Interpretation of well log, VSP, and streamer seismic data from the White Rose oilfield, offshore Newfoundland

Jessica Jaramillo Sarasty, Robert R. Stewart, and David Emery*

ABSTRACT

A multi-offset-VSP dataset was acquired in Husky Energy's H-20 well in the White Rose field, (Jeanne-d'Arc basin, offshore Newfoundland). The processing of the multi-VSP dataset acquired by Husky Energy Inc. was conducted by Schlumberger Canada Ltd and generated various outputs such as corridor stack, CDP mapping of PP data and of PS data. The interpretation of the results from the multi-VSP data is in this paper.

The best correlations are between the PS synthetic seismograms and the PS offset VSP data. The PS images from these synthetic seismograms are better at the top of the Avalon Formation showing higher amplitude over the adjacent signals.

There are good correlations between PS synthetic seismograms generated from well logs and the PS offset VSP data. The PS images from these synthetic seismograms are better at the top of the Avalon Formation showing higher amplitude over the adjacent signals.

There were several wavelets with different frequency content that were used to obtain the best match possible; the final wavelet used was a 45-Hz zero-phase Ricker wavelet.

Synthetic and field data indicate that converted-wave (Ps) data may be useful in mapping the Avalon reservoir at White Rose.

INTRODUCTION

The White Rose field is located on the eastern edge of the Jeanne d'Arc Basin, approximately 350 km east of St. John's, Newfoundland (Figure 1). The White Rose H-20 well was drilled during the summer of 2000, with the purpose of delineating the northern limit of the South Avalon Pool. Following the drilling, a multi-offset Vertical Seismic Profiling (VSP) study was conducted. There were several reasons to acquire the multi-offset VSP survey (Hoffe et al., 2000): to investigate the possibilities of imaging small throw faults in the Avalon reservoir; to determine if the PS waves could give a better image of the reservoir; provide PP and PS seismograms for interpretation, and to extract in situ rock properties.

Imaging challenges at White Rose field

Several successful seismic surveys have been acquired in the area of the White Rose field, but there are imaging challenges Hoffe et al., (2000):

** Husky Energy Inc., Calgary, Alberta*

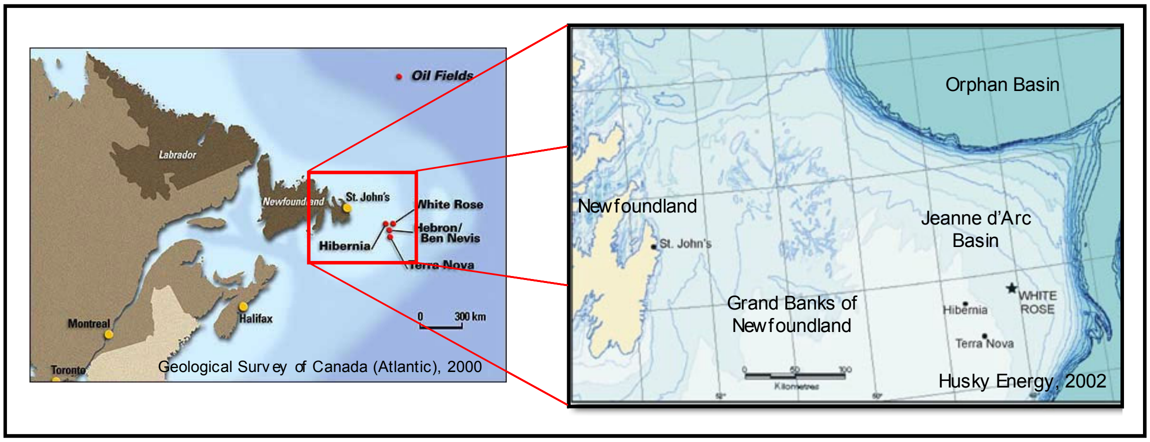


FIG. 1. White Rose location (Modified after Husky Energy, 2002 and Geological Survey of Canada (Atlantic), 2000)

Hard water bottom in approximately 125 m of water depth.

High ocean-bottom reflection coefficients create serious water-column reverberations. The hard seafloor is due to the presence of glacial deposits of large boulder/cobble fields and a probable hardpan surface due to Grand Banks aerial exposure during glaciations. The quality of the final seismic image created from data acquired with towed streamers over these hard ocean bottom areas, is diminished, due to associated water-column reverberations.

Strong P-wave impedance contrast at the Tertiary-Cretaceous Unconformity.

The erosional unconformity at the Tertiary-Cretaceous boundary within the White Rose field shows a strong seismic impedance contrast. The reflection coefficient at this interface is large and significant energy is reflected from it (reflection coefficient of 0.16), which then becomes trapped in overlaying sediments as well as in the water column also producing strong multiples. These Base-of-Tertiary multiples interfere with the primary reflections from the Avalon reservoir level, degrading the final seismic image of the reservoir.

