Using V_P/V_S to explore for sandstone reservoirs: well log and synthetic seismograms from the Jeanne d'Arc basin, offshore Newfoundland

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ABSTRACT

This investigation in the Jeanne d'Arc Basin, offshore Newfoundland, involves a petrophysical analysis to determine the relationship of Vp/Vs to lithology and the evaluation of PP and PS synthetic seismograms for these Vp/Vs values.

The petrophysical analysis indicates that the sediments in the Jeanne d'Arc Basin fit quite well with the Castagna (1985) mud rock line. Our key finding is that for rock in the Jeanne d'Arc Basin, a Vp/Vs of 1.75 should differentiate a clay or calcite-rich bed from a quartz-rich deposit. Analysis of the synthetic seismogram indicates that the Garotta (1987) interval travel-time calculation will successfully determine lithology for formation scale events. Analysis of individual beds indicates that tuning and resolution issues dominate the calculated Vp/Vs. It is recommended that Vp/Vs analysis using interval times should be limited to intervals greater than a wavelength.

Vp/Vs analysis using multi-component seismic in the Jeanne d'Arc Basin shows significant promise.

INTRODUCTION

The Jeanne d'Arc Basin is located 300 km east of St. John's Newfoundland (Figure 1). The basin has been an active area of exploration since the early 1970's. Initial stages of exploration were based on ship borne gravity, magnetic and multi fold streamer 2-D seismic data (Enachescu et al., 1998; Enachescu and Hogg, 2005). The present round of exploration and exploitation has been driven both by improved oil prices and the interpretation of 3-D streamer seismic. In addition, research has been started on multi-component seismic acquisition (Hoffe, 2000; Cary, 2003; and Jaramillo, 2005). At present, cost has been the limiting factor in applying these emerging technologies in the offshore of eastern Canada (Hoffe, 2000). This paper uses modern well-log data to model the expected results from interpreting Vp/Vs values from multi-component seismic data in the Jeanne d'Arc Basin.

As Pickett (1963), Tatham (1980), Garotta (1987), Castagna (1993), Miller (1996), Margrave (1998) and Stewart (2003) have demonstrated, changes in lithology can cause a change in the Vp/Vs. Garotta (1987) proposed that Vp/Vs could be determined from ΔT_{PS} and ΔT_{PP} travel times between the top and base reflections of a formation (equation 1).

The Garotta equation is:

$$V_P / V_S = 2 \times \Delta T_{PS} / \Delta T_{PP} - 1, \quad (1)$$

where Vp/Vs is equivalent to two times the PS travel time divided by the PP travel time minus 1.

Assuming the top and base reflectors can be clearly defined and picked, the resulting Vp/Vs values should represent both the average lithology and porosity between the picked horizons. The calculation of the seismic time thickness therefore becomes a practical issue of the seismic resolution, horizon correlation and wavelet tuning.

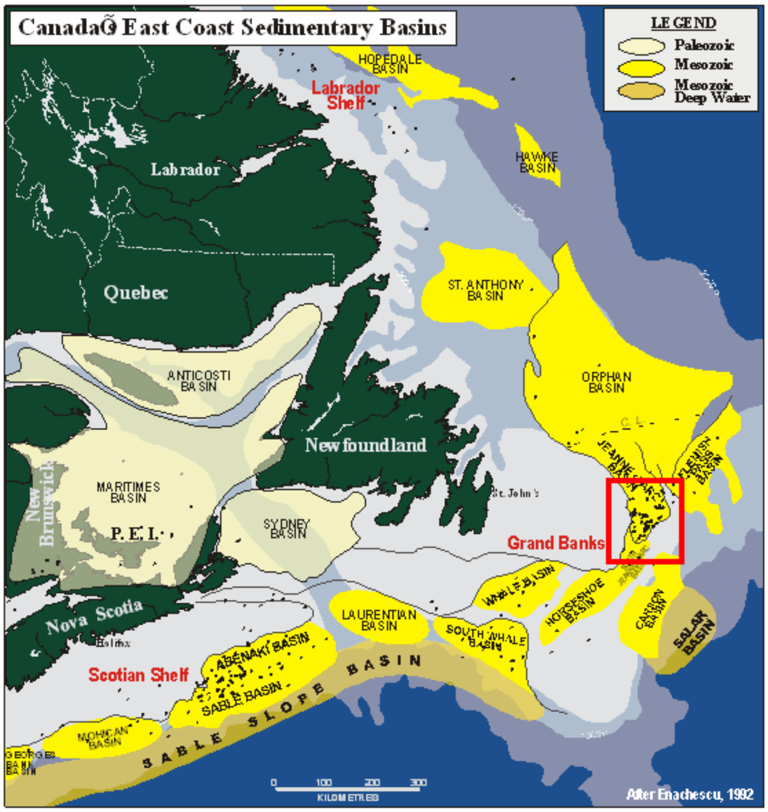

FIG. 1. Mesozoic Basins of the Grand Banks of Canada. The location of the Jeanne d'Arc Basin is outlined in red.

DATA

The twelve wells (FIG. 2 and) available for this study, drilled between 1997 and 2001, have various hole sizes, a mixture of different contractors and down-hole tools. The neutron porosity logs have the most significant disparity, with various instrument measurements and lithology corrections. Parts of several density and S-wave log runs were rejected as they appeared to have been calculated from the P-wave sonic log using either Gardner (1974), Castagna (1985) mud rock relationships, or a constant Vp/Vs.

