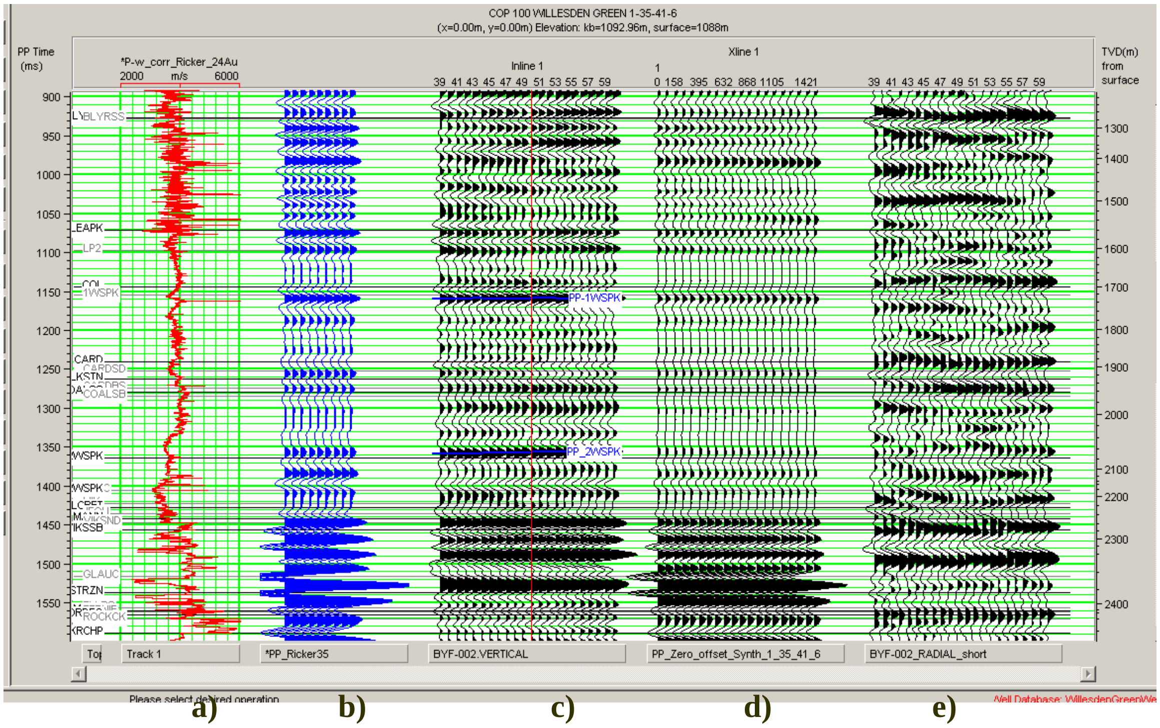


FIG. 8. Well log 1-35-41-6W5 in PP time correlated with seismic line WG2: a) P wave sonic, b) zero-offset synthetic seismogram, c) PP seismic, d) PP offset prestack synthetic, e) PS seismic (in PP time).

In Figure 8, we note from left to right: a) the P wave sonic, b) the zero offset synthetic seismogram (blue), c) the vertical surface seismic, d) the PP offset prestack synthetic and e) the radial surface seismic, all in PP time.

In Figure 9, the correlation coefficient is almost zero phase, with a correlation of 80%.The interpreted horizon for 1WS is at time 1160 ms and for the 2WS at 1360 ms.

The Zoeppritz application from ProMC was used to create the prestack synthetics (Figure 8) with the number of offsets 20 and maximum offset 1500 m. However, the solution of Zoeppritz's equation cannot be taken as the exact seismic response, because (among other things) the Zoeppritz equation describes plane waves, while actual seismic waves are spherical (Lines and Newrick, 2004). In addition, the synthetic seismogram is calculated in the absence of external effects such: attenuation, transmission loses coherent or random noise, geophone coupling, etc.

We can notice an increase (kicks) in velocities on the sonic logs at the three markers: 1WS, 2WS and Cardium. According to the correlation we can describe the following depth of tops: 1WS at 1710 m, Cardium 1890 m and 2WS at 2070 m.

A 35 Hz Ricker wavelet was created (the vertical seismic data was bandpass filtered at 8-12-60-75 Hz after the processing) to match the PP seismic data. The wavelet parameters are: dominant frequency = 35Hz, sample rate = 2 ms, wavelet length = 100ms, phase type = constant phase (See Figure 10).

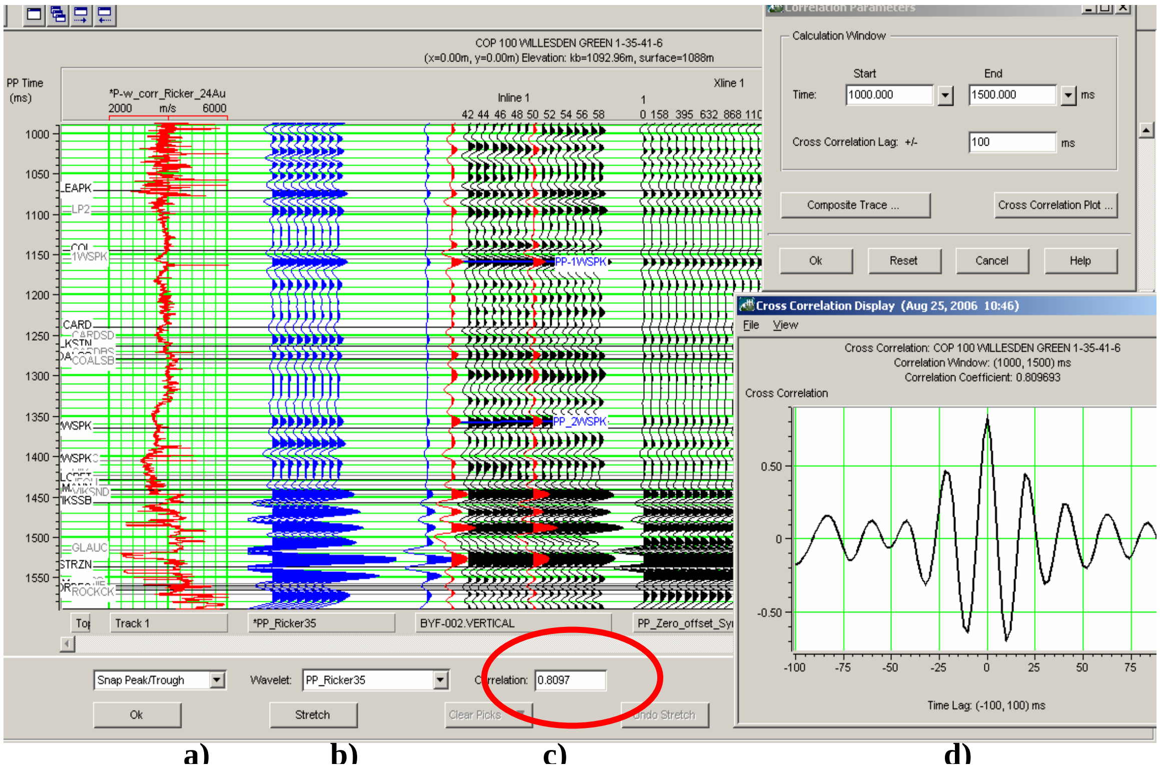
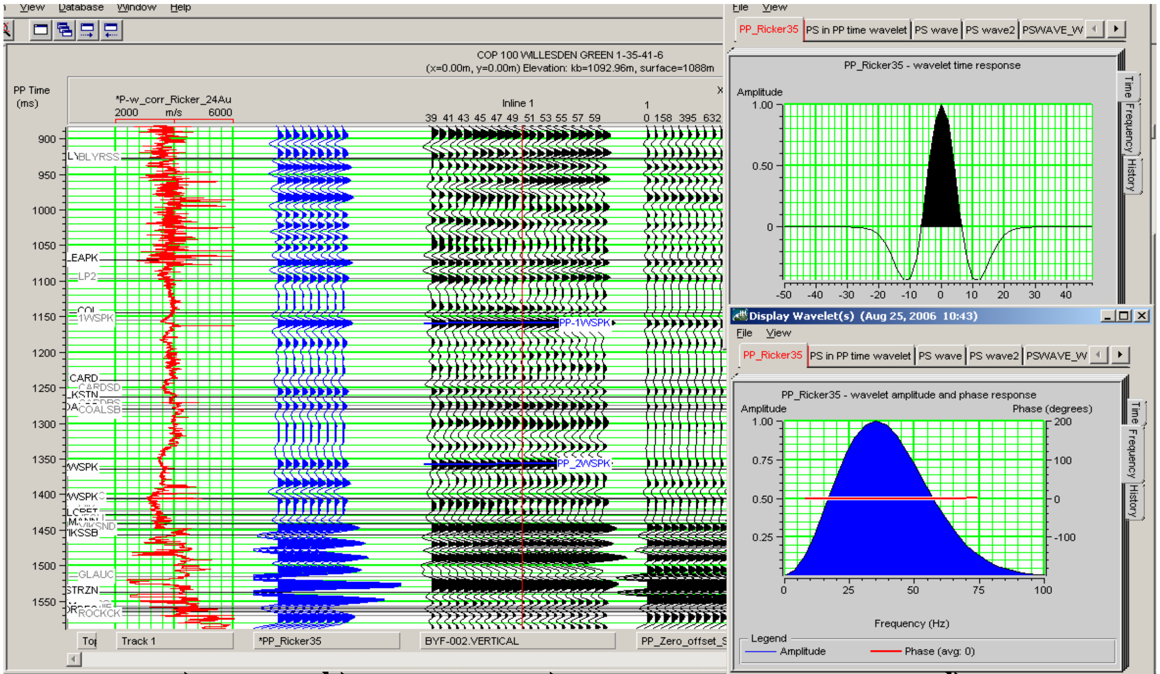


FIG. 9. Well 1-35-41-6W5 in PP time: a)P wave sonic and b) zero-offset synthetic, c) PP seismic, the correlation of 80% with seismic and d) the crosscorelation plot showing almost zero phase.



a) b) c) d)

FIG. 10. Well 1-35-41-6W5: a) P wave sonic, b) zero-offset synthetic, c) PP seismic and d) the created wavelet for the synthetic trace- Ricker wavelet (the dominant frequency is 35 Hz).