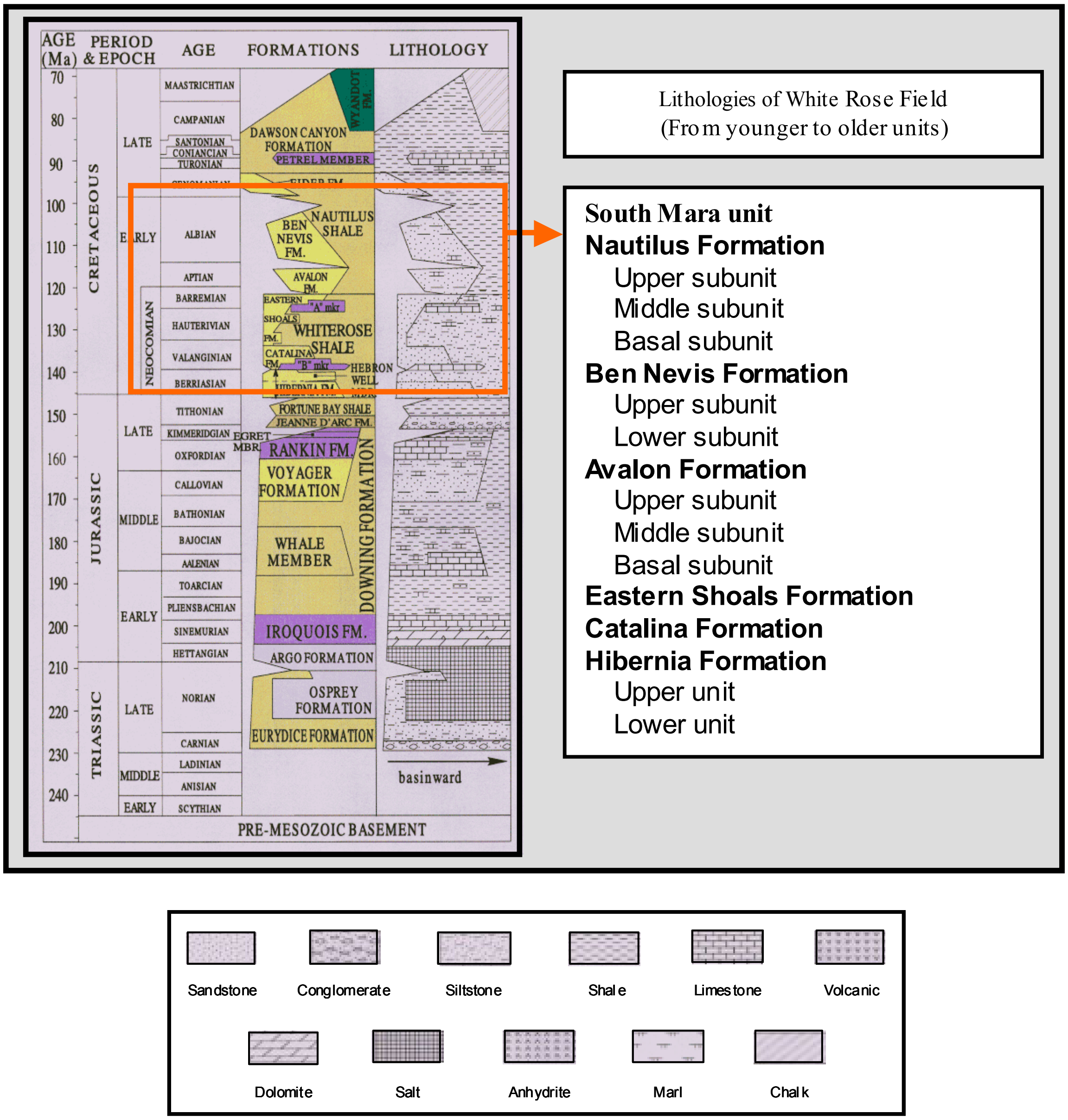
Poor P-wave impedance contrast between the Avalon Formation (the main reservoir in the White Rose field) and the overlying Nautilus Formation (shale).

The sandstone of the Avalon Formation, is up to 300 m thick, with good porosity and permeability, is overlain by shales of the Nautilus Formation. The P-wave impedance contrast between these two formations is small, resulting in a weak Top-of-Avalon reflector.

Distortion of the reservoir image by the presence of gas clouds in the overlying Tertiary sediments.

Faults from extensional movements affect the reservoir level, breaking the Base of Tertiary unconformity and forming gas clouds by up-dip leakage of gas along the fault structures. The presence of vapour gas and dispersed gas in fine clastics can obscure and distort the reservoir image. These gas clouds have a damaging effect on the final stacked PP image from the White Rose.

This paper will look at the P-wave impedance contrast at the Tertiary-Cretaceous Unconformity and the weak P-wave impedance contrast between the Avalon Formation and the overlying shale Nautilus Formation.



South Mara unit
Nautilus Formation
- Upper subunit
- Middle subunit
- Basal subunit

Ben Nevis Formation
- Upper subunit
- Lower subunit

Avalon Formation
- Upper subunit
- Middle subunit
- Basal subunit

Eastern Shoals Formation
Catalina Formation
Hibernia Formation
- Upper unit
- Lower unit

FIG 2. Stratigraphy of Grand Banks. (Modified after Geological Survey of Canada (Atlantic), 2000)

GEOLOGY

The Jeanne d'Arc Basin, located at the northeastern part of the Grand Banks of Newfoundland, is a Mesozoic failed-rift basin containing in excess of 22 km of sedimentary fill. The sedimentary evolution of the Basin is a response to the structural framework of the basin and to regional tectonic episodes related to the breakup of Pangea (McAlpine, 1990).

Reservoir Lithologies of the White Rose field

The White Rose field (Figure 1) is situated in the northeastern Jeanne d'Arc Basin, 50 km equidistant from Hibernia and Terra Nova oilfields and in water depths of about 125 m. Structurally, the White Rose field is a complexly faulted region located above a deep-seated salt ridge and situated in the hanging wall of the Voyager Fault. Figure 2 illustrates the formations of the White Rose field, from younger to older sequences.

WHITE ROSE H-20 - WELL LOGS

The logs of interest (Figures 3 and 4) to this project are: gamma-ray log, the delta-t shear (P-and S-mode Shear Dipole Tool, SDT) log, the delta-t compressional (P-and S-mode Shear Dipole Tool SDT) log, and bulk density log. In Figure 4, the log curves are given as velocities (the reciprocal of the $\triangle t$ shear into S-wave velocity, Vs, and the reciprocal $\triangle T$ compressional into P-wave velocity, Vp). The top of each formation is given (Table 1) for each formation of interest.

Table 1. H-20 well tops in True Vertical Depth (TVD). The important tops for this project are BTUN and AVAL.

Formation	Abbreviation	Depth (m)
Eocene	EOCN	2234.0
South Mara unit	SMAR	2321.9
Base Tertiary unconformity	BTUN	2384.0
Top Nautilus Shale (Mid-Cenomanian Unconformity)	NTLS	2522.5
Top Avalon Siltstone	AVAL	2810.0
Top Avalon Sandstone	AVSS	2831.0
Oil-Water contact	OWC	3009.0
Base Avalon - Eastern Shoals Formation	ESHL	3251.0

As a density log was not acquired from the top of the well to 2772m, so we used Gardner's Rule (Gardner et al., 1974), Figure 5, to derive a density value (Figure 4). The RHGA log curve is the predicted density value, which is going to be used in the interpretation stage of this project, when attempting to attain better quality results for the synthetic seismograms.

Table 2. H-20 well logs in True Vertical Depth (TVD).