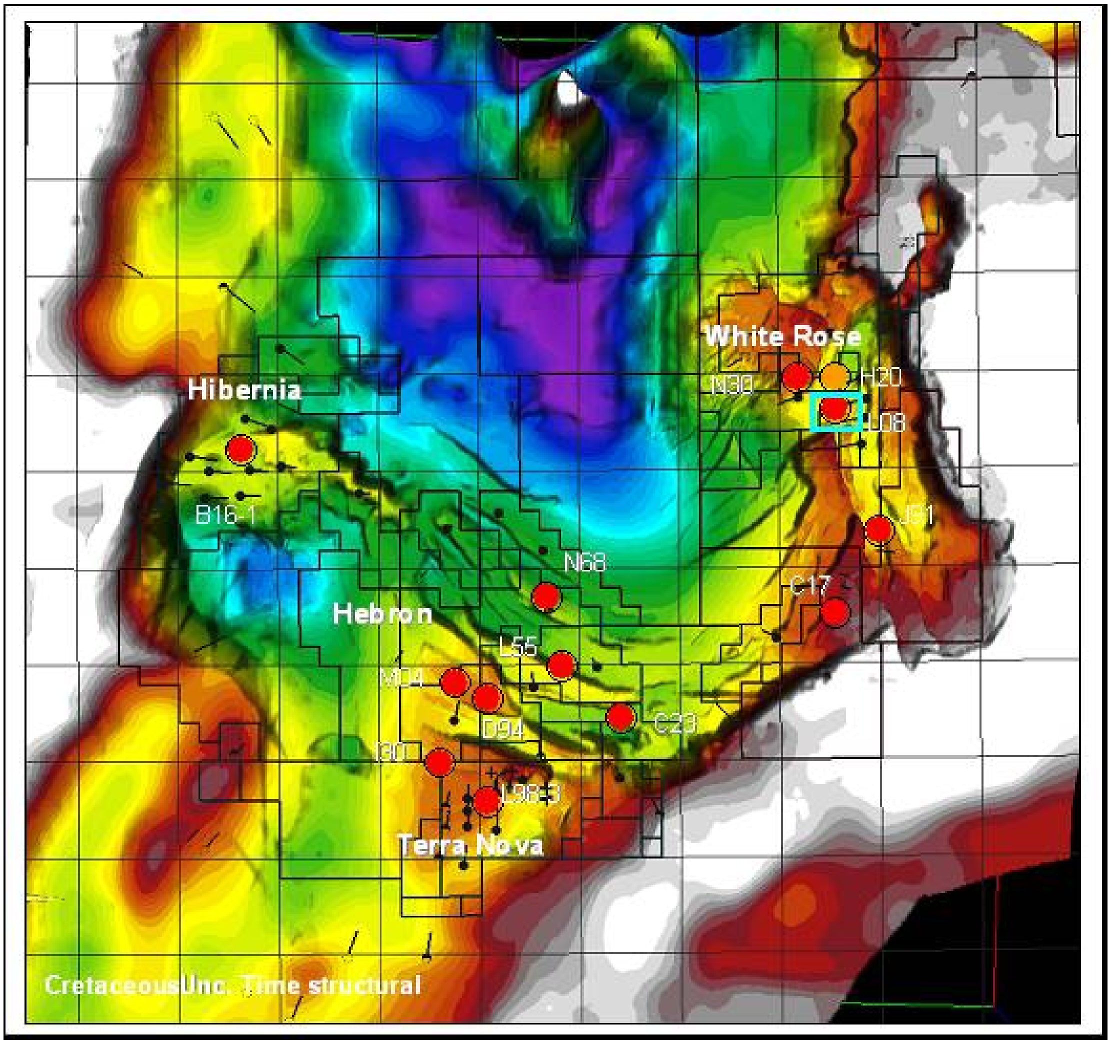

FIG. 2. Study data location – Isochron map of the Jeanne d'Arc Basin Late Cretaceous interval (white 0 ms to purple 4000 ms). Red and Orange dots are the location of individual wells in the study. The Orange dot is the location of White Rose H20 offset VSP and the Blue Square is the location of the CREWES White Rose L08 OBS survey.

Table 1. Project wells with associated logs and measured depth intervals. *The White Rose H20 Neutron porosity log has a gap from 1602 to 1929. Log abbreviations are: NPR – neutron porosity, GR – gamma ray, DT – compressional sonic, SDT - shear sonic and, RHOB – density.