Well 1-35-41-6W5 has a gamma ray log which is a good indicator of the natural radioactivity of the rocks. Radioactive isotopes tend to concentrate in clay and shale. We can notice in Figure 11 high gamma kicks on the three markers: 1WS, Cardium and 2WS formations.

The same steps were used in the PP correlation on line WG1 with the well 6-15-41-6W5 (See Figure 12). The correlation coefficient was around 81%. A 35 Hz Ricker wavelet was created for the zero offset synthetic (in blue). The Zoeppritz offset prestack synthetic was created with number of offsets 20 and maximum offset 2500 m. The interpreted horizon for 1WS is at time 1160 ms and for the 2WS at 1370 ms, quite similar with line WG2.

On line WG1, two wells were correlated with the seismic: 6-15-41-6W5 and 8-13-41-6W5.

On line WG2, three wells were correlated with the seismic: 1-35-41-6W5, 8-26-41-6W5 and 8-13-41-6W5.

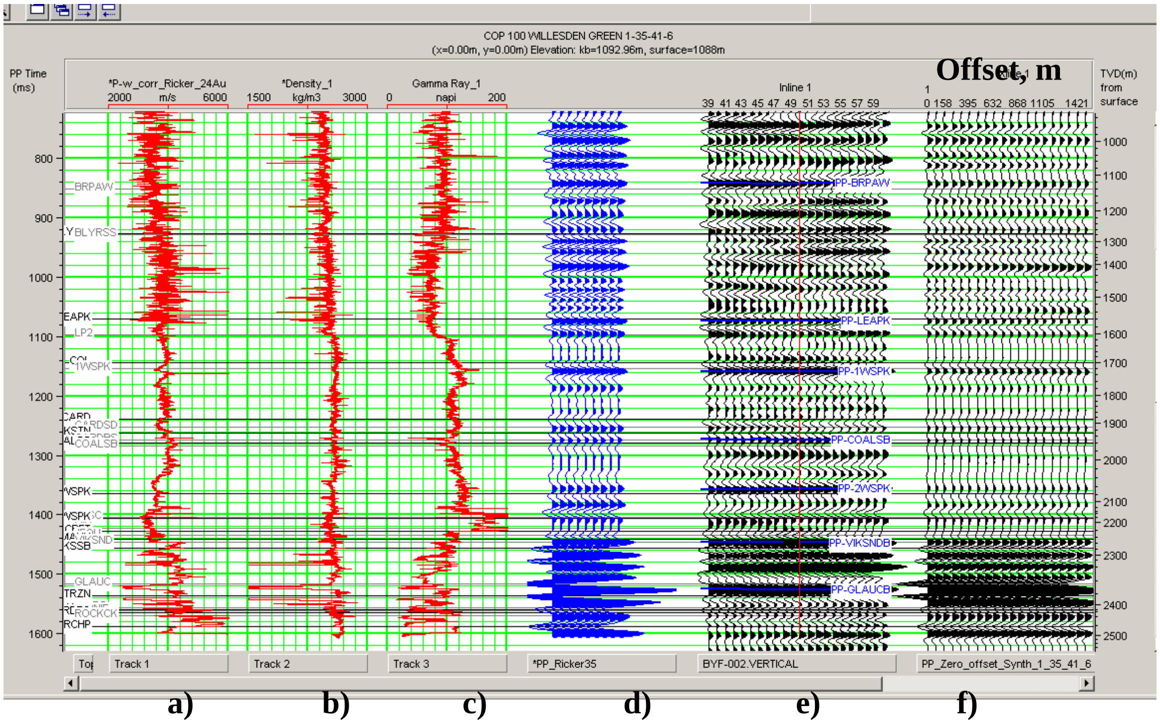


FIG. 11. Well 1-35-41-6W5: P-sonic, b) density, c) gamma ray, d) zero offset synthetic, e) PP stacked section, f) PP Zoeppritz synthetic and the interpreted horizons on line WG2.

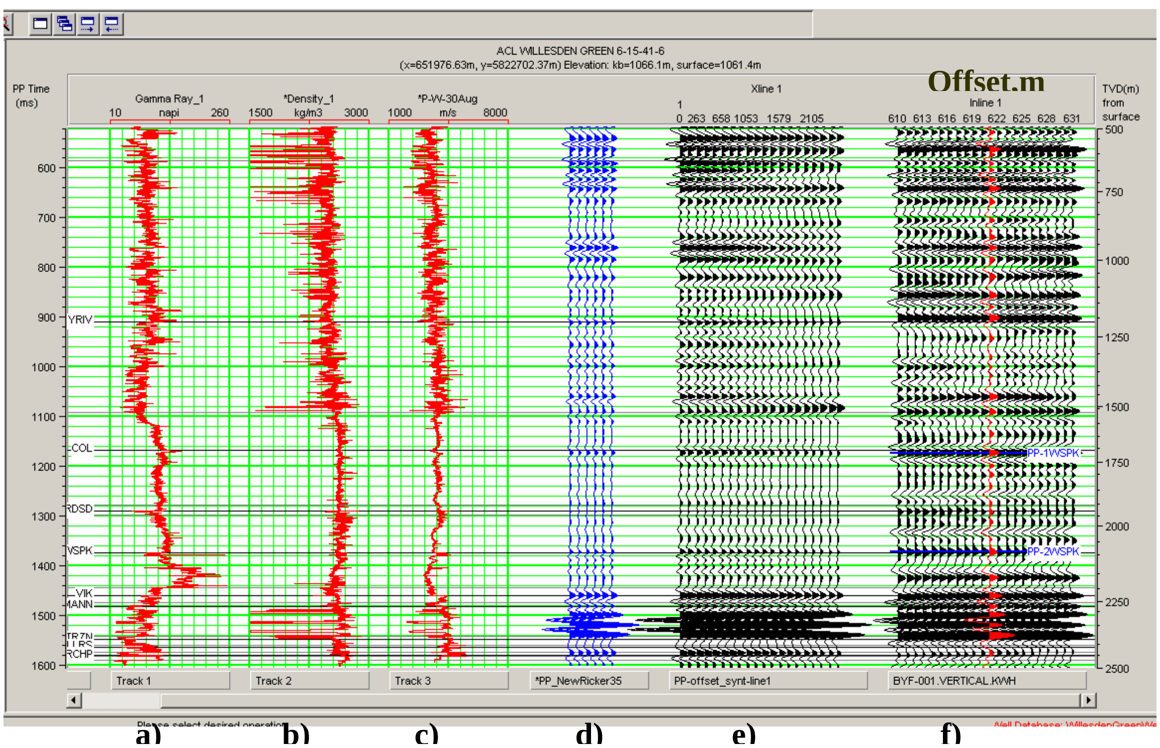


FIG. 12. Correlation of seismic line WG1 with well 6-15-41-6W5: a) gamma ray, b) density, c) P wave, d) zero offset synthetic, e) PP Zoeppritz offset synthetic and f) the PP stacked section.

PP INVERSION

Inversion can be defined as a procedure for obtaining a model which describes a dataset (Treitel and Lines, 1994). For our case, the migrated section is the data to be inverted, and the acoustic impedance is the property to estimate. Well log data provide additional information to constrain the model and make the inversion result more accurate. The impedance is the product between density and velocity and it is measured in m/s*g/cc.

To estimate the PP acoustic impedance three post stack seismic inversions were used: model based, recursive and sparse-spike. Model-based inversion was chosen on both lines because of his better high frequency result. The parameters for the model based inversion are: inversion option-constrained, average block size 6ms, number of iterations-5, processing sample rate-2, separate scalar for each trace, single trace inversion. This type of inversion follows from the convolutional model:

seismic trace = wavelet* reflectivity + noise

We assume that the seismic trace and the wavelet are known, and the noise is uncorrelated and random.

The P wave impedance model was constructed by blocking an impedance log from the wells and interpolating the values between the wells (See Figure. 13). We notice the increase of impedance with depth. The 2WS shale horizon shows an increase of impedance and the Cardium sandstone an impedance decrease, as we expect.

After inversion, on Figure 14, we notice a low-impedance anomaly around the 2WS shale horizon. Well 8-26-41-6W5 is producing oil and gas from the 2WS horizon. On the same line WG2, one km to the north, well 1-35-41-6W5 is not producing from the 2WS. See Figure 16. As we expected, the 2WS horizon shows an impedance increase.

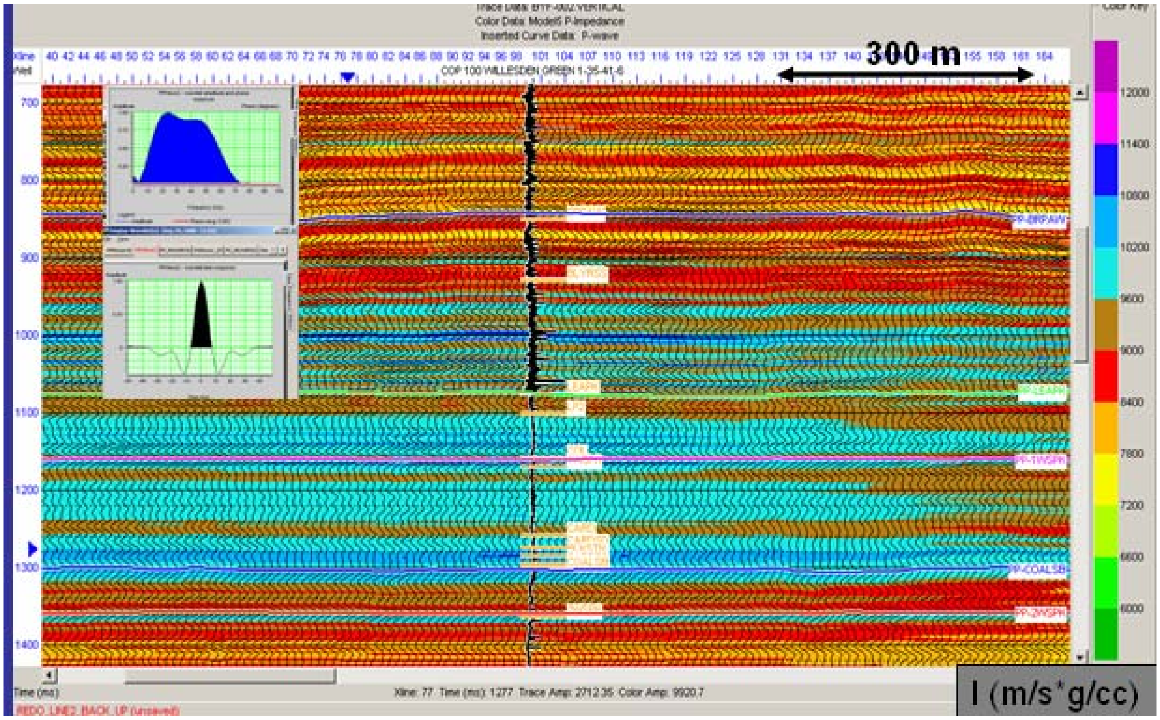


FIG. 13. P Impedance model for PP model based inversion and the wavelet employed at well 1-35-41-6W5 on line WG2.