Well log	**Top (m)**	**Bottom (m)**
Vp/Vs	824	3271
Vs	824	3271
Vp	824	3271
Gamma Ray	824	3271
Rhob	2772	3271
Rhga	824	3271

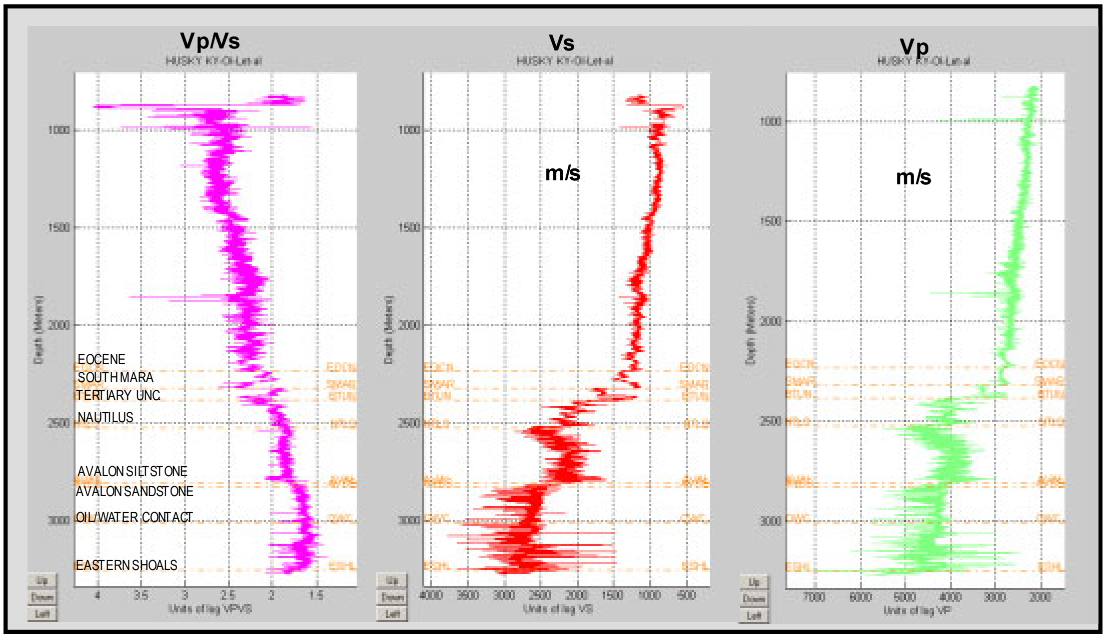


FIG. 3. H-20 well logs. From left to right Vp/Vs, Vs, Vp log curves.

Before applying the Gardner's relationship to the upper portion of the well, it was applied to the bottom of the well to see if its use was acceptable (Figure 6). Plotting the density and Vp values from the bottom of the well, shows a reasonable match and encourages us to use it for the rest of the well.

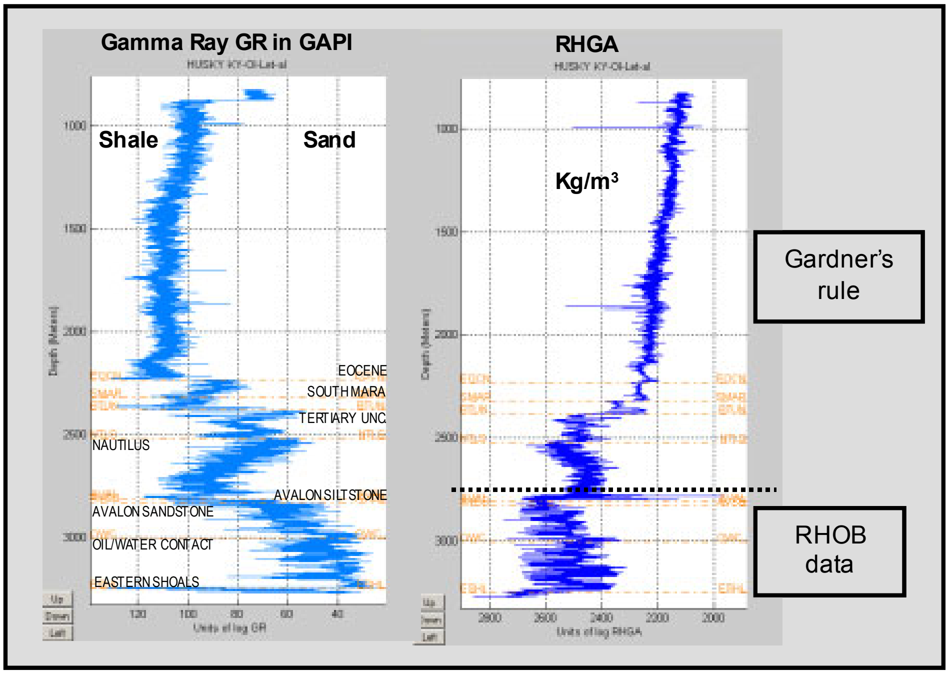


FIG. 4. H-20 well logs. From left to right, gamma-ray, RHOB (constant density log), RHGA (predicted density log) log curves.

$$\boxed{\rho = a\alpha^m}$$

$m=.25$ **Are constants given by**
$a=310$ **Gardner et al. (1974)**
α **Compressional velocity in m/sec**

FIG. 5. Gardner's rule, relating P-wave velocity to density (in kg/m^3).

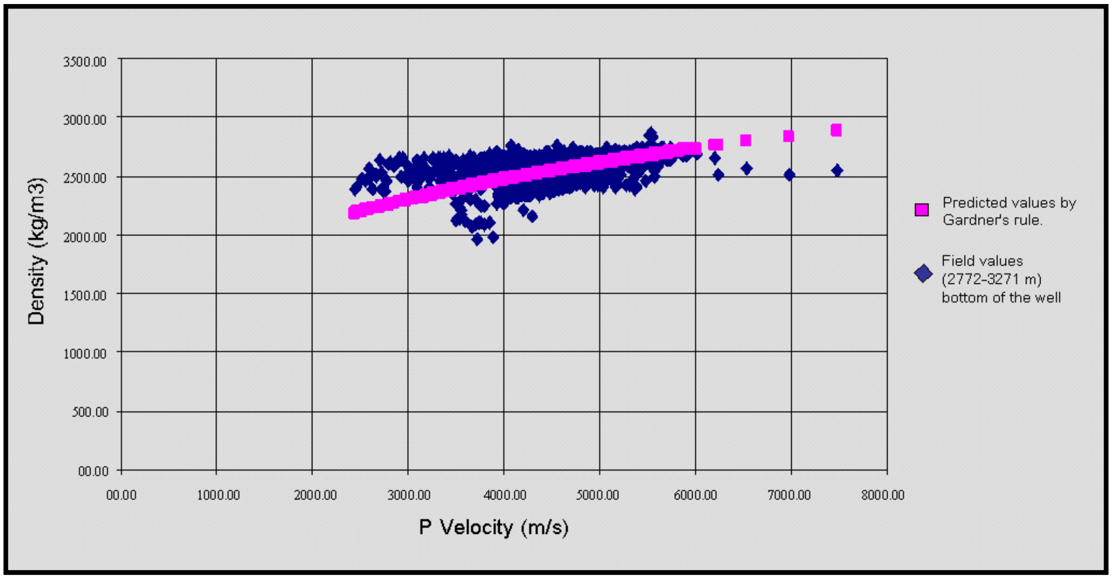


FIG. 6. Gardner's rule between P-wave velocity (m/sec) and density (kg/m3), for H-20 well (the values are from 3271m to 2772m true vertical depth).