	Depth		Logs available for study (MD)									
	Min	Max	NPR		GR		DT		SDT		RHOB	
Ben Nevis L55	872	2612	872	2612	872	2612	872	2612	2405	2502	872	1698
Brents Cove I30	920	4062	920	4057	958	4062	920	3288	1522	3231	995	4060
Cape Race N68	1024	2948	1024	2948	1024	2948	1024	2948	1024	2948	1024	2948
Gros Morne C17	1230	2260	1230	2260	1230	2260	1230	2260	1230	2260	1230	2260
Hebron D94	900	2082	900	1994	900	2082	1475	1994	1475	1994		
Hebron M04	1305	4586	1305	4586	1305	4586	1305	4586	1458	4571	1305	4586
Hibernia B16-1 (MD)	423	4590	423	4590	423	4590	423	3888	423	3888		
Terra Nova L98-3	1370	3694	3291	3694	1370	3694	1380	3694	1425	3694	3320	3694
West Bonne Bay C23	84	4318			3808	4317	84	4318	1521	4318		
White Rose N30	908	3275	2720	3275	908	3275	908	3275	908	3275		
White Rose H20	850	3380	850	3380	850	3380*	850	3380	850	3380	2810	3380
White Rose L08	820	3120	820	3120	820	3120	820	3120	820	3120	820	3120

As the study concentrates on seismic scale effects, small-scale heterogeneities were removed using a 5m median filter. Porosity values were estimated from both the density and neutron porosity logs with lithology-based corrections done for each formation.

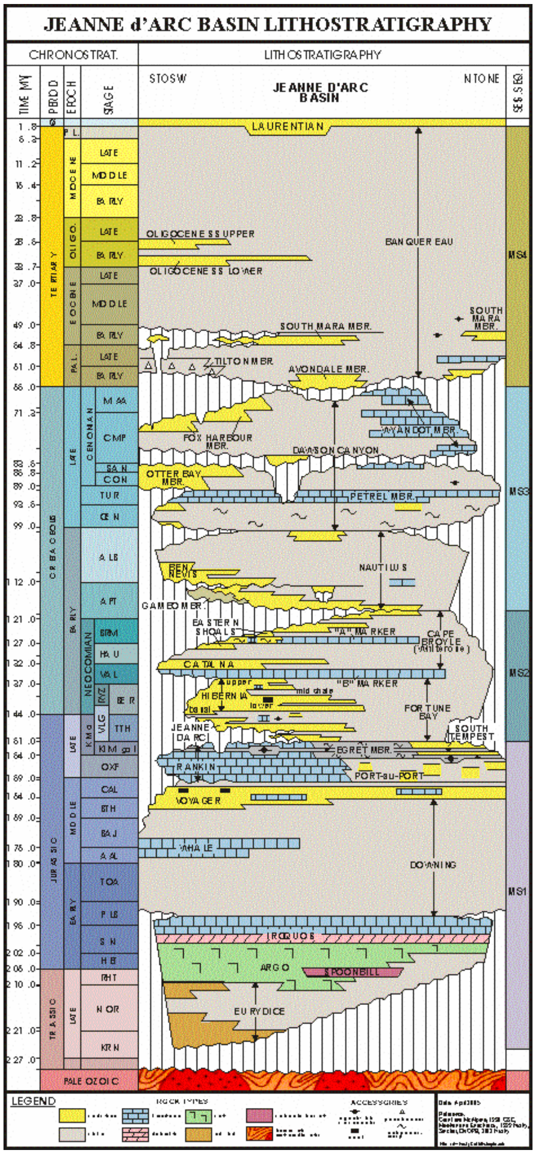

FIG. 3. Stratigraphy of the Jeanne d'Arc basin, offshore Newfoundland.

The PP and PS synthetic seismograms generated for Vp/Vs analysis were from a composite log created from the parts of six of the twelve wells in the study. P-sonic, S-sonic and density logs intervals were selected to represent the type sections described by Sinclair (1988; 1993) and McAlpine (1990) for each of the formations in the Jeanne d'Arc basin (FIG. 3). Regrettably, the wells drilled since 1997 do not penetrate all formations. When pre-1997 wells were used, the missing S-sonic logs were created using the Castagna (1985) mud rock relationship. When density information was missing or questionable, the log was replaced with Gardner's (1974) density values.

The resulting Jeanne d'Arc composite log (FIG. 4) has shear-wave information down to 6207 m. As the wells in the Jeanne d'Arc Basin have TD's from 2000-4500m and most of the zones of interest were extracted from 2800 to 4300 m, no compaction corrections were applied. The type section selected for the major reservoirs were White Rose L-08 for the Ben Nevis formation, Cape Race N-68 for the Avalon fm, Hebron M-04 for the Hibernia fm and Terra Nova L98-3 for the Terra Nova formation.

A plot of the entire Jeanne d'Arc Basin dataset (FIG. 5) indicates a reasonable fit to the Castagna mud-rock relationship. As the dataset is substantial, FIG. 6 contains only the subset that was selected to represent the formation-type section that was used for petrophysical analysis, synthetic generation and the travel-time analysis.