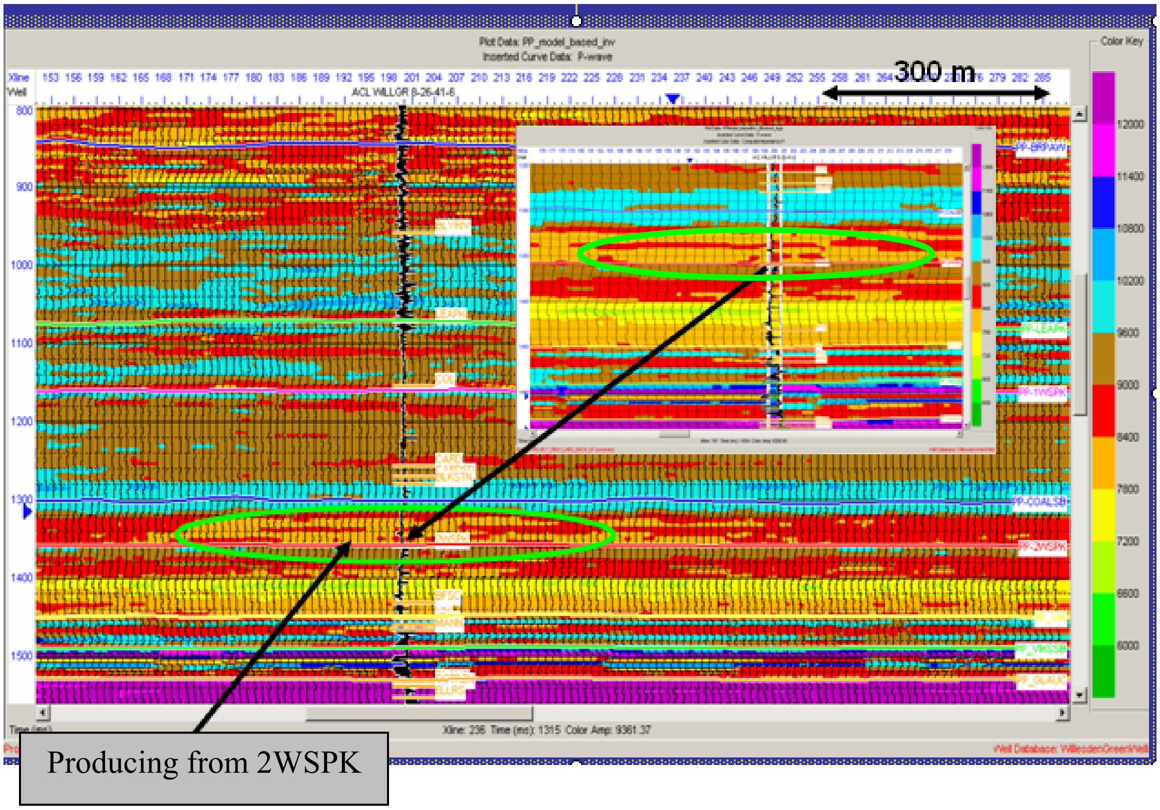


FIG. 14. PP model based inversion on line WG2 at the well 8-26-41-6W5. This well is producing from the 2WS horizon.

Figure 14 shows a PP impedance drop before and after the 2WS horizon. The 8-26-41-6W5 well is producing oil and gas from the 2WS interval. See figure 15 with production details from Accumap in the last year.

Line WG2: For well 1-35-41-6W5 the 2WS horizon is not producing. This well is producing some oil and mainly gas from the Glauconitic horizon. We can notice the impedance drop around the Glauconitic, and an increase in impedance (around 10 000 m/s*g/cc) values at the 2WS shale which at this time is not producing (See Figure 16). We can suggest that zones of porosity increase are associated with lower acoustic PP impedance.

Line WG1: The P-impedance model is similar with the model created for line WG2. In Figure 18, we can see the inversion around the well 6-15-41-6W5. We can notice a major decrease in impedance at the 2WS shale and an increase after. This well is producing mainly gas from this horizon.

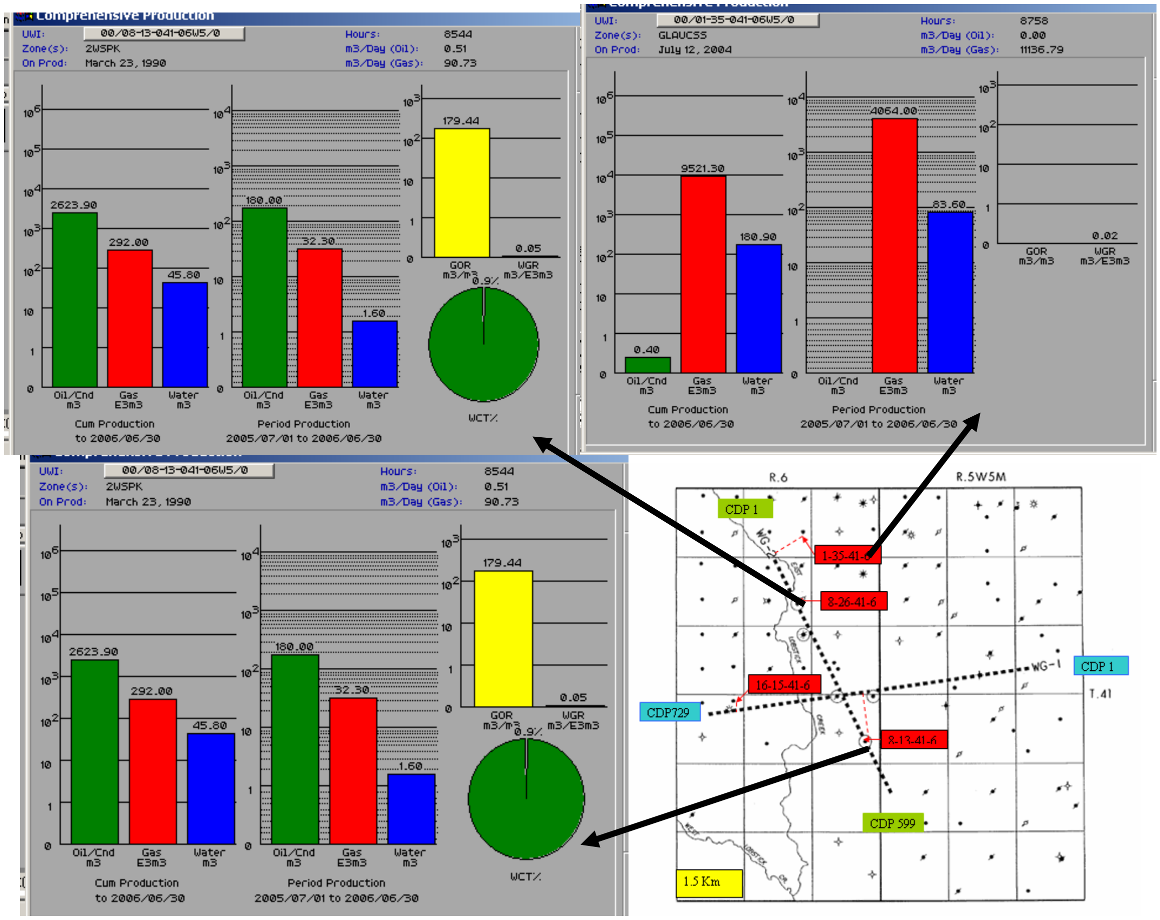


FIG. 15. Accumap with last year production for line WG2. Well 8-13-41-6W5 (left up) and 8-26-41-6W5 (left down) is producing from the 2WS shales horizon. Well 1-35-41-6W5 is producing from the GLAUCSS horizon. Oil production (m^3) is shown in green; gas (m^3) is shown in red and water in blue (m^3).

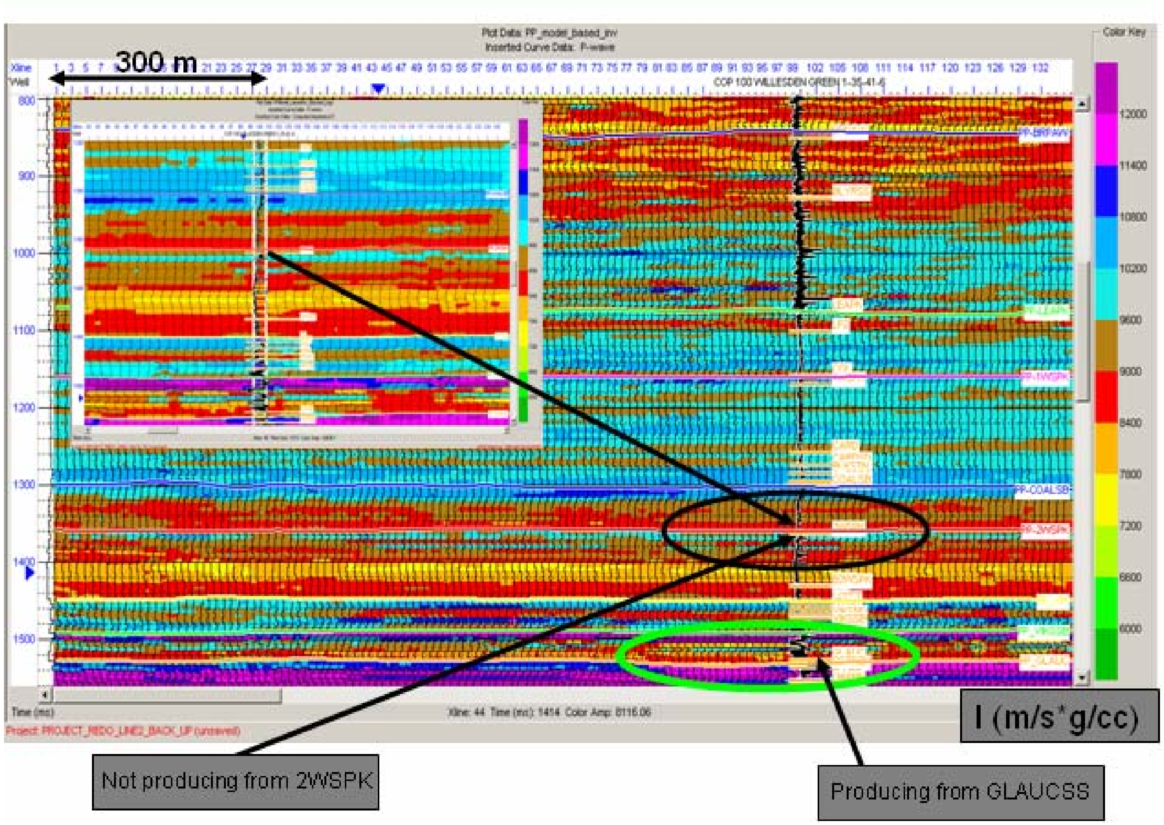


FIG. 16. PP model based inversion on line WG2 .Well 1-35-41-6W5 is not producing from 2WS horizon but is producing from the GLAUCSS (Galuconitic sandstone) horizon.