MULTI-VSP ACQUISITION

To image the White Rose field, two VSP techniques were used: the offset VSP and walkabove VSP. The geometry of each of these surveys is described below.

H-20 offset-VSP

The offset VSP survey (Figure 7) had a fixed-source offset of 1000 m, located north of the H-20 well, and the VSP receivers (3 component geophones) were located (in the vertical part of the borehole) between 2080 and 2500 m measured depth in the well.

H-20 walkabove-VSP

The survey (Figure 8) had a varied position, for the source offset (from 40 m to 250 m) away from the surface location of the H-20 well. To keep the source positioned vertically above the receivers in the deviated well, the VSP receivers were located between 1660 m and 3280 m measured depth in the well.

MULTI-VSP PROCESSING

The Multi-VSP dataset from H-20 well of White Rose field was processed by Schlumberger Canada Ltd. for Husky Energy Inc.

INTERPRETATION

The synthetic seismogram package, SYNTH (Larsen et al., 1997), was used to create the synthetic seismograms. A Ricker wavelet of 45 Hz, and shallow velocities of $P_{velocity}$=1500m/s and $S_{velocity}$=750m/s, plus a maximum offset value of 3000m (according to Hall et al., 2001) were employed for this modelling.

The offset VSP (P-wave) section and the Synthetic Seismogram (P section) section it is shown in Figure 9, we made the following correlations:

The Eocene (EOCN) top can be followed from the near offsets to 2200m, on the synthetic data, but in the VSP section it is less defined. The South Mara Unit (SMAR) top, shows on the VSP section as a strong event, the synthetic seismogram gives more detail of this top, more detail of the lithology. The top of the Tertiary Unconformity (BTUN) is a strong event on both sections, the amplitude decreases (in some parts) with the offset in the synthetic seismogram (Figure 11). The Nautilus Shale Formation (NTLS) top is easy to recognize, the amplitude on both sections is strong, decreasing slightly with offset in the synthetic seismogram. We can see on both sections several events that could be related to the three subunits of the Nautilus shale, although the events are difficult to discern.

The top of the Avalon Formation is a siltstone that is in contact with the basal unit of the Nautilus, a silty sandstone that grades upward into siltstone; so, the low amplitude that is in this area is probably due to the fact that the reflection coefficient between these two units is almost imperceptible, it is possible that there is a low reflection coefficient product to the presence of the Nautilus silty sandstone.

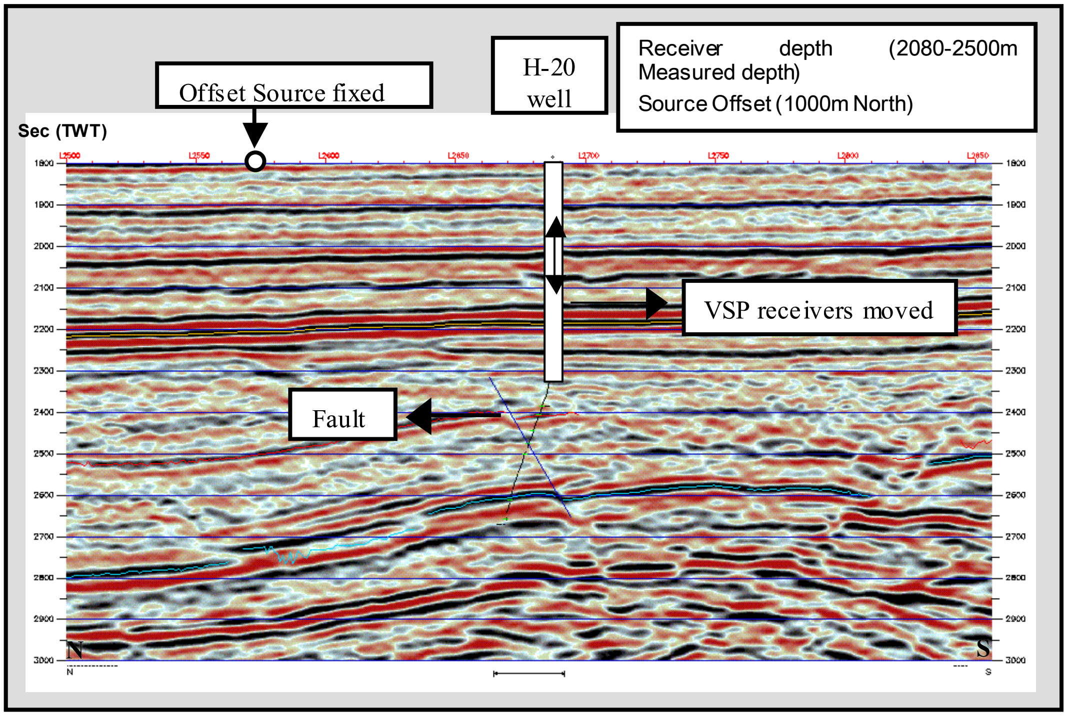


FIG. 7. North-South seismic line, intersecting the H-20 well. Details of the H-20 offset VSP geometry (modified after Emery, 2001).