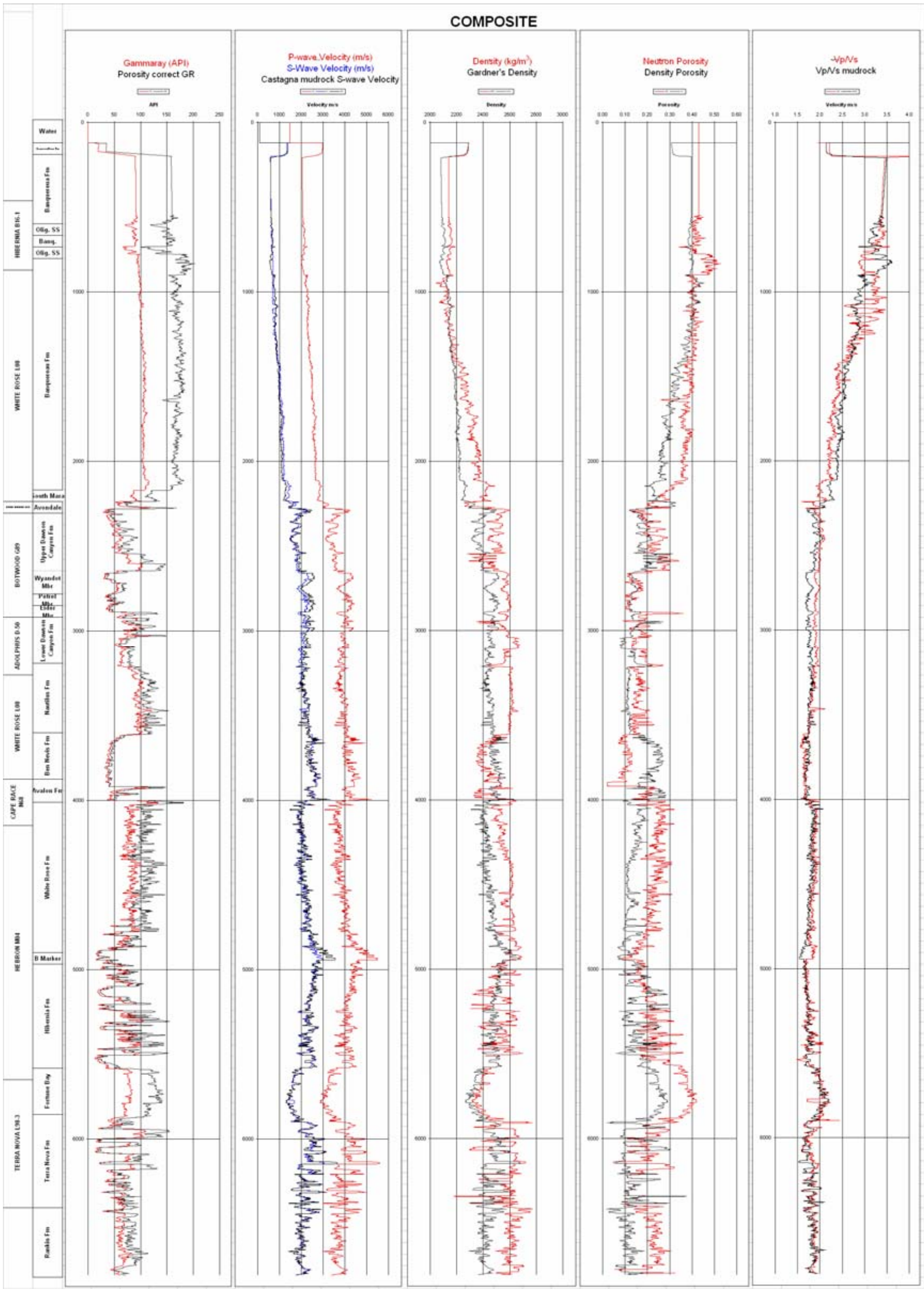

FIG. 4. Composite Log – Display depth has been limited to correspond to the measured S-wave velocity. Shear-wave information at the sea floor, between 2282-3468 and below 6207 m was calculated using the mudrock line (Castagna 1985). Density data down to 600 and between 5585-5872 was estimated using Gardner's (1974) density relationship.