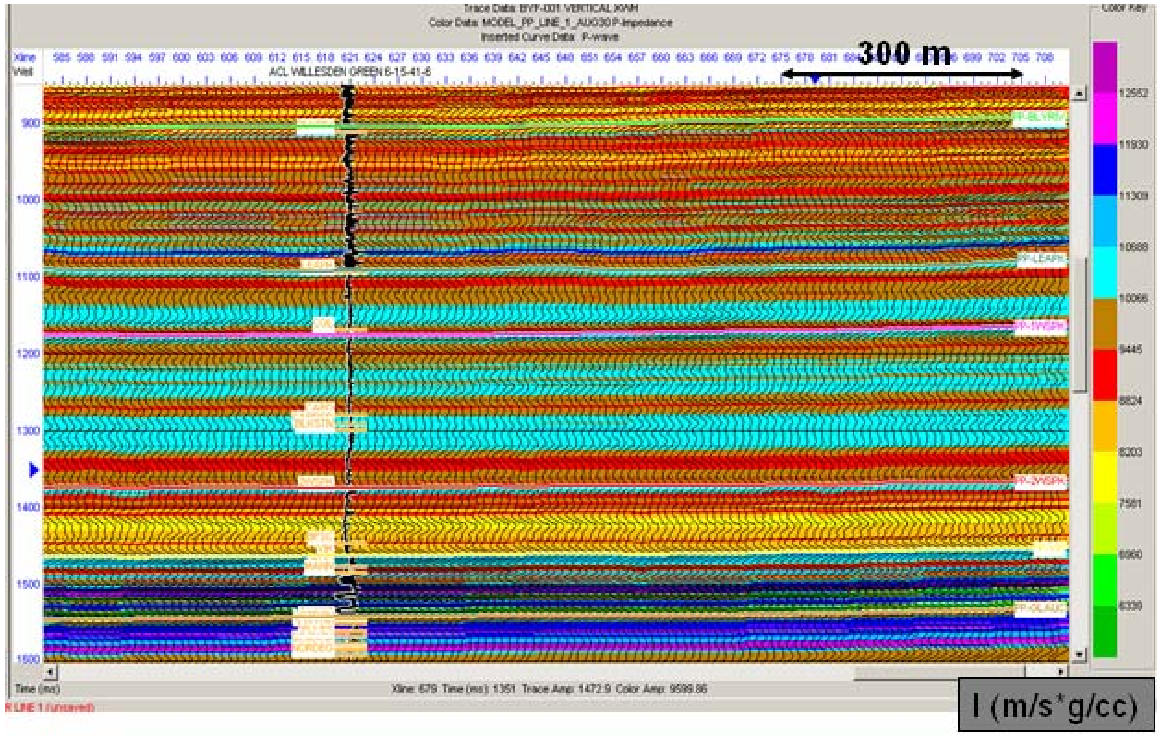


FIG. 17. P Impedance model for model based inversion on line WG1 at well 6-15-41-6W5.

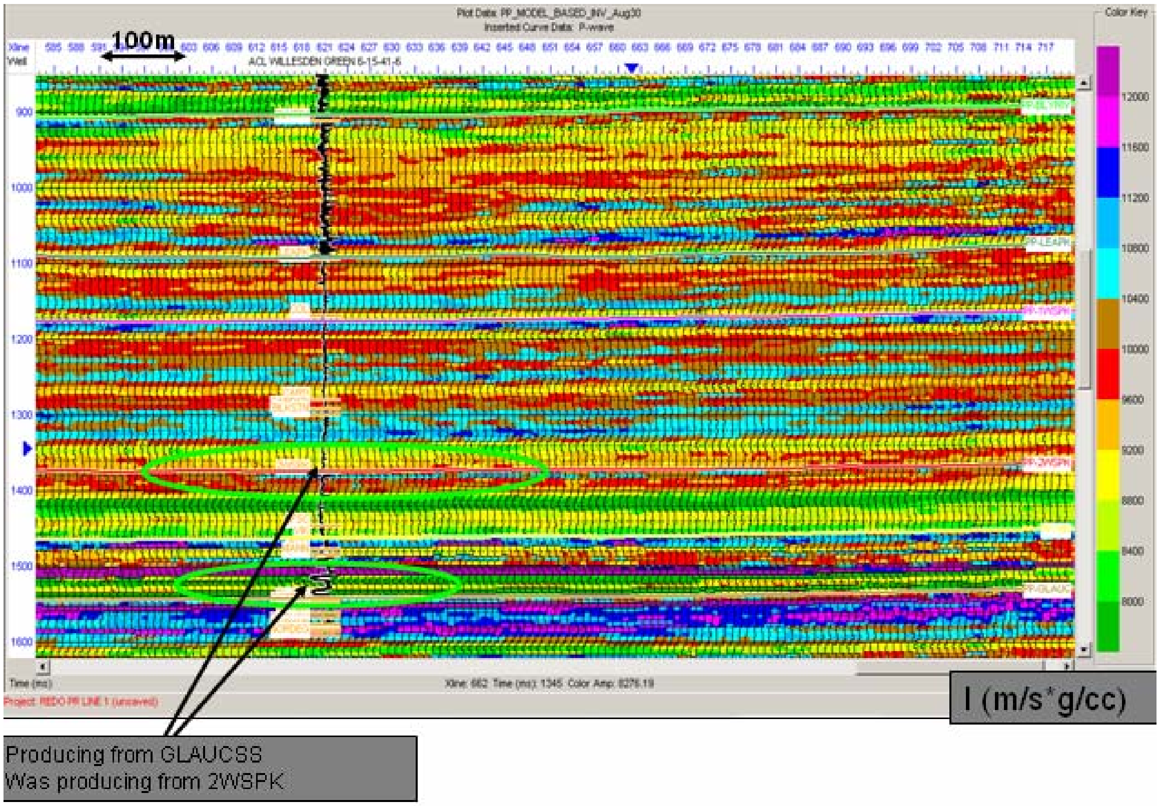


FIG. 18. PP model based inversion at well 6-15-41-6W5 on line WG1. This well is producing mainly gas from the (GLAUCSS) Glauconitic sandstone.

PS INTERPRETATION

The correlation of the PS seismic data with a shear log was done in the same way as for PP seismic data. The S log was created in ProMC using Castagna's equation:

$$\boldsymbol{Vp} = 1369 + 1.6\boldsymbol{Vs} \tag{1}$$

Because there is no PS response at zero offset, a range of offsets were stacked to obtain a synthetic response to compare with the seismic data. . For line WG2, a 25 Hz Ricker wavelet was created (the radial seismic data was bandpass filtered at 5-10-40-50 Hz after the processing) to match the PS seismic data. The wavelet parameters are: dominant frequency = 25 Hz, sample rate = 2 ms, wavelet length = 100 ms, phase type = constant phase.

On both lines, the correlation was around 60% with the wells. In Figure 19, we can see the correlation of line WG1 with well 6-15 -41-6.

For line WG1, a 20 Hz Ricker wavelet was created (the radial seismic data were bandpass filtered at 5-10-30-40 Hz after the processing) to match the PS seismic data. The horizons in PS time are shown in Figure 19.

After the PS horizons were picked, the next step is the horizon matching in ProMC. The registration was done in PP time.