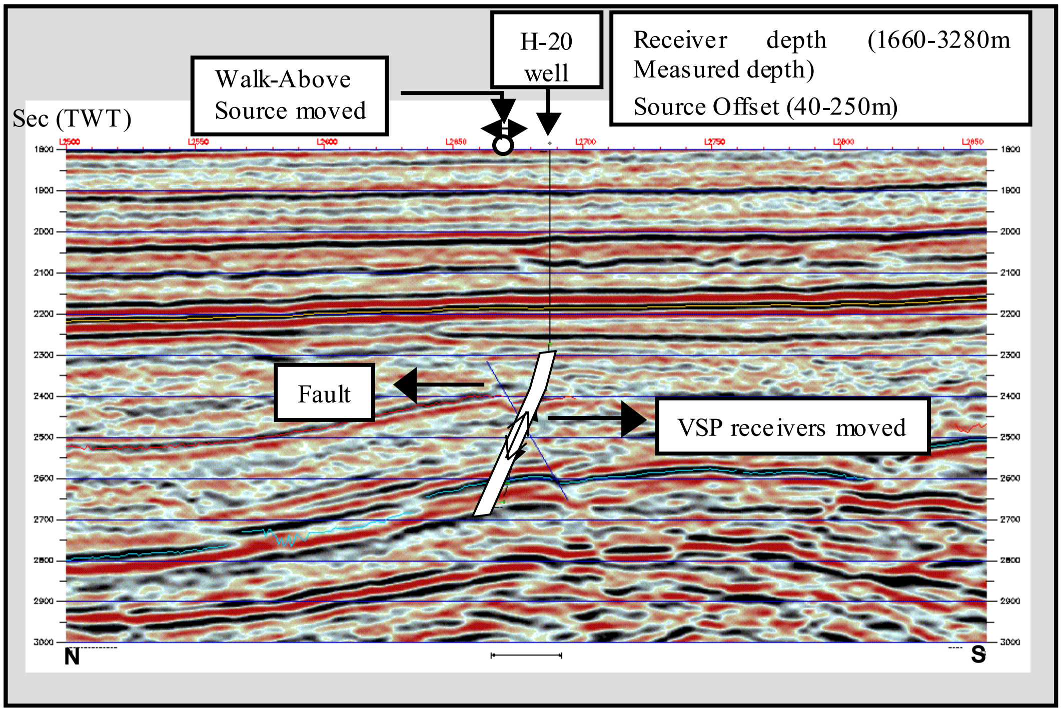


FIG. 8. North-South seismic line, intersecting the H-20 well. Details of the walk-above VSP geometry (modified after Emery, 2001).

The Avalon Siltstone (AVAL) top is a strong event in the synthetic seismogram, which can be followed from near offsets to far offsets (2000m), but it is not strong in the VSP section. The Avalon Sandstone (AVSS) event in the synthetic seismogram is not as strong as it is in the VSP section, but can be followed from near offsets to far offsets, having almost the same amplitude (Figure 11).

The Oil-Water Contact (OWC) shows low amplitude on both sections, but still can be recognized and the Eastern Shoals Fm (ESHL) is a strong event on both sections.

After comparing the Offset VSP (S-wave) section and the Synthetic Seismogram (S-wave) section, in Figure 10, we made the following correlations: the Eocene (EOCN) top is a strong event from 700m offset to far offsets in synthetic seismogram, it can be followed on both sections; the South Mara Unit (SMAR) shows a Strong event that increases amplitude with offset; the Tertiary Unconformity (BTUN) top is a strong event on both sections (Figure 11); and the top of Nautilus Shale Formation (NTLS) is strong on the synthetic seismogram, but not that strong on the VSP section. The events related to the variation of geology (three subunits) on this formation can be followed on both sections.

The top of the Avalon Formation is a siltstone that is in contact with the basal unit of the Nautilus, a silty sandstone that grades upward into siltstone; therefore, the low amplitude that is in this area is probably due to the fact that the reflection coefficient between this two units is small. The Avalon Siltstone (AVAL) top has a weak amplitude event on the synthetic seismogram, which can be followed from 250m offset to far offsets (2450m). In the VSP section the Avalon Siltstone (AVAL) event cannot be seen, and the Avalon Sandstone (AVSS) also shows a weak amplitude events on both sections but can be followed (Figure 11).

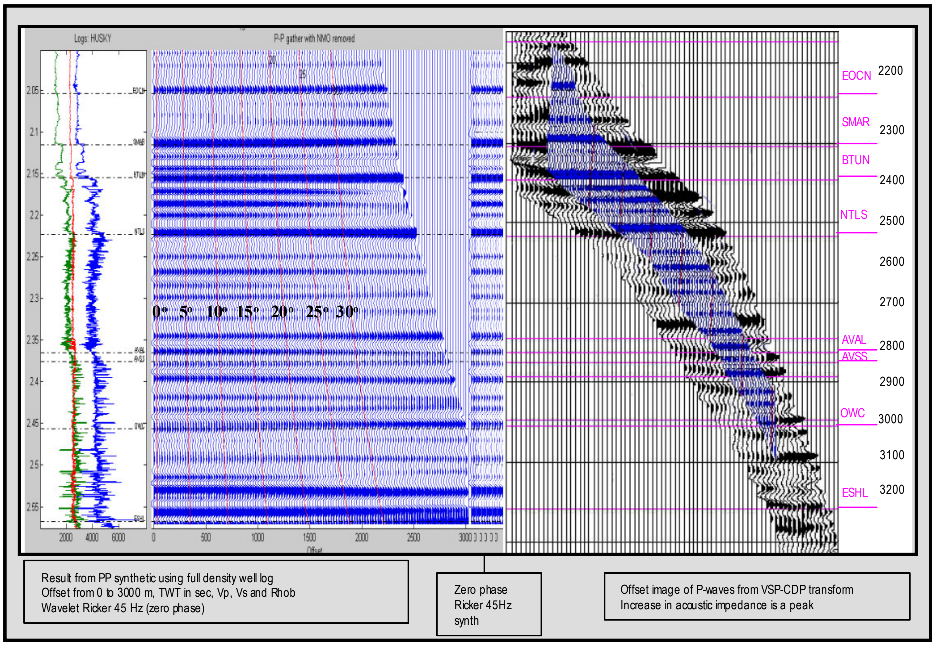
Oil-Water Contact (OWC) is a strong event on Synthetic seismogram, but not perceptible in the VSP section. The Eastern Shoals Formation (ESHL) is a strong event on Synthetic seismogram, but not perceptible in the VSP section.

With the Walk-above VSP (P-wave) section and the Synthetic Seismogram (P-wave) section Figure 12, we made the following correlations:

Due to the geometry of the survey, the Eocene (EOCN), South Mara Unit (SMAR), Tertiary Unconformity (BTUN), and Nautilus Shale Formation (NTLS) are not sampling enough to give a detailed view of the tops.

The Avalon Siltstone (AVAL) top is a strong event on the synthetic seismogram, which can be followed from zero offset to far offsets (2250m). In the VSP section it is not too clear. And Avalon Sandstone (AVSS) top has a weak amplitude event on both sections but can be followed

The Oil-Water Contact (OWC), Event can be followed on both sections. Eastern Shoals Formation (ESHL) is a strong event on both sections.