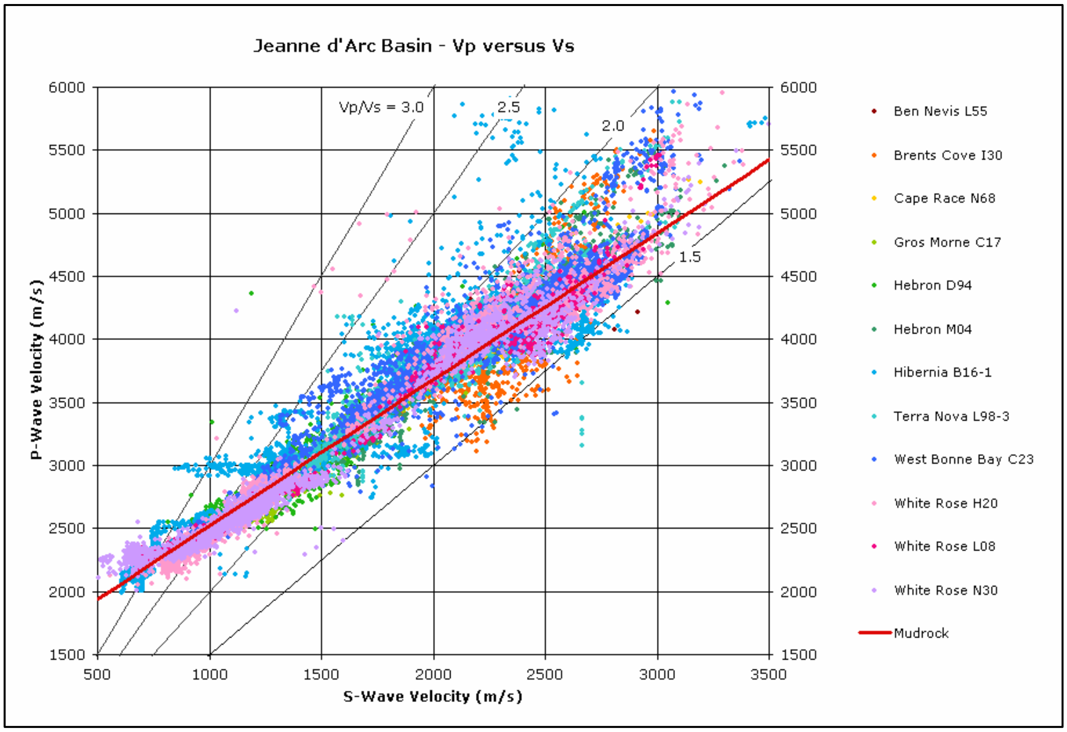

FIG. 5. Vp versus Vs for the Jeanne d'Arc Basin. Colour coded by well location with theoretical curves for a general Cretaceous sandstone (V_{Pma}=5000 and V_{Sma}=3100).

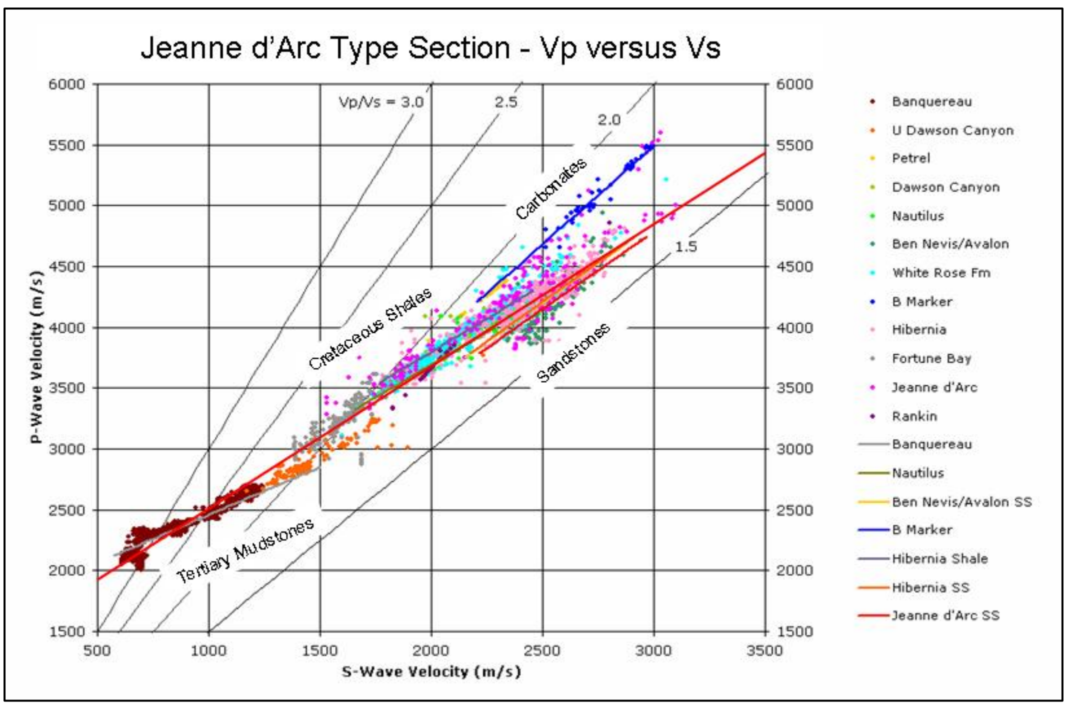

FIG. 6. Cross-plot of Vp versus Vs - the red line across the plot is the Castagna mud-rock line, formation lines are limited to the expected porosity range, the Fortune Bay formation shales (grey) have only partial log information.

Plotting Vp versus Vs by formation (FIG. 6) indicates a strong separation of lithologies across the chart. The lower left contains the Banquereau Formation that is predominately poorly consolidated shales with relatively high clay contents. The more consolidated Cretaceous shales of the Nautilus, White Rose, Hibernia and Terra Nova formations are contained above the Mud rock line in the middle of the graph. The Ben Nevis/Avalon, Hibernia and Terra Nova formations sandstones lie under the mud-rock line and slightly to the right of their associated shales. The limited carbonate formations (Petrel and B Marker) are located above the line and with near constant Vp/Vs, as expected. The over-pressured Fortune Bay Formation shales (grey point) have only partial log information and, while a clear analysis was not possible, the data points lie between the under-compacted Tertiary mudstones and the normally-pressured Cretaceous Shale.

Estimating the porosity was problematic because the neutron porosity and density logs are only indirect measurements of a rock's pore space. Neutron logs work by emitting particles that are preferentially affected by hydrogen atoms, meaning that the detector predominately measures the content of water atoms. As clay minerals contain bound water, the neutron response will be greater than the actual effective porosity (Schlumberger, 1998). Likewise the density tool works by emitted gamma ray particles that read the total number of atoms between the source and detector. The density tool is generally calibrated for reservoir mineralogy (limestone), causing a slightly erratic reading in non-homogeneous formations such as shale.

Estimation of the porosity, therefore, differed as a function of lithology. For clean formations (low gamma ray), the effective rock porosity was estimated using both the neutron and density logs. The consistent lithology Banquereau formation received a similar treatment. The density logs were omitted for estimating porosity in the Cretaceous shales.