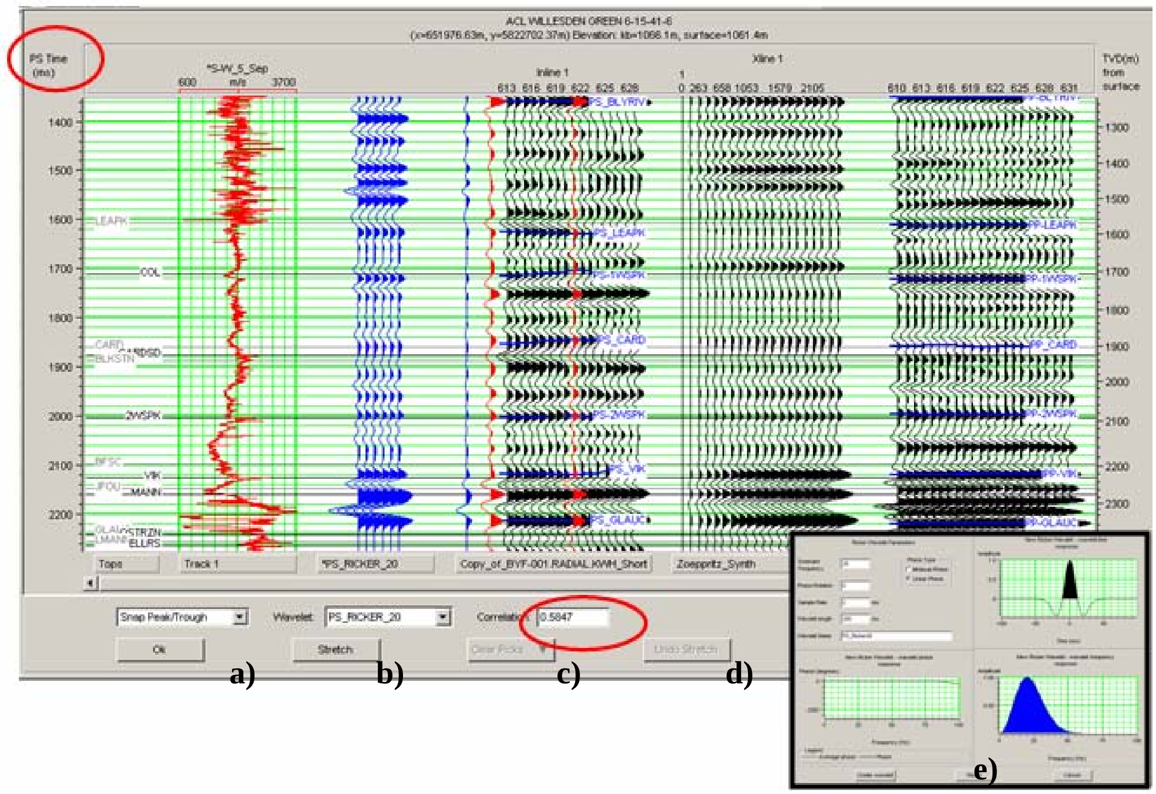


FIG. 19. PS correlation on line WG1 at well 6-15-41-6W5: a) S wave created with Castagna's equation, b) PS synthetic, c) PS stacked section, d) PS Zoeppritz offset synthetic, and e) the used 20 Hz Ricker wavelet.

PP AND PS INTERPRETATION

After PP horizons were picked in PP time and the PS horizons in PS time, the registration was accomplished with the Horizons Matching tool in ProMC. This tool allows us to link the selected horizons (PP and PS data is viewed in a split mode) and then visualize them in PP or PS time. The program can calculate a Vp/Vs value between the horizons and can show their colors along the entire line. Figure 20 shows the unmatched horizons for both radial and vertical component on lineWG1. We can compare them with the matched horizons from Figure 21.

Vp/Vs values along the seismic lines were calculated using interval traveltimes with the following formula:

$$\frac{V_p}{V_s} = \frac{2\Delta T_{ps}}{\Delta T_{pp}} - 1 \tag{2}$$

In Equation (2) ΔTpp and ΔTps are the time thicknesses between the interpolated horizons, on PP and respectively PS data. Equation 2 is derived by expressing the thickness of a depth interval in terms of P-wave and S-wave travel. A limitation of Equation 2 is the fact that it is considered an average over the time thickness interval.

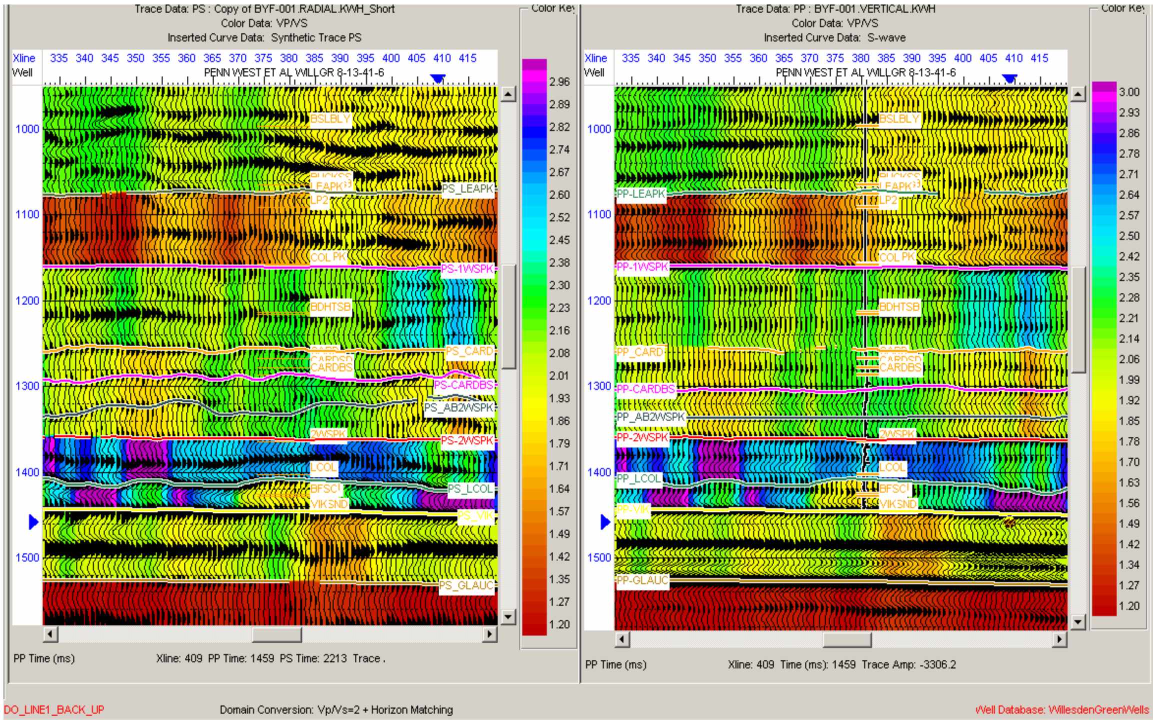


FIG. 20. Matched horizons on line WG1 at well location 8-13-41-6W5.For domain conversion were used the matched horizons.

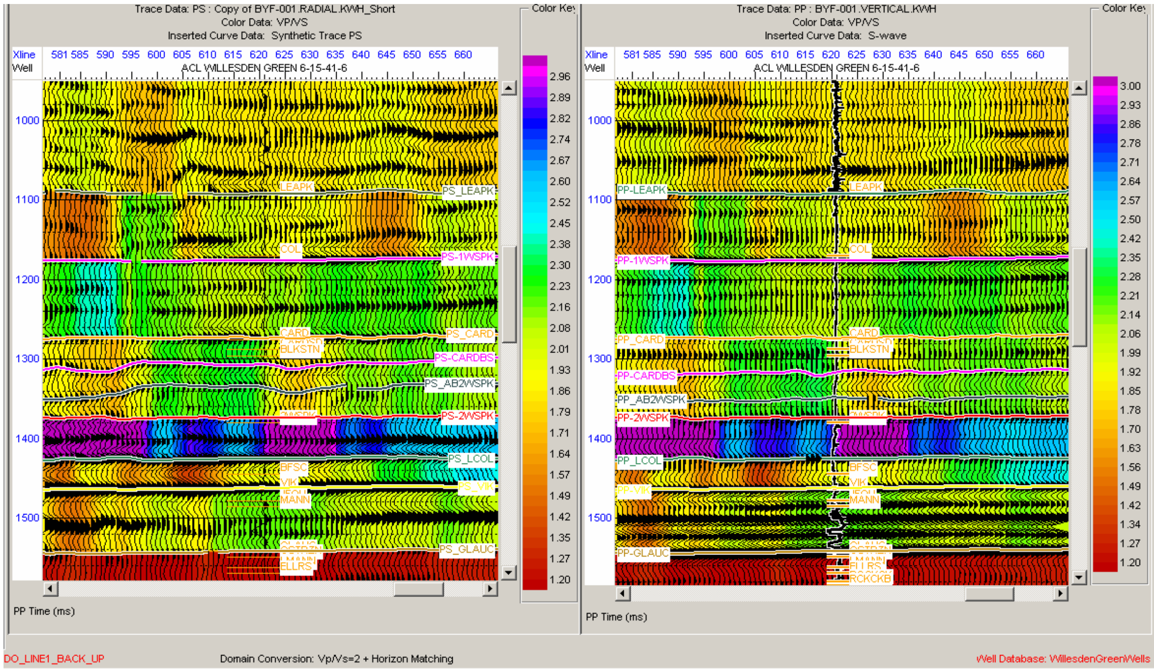


FIG. 21. Matched (linked) horizons on line WG1 on well location 6-15-41-6W5. For domain conversion were used the matched horizons.

For line WG1, after event matching we can delimit the 2WS shales with higher Vp/Vs values ranging from 1.7. to 3, on both, PP and PS data (See Figure 20 and 21). The Cardium sandstones have lower values, from 1.4 to 2, as we expected. The separation from shales to sandstones is clearly shown.

Figure 22 shows the Vp/Vs ratio on line WG1 from time thickness (a constant Vp/Vs is calculated between the matched horizons). Vp/Vs ratio is overlain with the PS section, in PS time. We can notice the lower values for Cardium formation (around 1.4-2.2) and the higher values for the 2WS shales (1.6 to 3). Well 6-15-41-6W5 is not producing from the 2WS horizon and well 8-13-41-6W5 is producing from 2WS horizon.