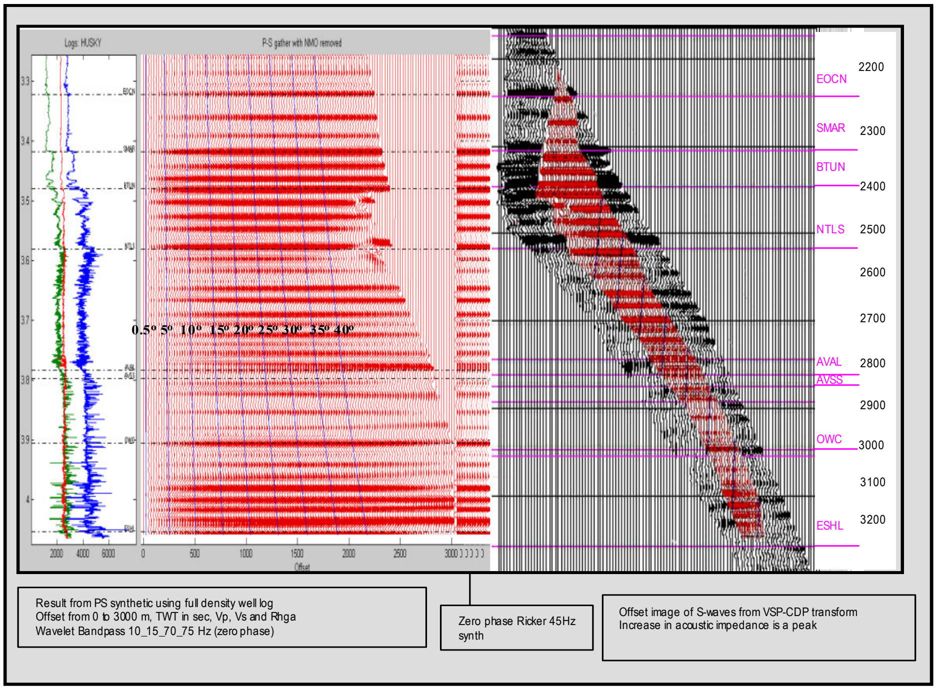


Result from PP synthetic using full density well log
Offset from 0 to 3000 m, TWT in sec, Vp, Vs and Rhob
Wavelet Ricker 45 Hz (zero phase)

Zero phase
Ricker 45Hz
synth

Offset image of P-waves from VSP-CDP transform
Increase in acoustic impedance is a peak

FIG. 9. Correlation of the PP synthetic seismogram, using the predicted/recorded density value (curve RHGA in Figure 4). The following acronyms are used: Eocene, EOCN; South Mara Unit, SMAR; Base Tertiary Unconformity, BTUN; Top Nautilus Shale, NTLS; Top Avalon Siltstone, AVAL; Top Avalon Sandstone, AVSS; Oil-Water contact, OWC; Eastern Shoals, ESHL.



Result from PS synthetic using full density well log
Offset from 0 to 3000 m, TWT in sec, Vp, Vs and Rhga
Wavelet Bandpass 10_15_70_75 Hz (zero phase)

Zero phase Ricker 45Hz
synth

Offset image of S-waves from VSP-CDP transform
Increase in acoustic impedance is a peak

FIG. 10. Correlation of the PS synthetic seismogram and the Offset VSP section, using the predicted/recorded density value (curve RHGA in Figure 4). The following acronyms are used: Eocene, EOCN; South Mara Unit, SMAR; Base Tertiary Unconformity, BTUN; Top Nautilus Shale, NTLS; Top Avalon Siltstone, AVAL; Top Avalon Sandstone, AVSS; Oil-Water contact, OWC; Eastern Shoals, ESHL.