From the Vp/Vs petrophysical analysis results (Figure 7), a Vp/Vs value of 1.75 should divide the quartz-rich formation from the more clay and calcite-dominated formations. The Vp/Vs range for the sandstone reservoirs (Ben Nevis/Avalon, Hibernia, and Jeanne d'Arc Fms) varies from a low of 1.58 to a high of 1.75. While the Cretaceous shale formations (Nautilus, White Rose, Hibernia and Jeanne d'Arc fms) all have Vp/Vs values from 1.75 to 2.1 with the tight low porosity shales having Vp/Vs values vary similar to the better sandstone reservoirs (both near 1.75). Differentiation between the shales and carbonates would be difficult as both have Vp/Vs around 1.8. A Vp/Vs above 2 indicates a decrease in compaction as both the Cretaceous Shales and the Banquereau formation mudstones indicate a sharp increase in Vp/Vs with increasing porosity.

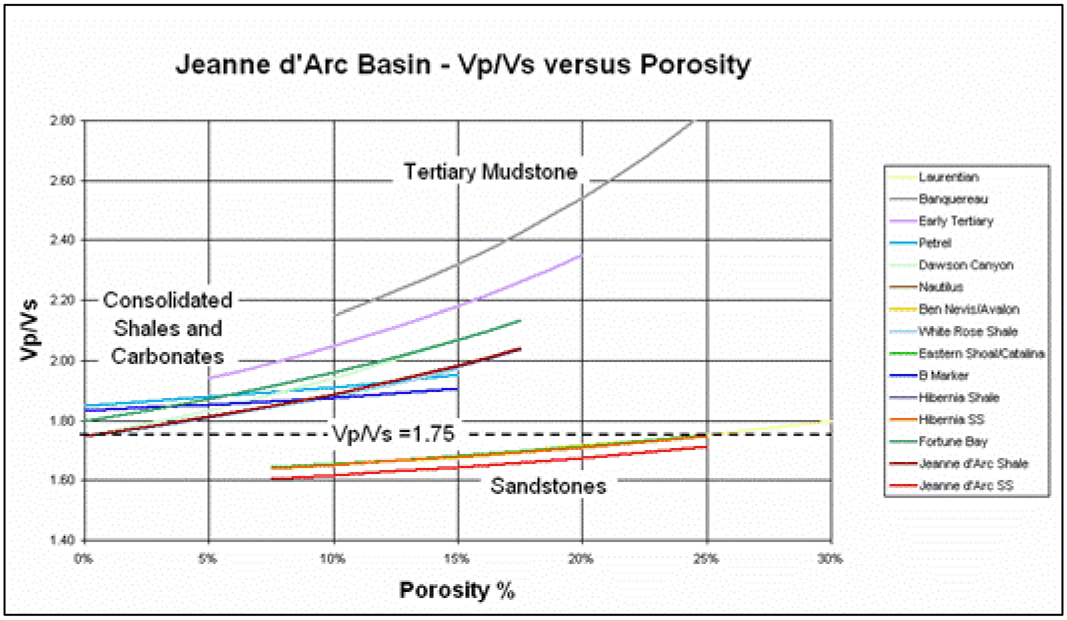

FIG. 7. Plot of the petrophysical relationships for Vp/Vs versus Porosity – The consolidated Cretaceous sandstones have Vp/Vs's below 1.75 while the shales and carbonate have Vp/Vs greater than 1.75. Vp/Vs crossover will cause problems in differentiating between porous sandstones and lower porosity shales (Vp/Vs ~ 1.75).

SYNTHETIC GENERATION

The *SYNGRAM* program, from the CREWES project, was used to model the multi component responses of lithologic changes for the Jeanne d'Arc Basin. The *SYNGRAM* software (Larsen et al., 1997) creates both PP and PS synthetics using the explicit Zoeppritz equation (Aki and Richard 1980). The program creates PP and PS synthetics by stacking offset gathers that are created assuming a maximum offset as a function of depth, horizontal bedding, and straight ray geometry. For this study, an offset range was selected to generate incident angles between 0 and 30-35°. While the program provides the option of applying transmission losses and calculating multiples, the synthetics were created using reflection energy only.

The PP and PS synthetic seismograms were created with an Ormsby 5/10-80/95 PP and 5/10-70/85 PS zero-phase wavelet. The stacked seismic traces were duplicated 25 times while loading to Landmark Graphic *SeisWork* software and then bandpass filtered in 2 Hz increments. Geological tops and seismic correlation were selected on the nearest peak, trough or zero crossing from the PP and PS synthetics.

FORMATION SCALE ANALYSIS

FIG. 8 demonstrates the effectiveness of interval travel time analysis for large-scale formation evaluations. The quartz-rich Ben Nevis/Avalon and Hibernia formations have average Vp/Vs values below the 1.75 reservoir cutoff determined during the petro-physical analysis. The Terra Nova formation contains the third major reservoir in the Jeanne d'Arc basin but also a significant number of shale beds resulting in a Vp/Vs of

1.82. While this value is greater than the 1.75 Vp/Vs cutoff, it is still significantly less than the 2.1 calculated for the overlying Fortune Bay Formation shales.