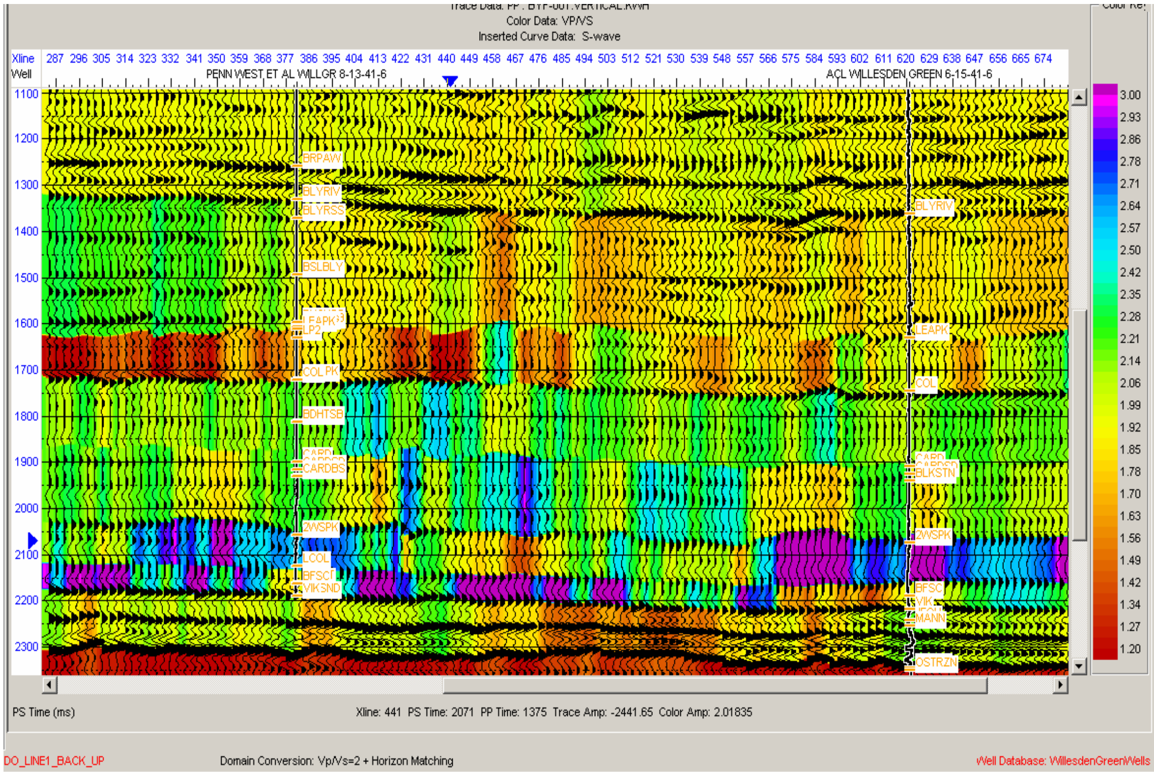


FIG. 22. Vp/Vs value computed from time thickness, overlain with PS section at well 8-13-41-6W5 and 6-15-41-6W5 on line WG1.

In figure 24, for well 8-26-41-6W5 and well 8-13-41-6W5 (which are producing from the 2WS horizon on line WG2) we note higher values of Vp/Vs above and below the 2WS horizon (2.4 - 2.8). The productive zones are not clearly delineated at this interpretation step. The well production is shown on figure 15.

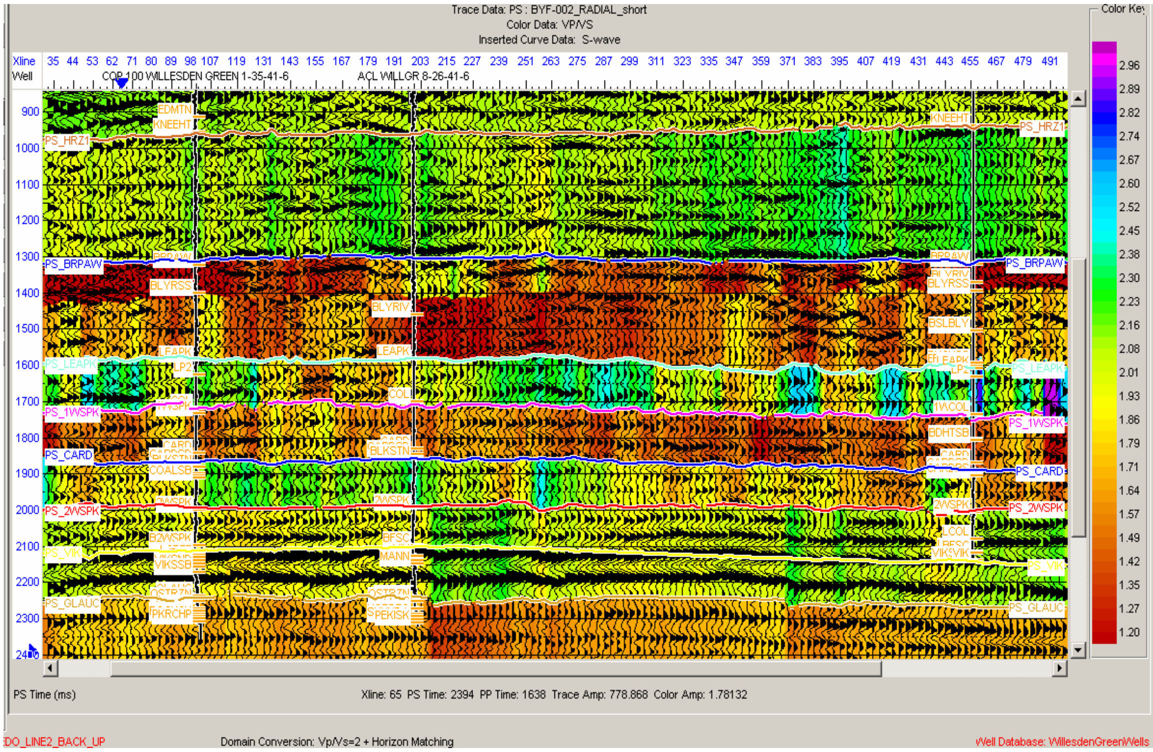


FIG. 23. Linked horizons and Vp/Vs values computed only from time thickness overlain on PS section (in PS time) on line WG2.

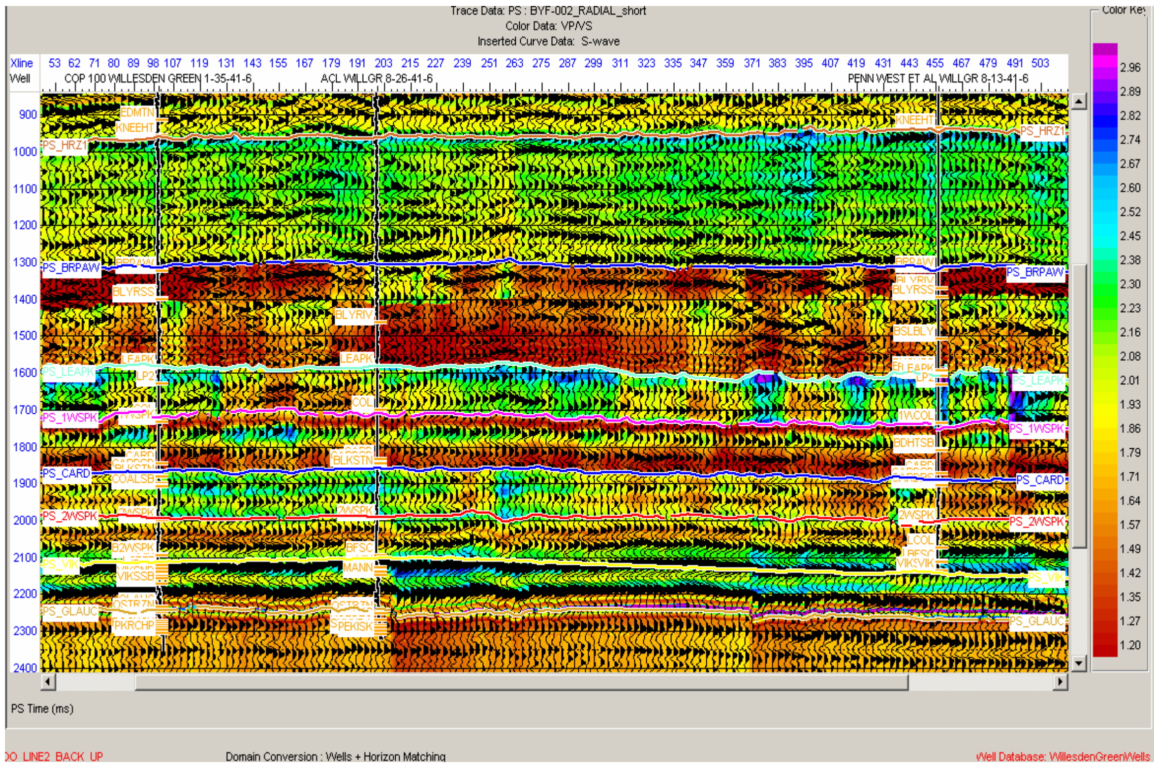


FIG. 24. Linked horizons and Vp/Vs values computed from time thickness and wells overlain on PS section (in PS time) on line WG2. Wells 8-28-41-6W5 and 8-13-41-6W5 are producing from the 2WS horizon.

PS INVERSION

After registration was done in ProMC, the PS data in PP time were imported to Strata and inverted. The same inversion procedure as in the P wave case was used, except the fact that to create the model the S-wave reflectivity was used.

With the PS data, a model based inversion (in PP time) at well 8-13-41-6W5 was performed. We notice a lateral impedance increase (between 4900-5900) at the 2WS shale, the productive formation on line WG1 (See Figure 26).

After the inversion of both PP and PS datasets we can take a ratio of them. See Figure 27. We notice similarities with the Vp/Vs ratio on Figure 22, at this well location. Low values in the impedance ratios (1.6-1.8) show us the productive 2WS formation. Higher values 1.9-2.2 could delineate the impermeable seals of this reservoir. The lower values of this ratio at exactly 2WS horizon confirm again the production from this well: 8-13-41-6W5. The laterally PS impedance increase on line WG2 at the productive well 8-26-41-6W5 shows us the producing 2WS formation. As well we can note the impedance increase, opposed to the impedance decrease in PP case. The Cardium sandstones are delineated by a high increase in the impedance, as we can expect.

After the inversion of both PP and PS data on line WG2 (See figure 29 and 30) we can take as well a ratio of them. Figure 31 shows the delineated anomalous zones on line WG2.

We can notice similarities with Vp/Vs (Figure 25) at the 8-13-41-6W5 well location and compare them with the values from Figure 31. Low values in the impedance ratios (1.6) show us the productive 2WS. Higher values 1.8-1.9 above and below could delineate the impermeable seal of the reservoir.