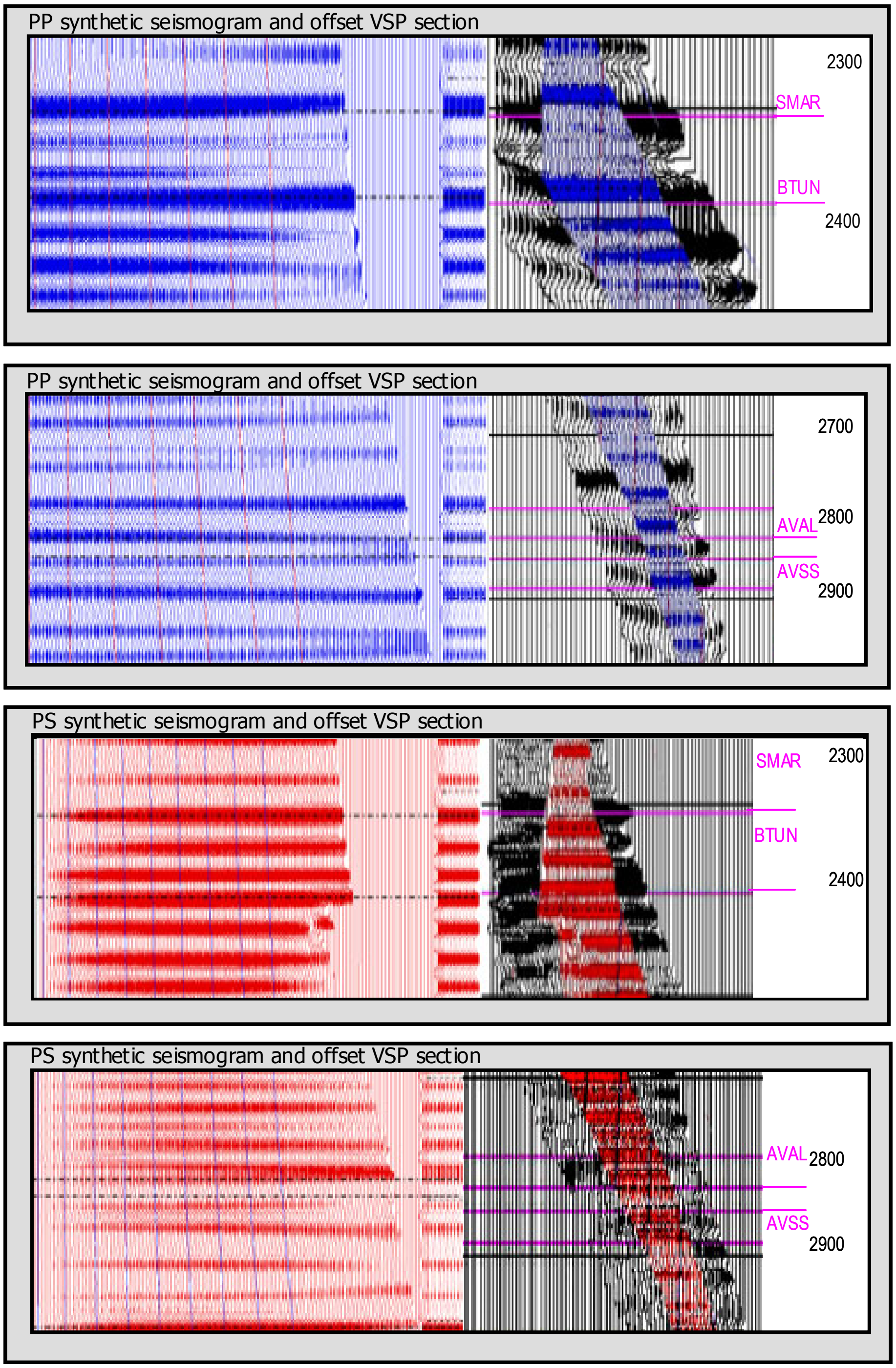


FIG. 11. Enlargements around the Tertiary Unconformity, BTUN, and Avalon Top, AVAL and AVSS, for both PP and PS sections. The following acronyms are used: South Mara Unit, SMAR; Base Tertiary Unconformity, BTUN.

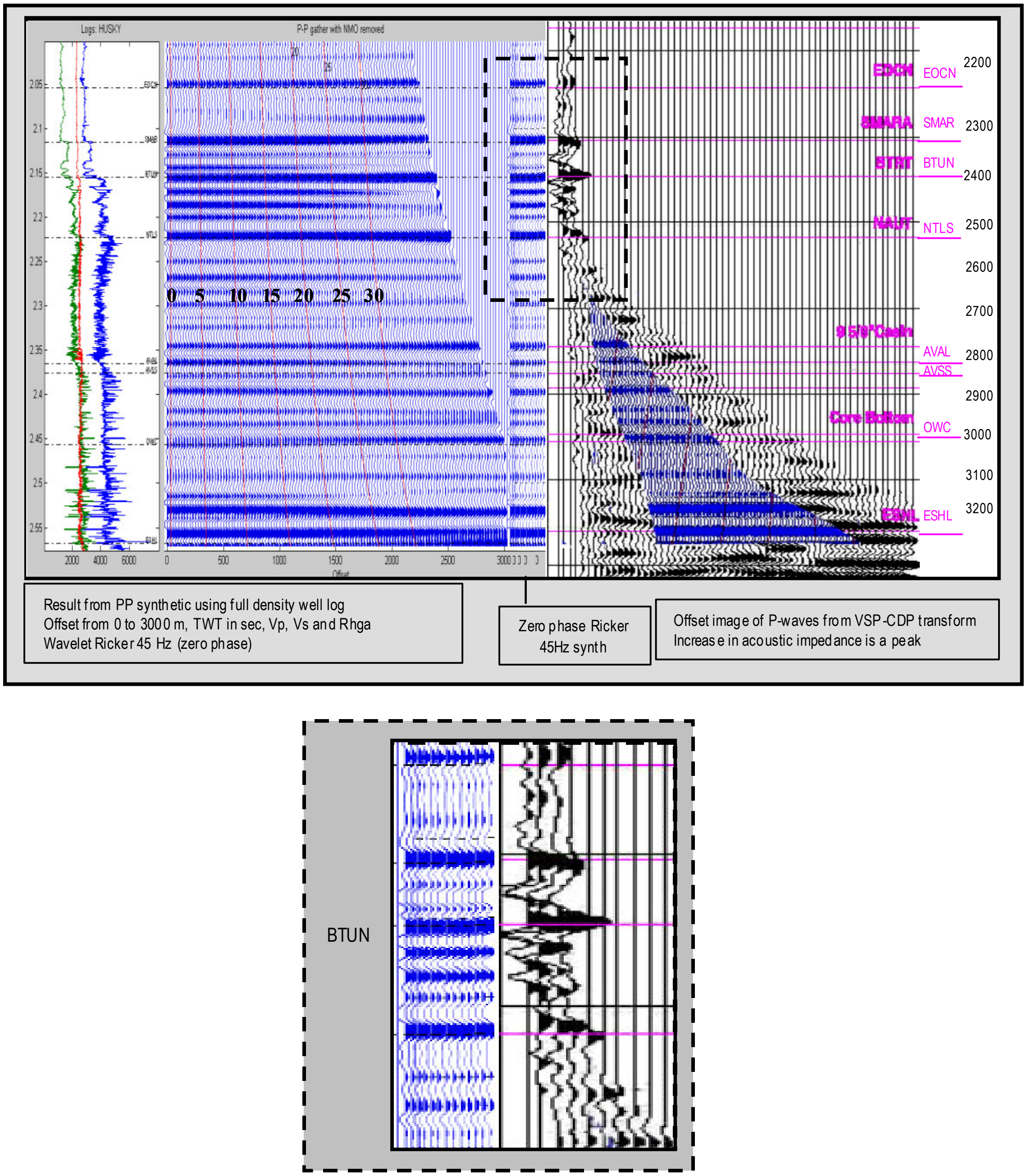
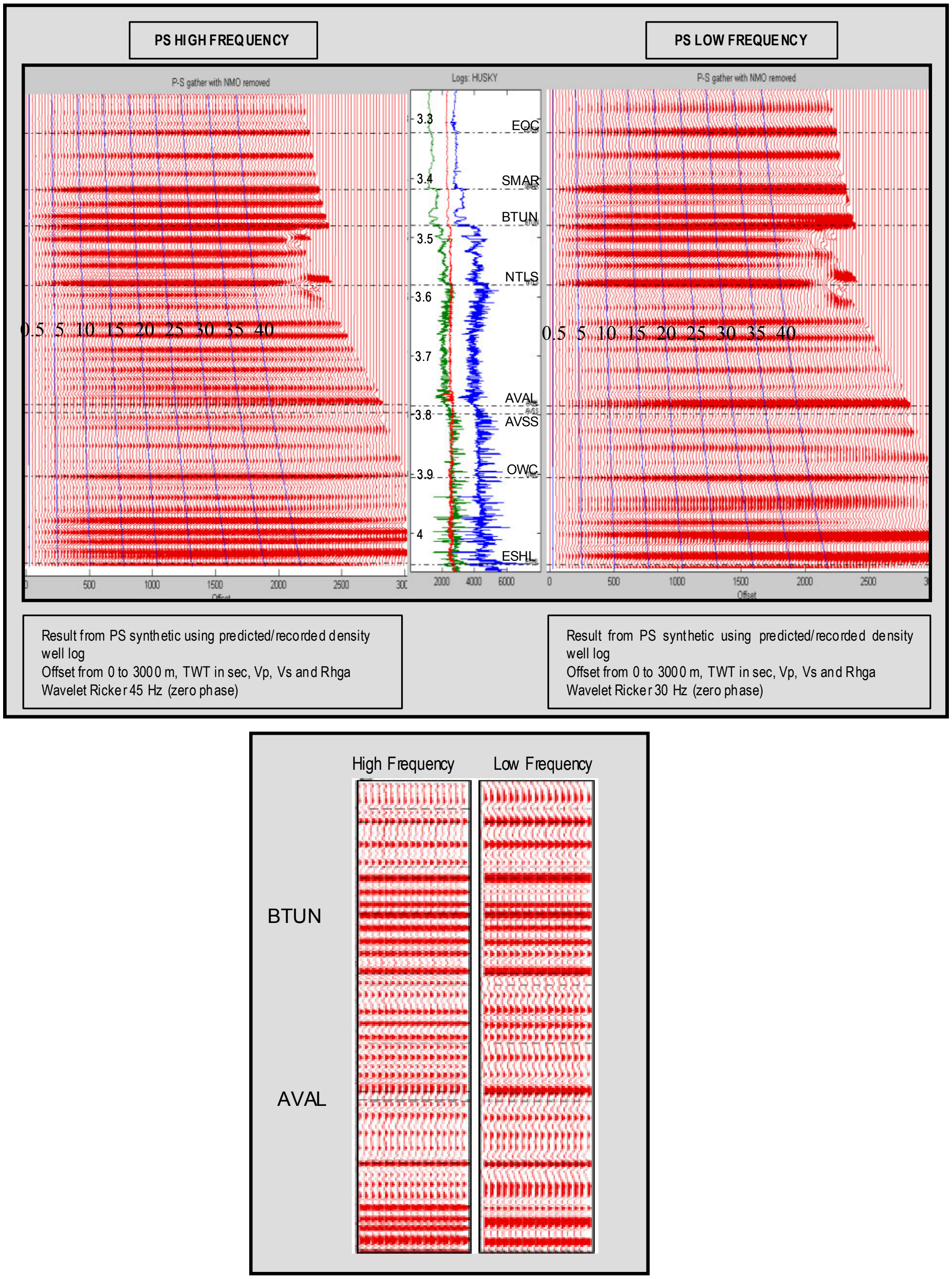