The non-reservoir Banquereau, Nautilus, White Rose and Fortune Bay formations all have Vp/Vs values greater than 1.85. Likewise the B Marker carbonate 1.85 Vp/Vs is equal to the expected values from logs. As the S-wave logs for the Dawson Canyon Formations and Petrel Member were created using the mud-rock line, little should be interpreted in their 1.93 and 1.95 calculated Vp/Vs values.

This first pass of Vp/Vs analysis indicates, when applied to formation scale analysis, that the Garotta (1987) relationship will work well in the Jeanne d'Arc Basin. While this analysis was undertaken using a 1-dimensional synthetic, extrapolation to a 2-D or 3-D geological model should also hold true. The Ben Nevis/Avalon Formation should have a pronounced shift from under 1.75 when the formation is dominated by shoreline sandstone and grade to 2.1 when the facies has changed into the equivalent offshore shale.

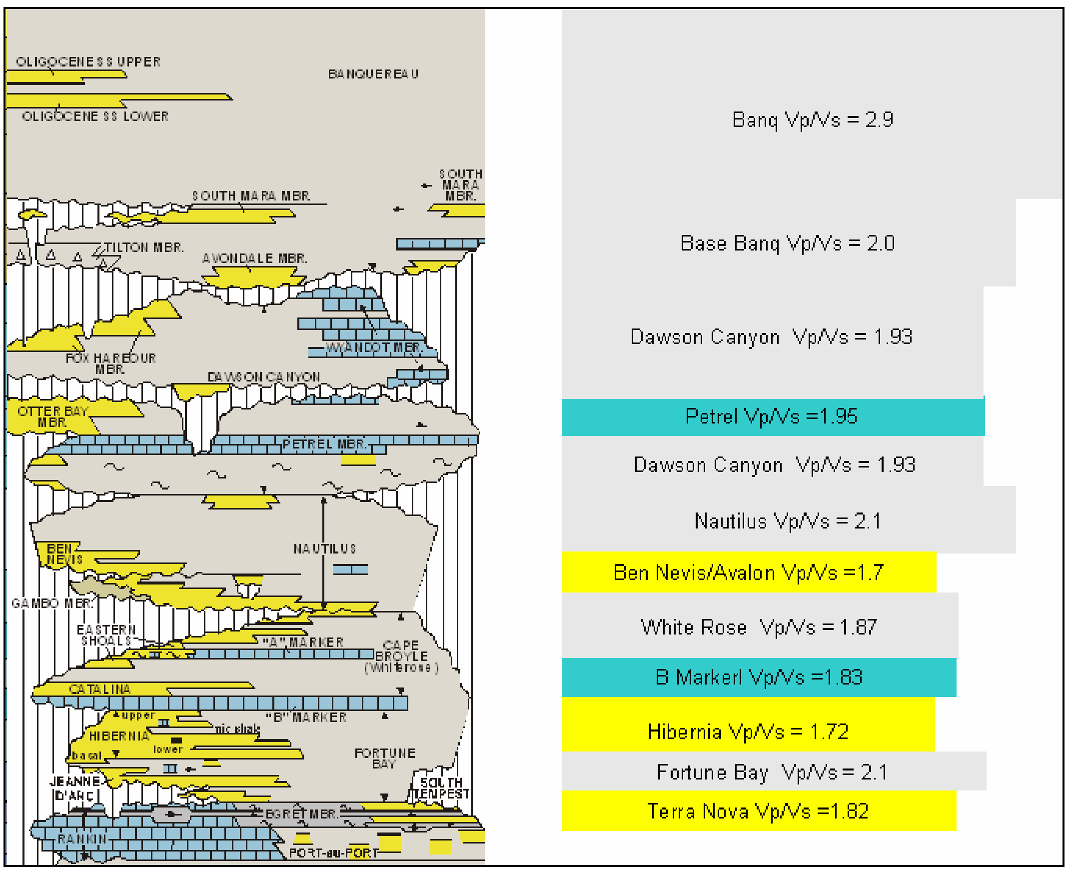

FIG. 8. Jeanne d'Arc Basin Vp/Vs analysis by formation.

The next sections will deal with a more detailed analysis of the intra-formational units that make up the major reservoir in the Jeanne d'Arc Basin.

BEN NEVIS AND AVALON FORMATIONS

The type section for the Ben Nevis/Avalon Formation is found in Ben Nevis I-45 from 2377 to 2880 m. The formation is divided into three subunits with the upper two (2377-2712 m and 2712-2755 m), defined as the Ben Nevis Formation, and a lower subunit (2838-2880 m), which has been formally named by McAlpine (1990) as the Avalon Formation. This formation is characterized as a fining upward, fine to very fine-grained quartzose sandstone having moderate to well-sorted, subangular grains, with isolated calcareous nodular overgrowths.

The equivalent section in White Rose L-08 (2818-3120 m) is a more massive shoreline deposit where the intra-formational shales do not exist. This White Rose L-08 section has previously been correlated to the lower Avalon Formation subunit but more recent work correlates the deposit to the Ben Nevis Formation (Sinclair, 2006, personal communication). Cape Race N-68 (2635-2829 m) has been placed under the Ben Nevis Fm reservoir to represent the shoreline equivalent to the Ben Nevis I-45 Avalon Formation.