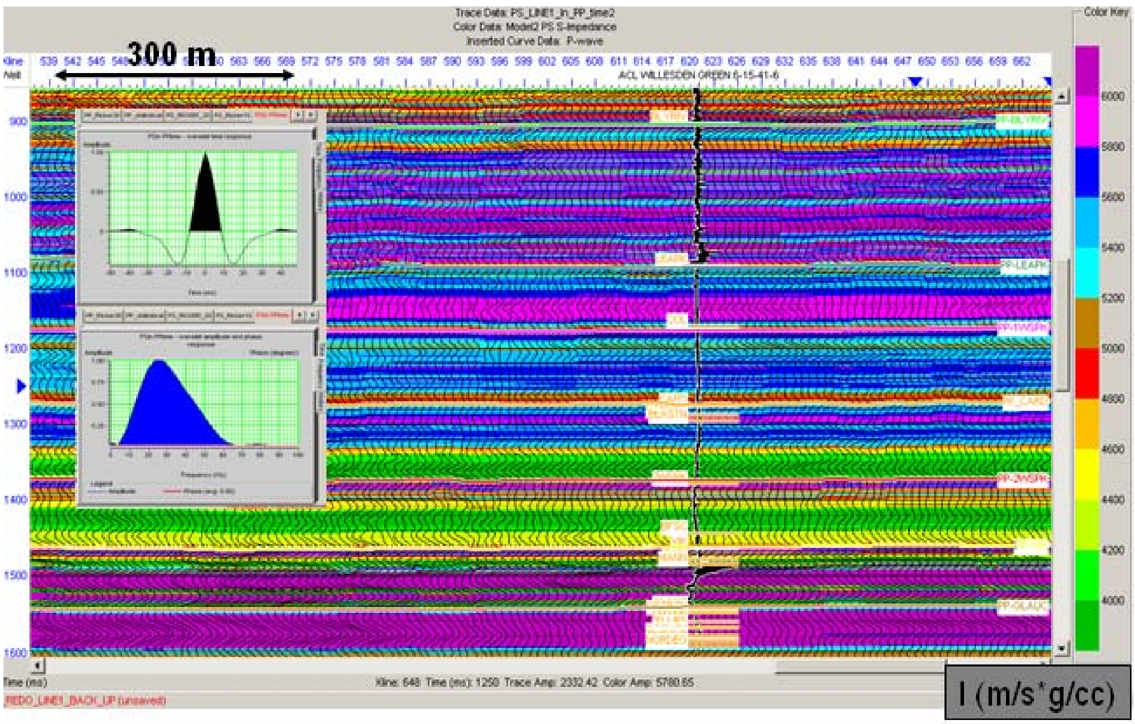


FIG. 25. PS Model-S Impedance for inversion at well 6-15-41-6W5 in PP time used on line WG1and the used wavelet.

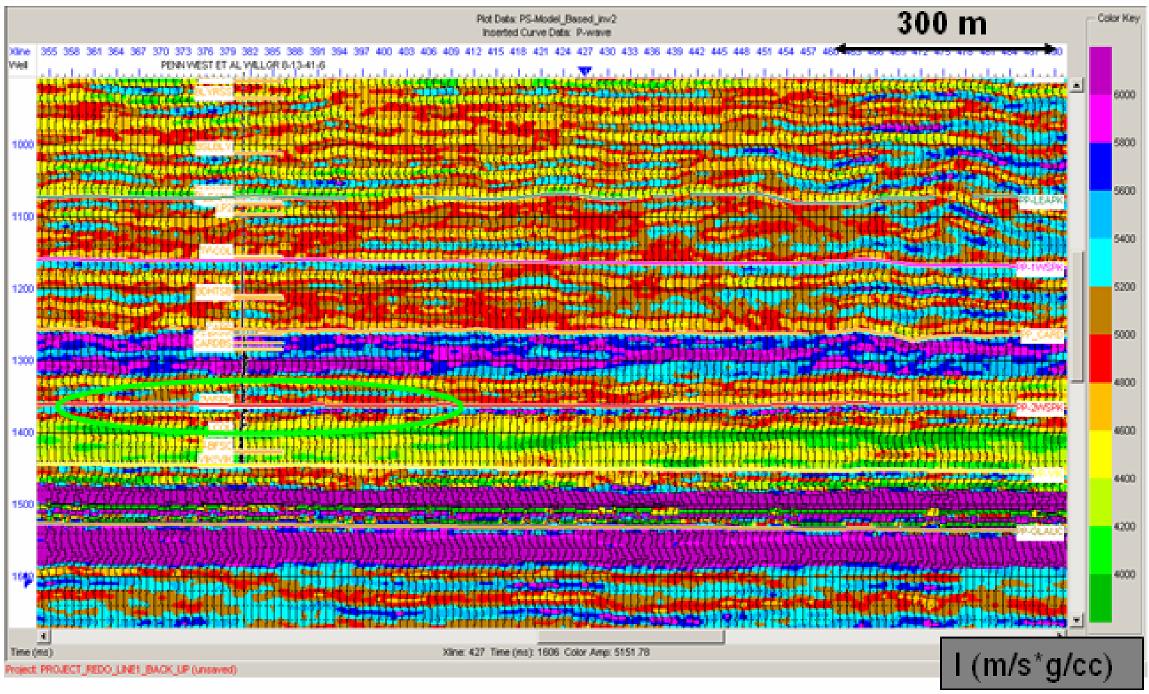


FIG. 26. PS model based inversion result for line WG1 at the well location 8-13-41-6W5.

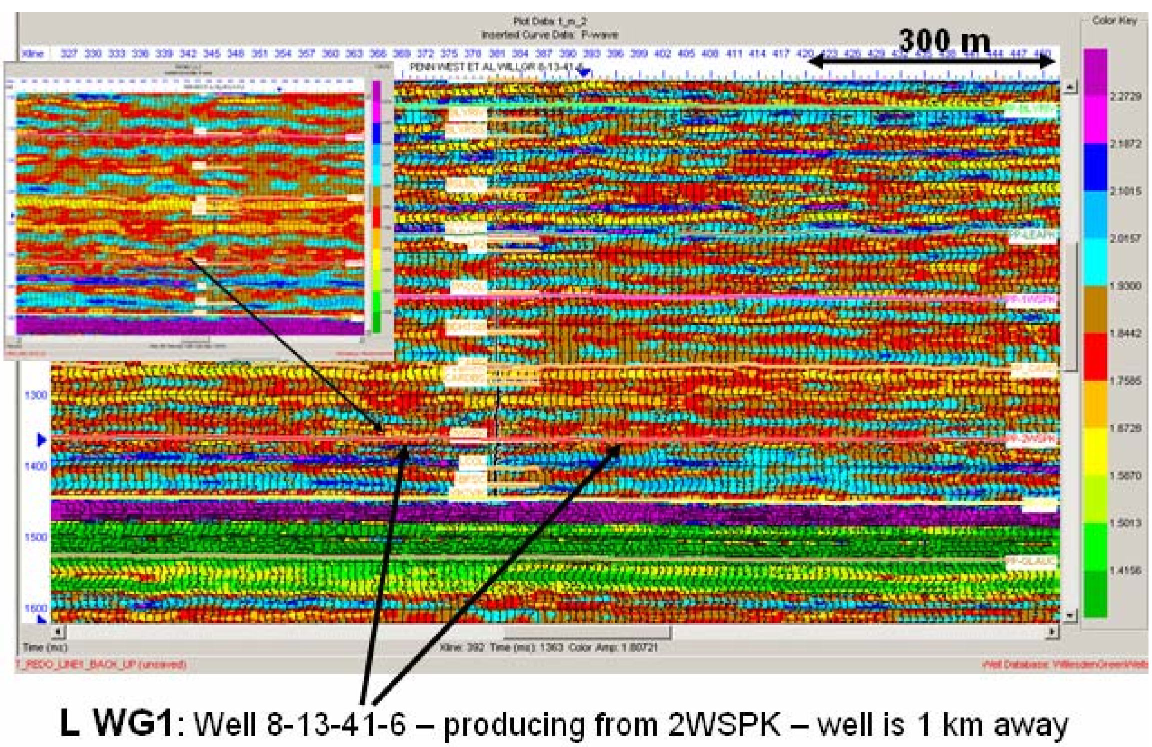


FIG. 27. The ratio of the PP inversion to PS inversion in PP time on line WG1.The anomalous zones can be noticed at well 8-13-41-6W5.

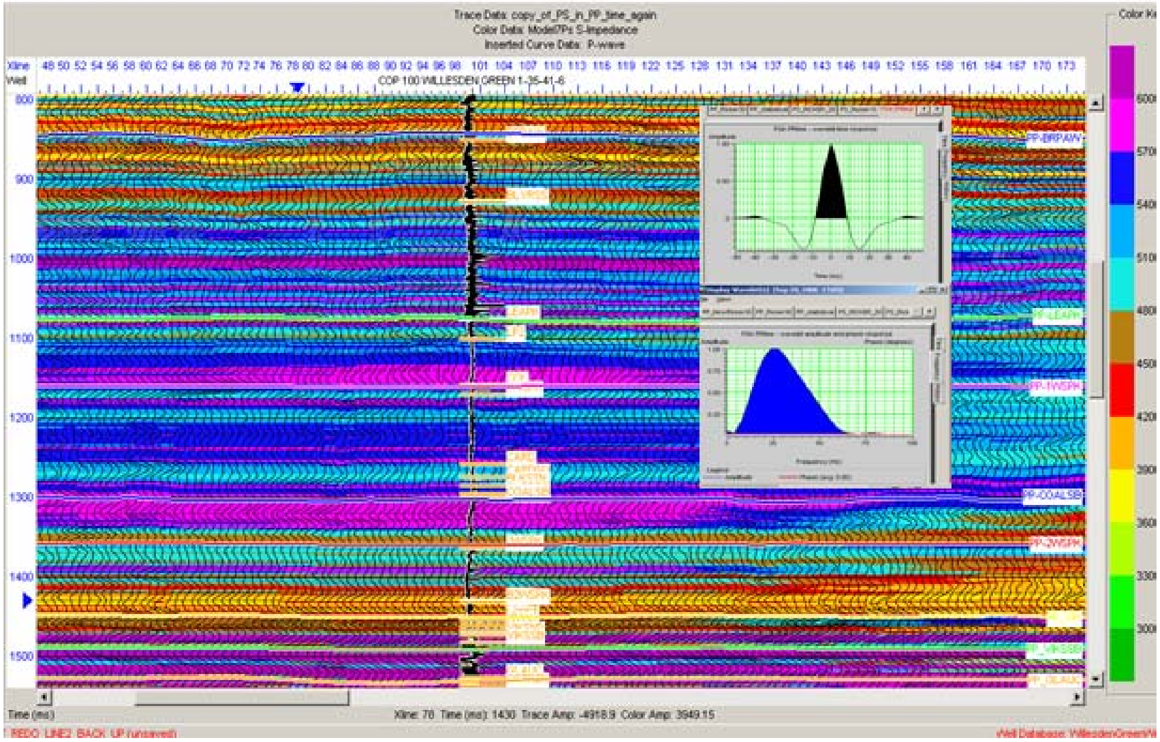


FIG. 28. PS Model-S Impedance for inversion in PP time on line WG2- at well 1-35-41-6W5 (this well is producing from GLAUCSS) and the used wavelet.