FIG. 12. This composite figure shows the results from matching the PP synthetic seismogram with the walk-above VSP section, using the predicted density value (curve RHGA in Figure 4). A zoom of the dashed area in the figure above; shows the stacked trace section is from the PP synthetic seismogram. The following acronyms are used: Eocene, EOCN; South Mara Unit, SMAR;, Base Tertiary Unconformity, BTUN; Top Nautilus Shale, NTLS; Top Avalon Siltstone, AVAL; Top Avalon Sandstone, AVSS; Oil-Water contact, OWC; Eastern Shoals, ESHL.



Result from PS synthetic using predicted/recorded density well log
Offset from 0 to 3000 m, TWT in sec, Vp, Vs and Rhga
Wavelet Ricker 45 Hz (zero phase)

Result from PS synthetic using predicted/recorded density well log
Offset from 0 to 3000 m, TWT in sec, Vp, Vs and Rhga
Wavelet Ricker 30 Hz (zero phase)

FIG. 13. Above: composite figure, showing a comparison of PS synthetics: high-frequency (45Hz) vs lower frequency (30Hz). The events of interest are in the rectangle. A close comparison of the stacked trace section of each of the synthetic seismograms of the figure above. The acronyms used in this figure are: Eocene, EOCN; South Mara Unit, SMAR;, Base Tertiary Unconformity, BTUN; Top Nautilus Shale, NTLS; Top Avalon Siltstone, AVAL; Top Avalon Sandstone, AVSS; Oil-Water contact, OWC; Eastern Shoals, ESHL.

The converted shear-wave (Figure 11) helps to identify the events in the area of interest (interface between the Nautilus and Avalon formations) more clearly than those in the PP matching (Figure 11). However, the difficulty to define the exact limit between the Nautilus shale with the Avalon siltstone remains. A 4C ocean bottom sensor (OBS) survey, and the generation of shear waves will increase the quality of the image of the reservoir.

What if in the OBS survey, the PS has lower frequency content than the PP? Isaac and Lawton (1995) observed that, in general, PS seismic sections have half the frequency content of PP seismic sections (60Hz vs 30Hz). Figure 13 compares the same synthetic seismogram but with a lower frequency content (from Ricker wavelet 45 Hz to Ricker wavelet 30 Hz). Under those circumstances the top of the Avalon Formation can still be identified.

CONCLUSIONS

It is important to remember that there is a low impedance contrast between the Avalon Formation and the overlying shale Nautilus Formation. The top of the Avalon Formation is a siltstone unit and the base of the Nautilus Formation is interbedded silty sandstone that grades upward into siltstone. There is little lithological contrast between the formations.

Looking at the different results, the PP synthetics match well with the PP Offset VSP field data, the PS synthetic seismograms match well with the PS (S-wave) Offset VSP field data, the PP synthetic seismogram match well with the walk-above VSP (PP only). The walk-above VSP was matched with the seismic section (PP only). The walk-above VSP shows the horizons and the fault well. The PP synthetic seismograms match well with the seismic section.

When comparing the PS to the PP synthetic seismograms and comparing the field results of the PS offset VSP to the PP offset VSP, the PS images (the top of the Avalon Formation) better (higher amplitude over the surrounding signals). In other words the results from the match between the PS synthetic seismograms with the PS offset VSP showed an improved image over the results from the PP synthetic seismograms and the PP offset VSP and the PP seismic.

Acquiring converted-wave data with the assistance of an Ocean Bottom Seismometer survey, should help to address the different image challenges of the White Rose field. In this paper it has been shown that converted waves could bring the following:

Some undesirable contrasts (e.g. Cretaceous-Tertiary boundary) may be weaker with converted waves given rise to less multipathins. There appears to be more reflection activities in the PS section that PP in the Avalon vicinities.

The poor image contrast, between the Avalon Formation and the overlying shale from the Nautilus Formation, can be improved with the help of converted waves.

After comparing the PS high-frequency and low-frequency synthetic seismograms, the events related to the top of the Avalon Formation can still be resolved.

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