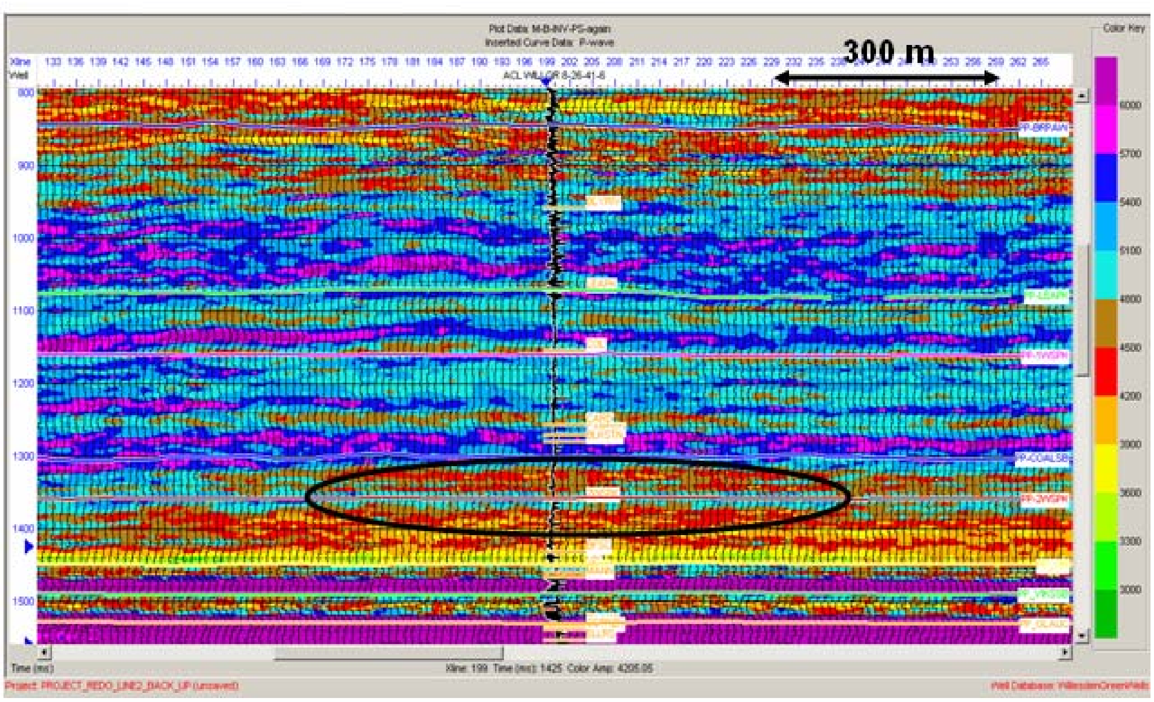


FIG. 29. PS model based inversion result for the line WG2 at well 8-26-41-6W5.

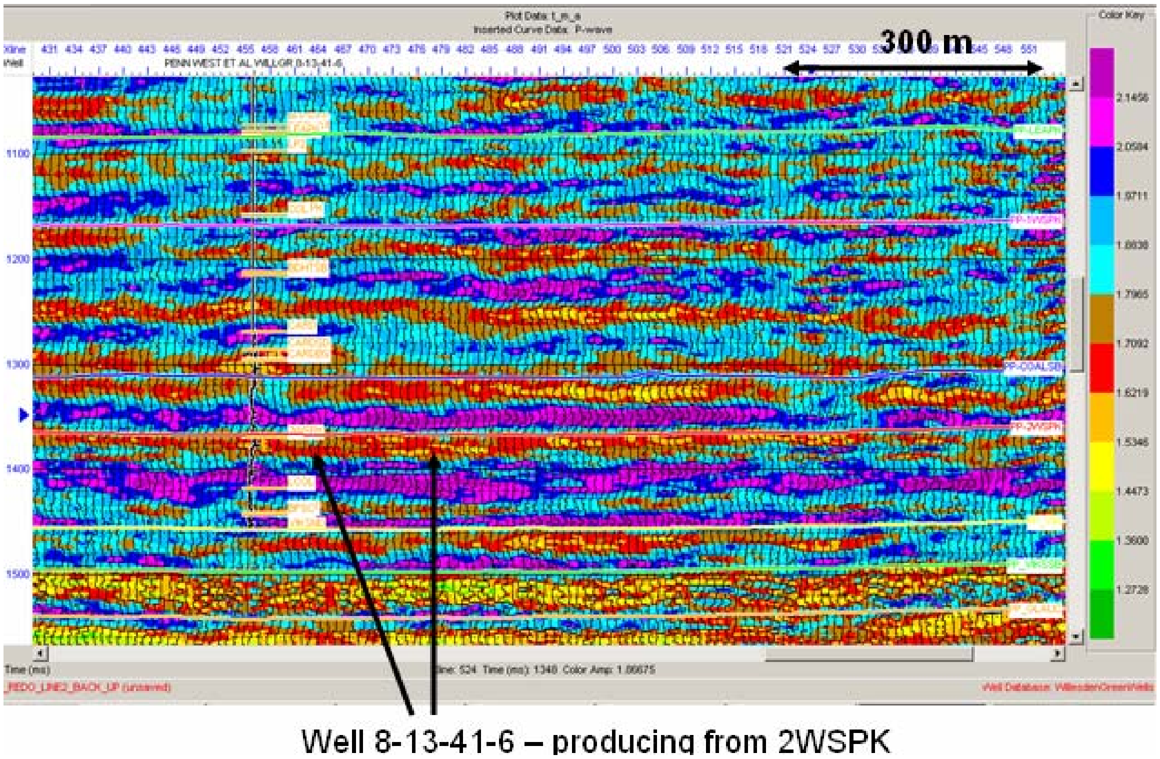


FIG. 30. The ratio of the PP inversion to PS inversion in PP time on line WG2 at well 8-13-41-6W5.

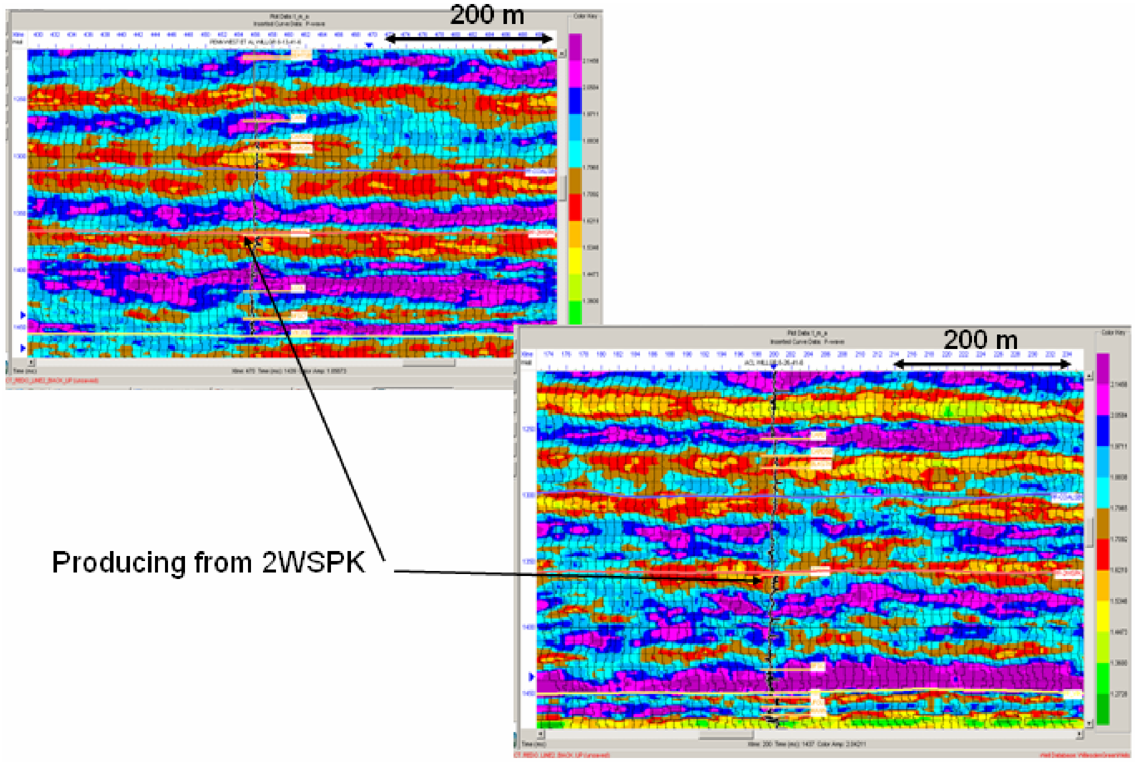


FIG. 31. The ratio of the PP inversion to PS inversion in PP time on line WG2 at the two producing wells: 8-13-41-6W5 and 8-26-41-65W5.

CONCLUSIONS

At Willesden Green the PP and PS inversion method was used to delineate the productive zones on three producing wells: 8-13-41-6; 8-26-41-6 and 6-15-41-6. The integration of well logs and multicomponent seismic has been described in this paper.

It was shown that the main changes in the well logs roughly correspond to the facies change.

The calculated Vp/Vs values and the ratio of PP inversion over PS inversion were helpful for sand/shale discrimination.

The Vp/Vs drop can show the producing horizons (increase in porosity) at the wells. The increase in the Vp/Vs values indicates the impermeable/shale content (decrease in porosity).

The Inversion Method using ProMC has been used to predict the reservoir properties along the seismic lines. PP and PS impedance sections were created and analyzed. The productive intervals have been interpreted as a PP impedance drop and an PS impedance increase.

In this paper, we showed that the ratio of the PP inversion to the PS inversion in PP time can be useful for delineating the reservoirs.

ACKNOWLEDGEMENTS

This work is supported by CREWES Project at the University of Calgary and we express our appreciation to the CREWES sponsors.

We are grateful to Response Seismic Ltd. for releasing these data, Hampson-Russell for the use of their software, and Dr. Peter Cary who processed the data, and provided a copy for our use.

We would like to thank Carmen Dumitrescu and Ianusz Peron for their help with Hampson Russell software and we are grateful to Kevin Hall for his continuous help.

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