The White Rose L-08 well was selected for analysis as it represents one of the end member cases for the interval travel-time technique. The alternative Ben Nevis L-55 or Hebron M-04, which are closer to Ben Nevis I-45, would have given a better match to the type section but the Vp/Vs analysis and the conclusion that can be inferred would have been very similar to the analysis for the Hibernia and Terra Nova Formations.

The resulting PP and PS sections (Figure 9) indicate significant character changes with frequency. The top Ben Nevis reflector changes from a peak-trough doublet-peak sequence to a broader and simpler peak-trough-peak sequence as the PP bandwidth is reduced from 6/12-78/93 (right side of Figure 9) to 6/12-30/45 Hz (left side of Figure 9). Other significant seismic tuning effects are the base reservoir trough effectively obscuring the underlying top Avalon reflector, while the base Avalon peak has a markedly upward trend as frequency/bandwidth is lost.

Figure 10 is a matrix plot of all the possible Vp/Vs values from the interpretation from the Top Ben Nevis to the Base Reservoir reflectors on PP and PS sections. The seismically derived average Vp/Vs is 1.72 with a range of ±0.10 (two times the standard deviation). This calculated Vp/Vs value is higher than the 1.65 determined directly from the log data. This bulk Vp/Vs shift is likely the result of slight picking errors on the top and base reflectors. The variation in results (1.61-1.84) appears to be the result of the systematic thinning of the isochron as frequency decreases.

The immediately overlying shales are part of the Nautilus fm. and have a significantly lower Vp/Vs than the 2.1 calculated for the complete formation but markedly higher Vp/Vs of 1.78 ±0.05 than the underlying sandstones (1.78 versus 1.72). The measured 1.78 is actually lower than the 1.82 Vp/Vs value calculated from the logs. This error many also be the result of the same picking error for the Top of the Ben Nevis.

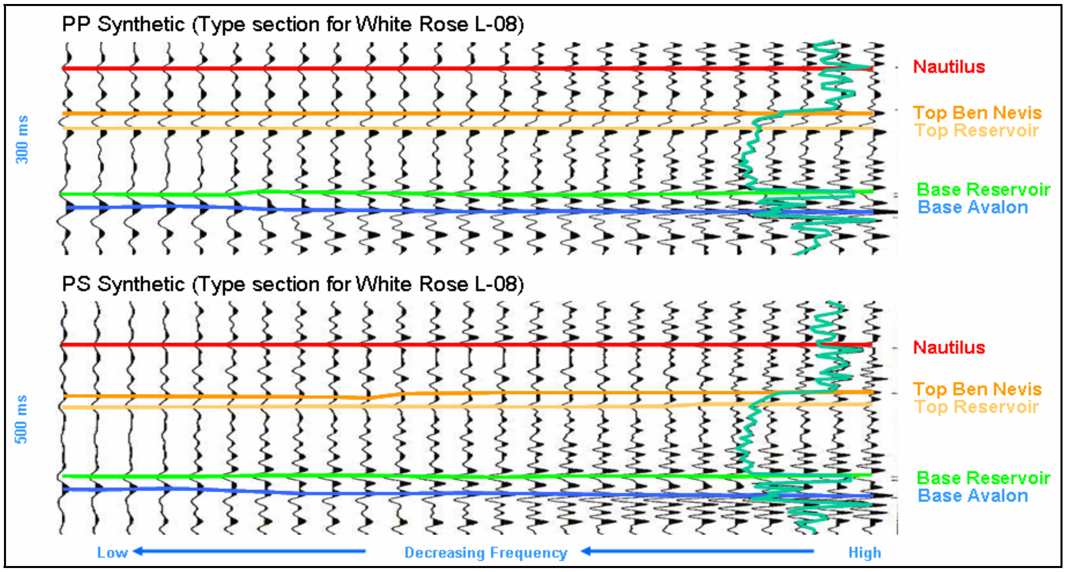

FIG. 9. Ben Nevis/Avalon Formation PP (top) and PS (bottom) synthetic response with gamma ray log and horizon interpretation.

Ben Nevis Sandstone - Vp/Vs

	ΔPP	6/12-30/45	6/12-32/47	6/12-34/49	6/12-36/51	6/12-38/53	6/12-40/55	6/12-42/57	6/12-44/59	6/12-46/61	6/12-48/63	6/12-50/65	6/12-52/67	6/12-54/69	6/12-56/71	6/12-58/73	6/12-60/75	6/12-62/77	6/12-64/79	6/12-66/81	6/12-68/83	6/12-70/85	6/12-72/87	6/12-74/89	6/12-76/91	6/12-78/93
PP	Top	2615	2615	2615	2615	2616	2615	2615	2615	2615	2614	2614	2614	2615	2616	2616	2616	2616	2616	2617	2617	2617	2617	2617	2617	2617
PP	Base	2763	2763	2764	2764	2763	2762	2761	2761	2761	2762	2762	2762	2762	2763	2763	2763	2763	2763	2760	2759	2758	2758	2758	2759	2759
PS	Top	4650	4654	4653	4653	4652	4652	4651	4651	4650	4650	4650	4653	4654	4654	4654	4654	4654	4654	4654	4653	4653	4653	4653	4652	4652
PS	Base	4851	4852	4852	4851	4850	4849	4849	4849	4849	4849	4850	4850	4850	4849	4848	4847	4846	4847	4847	4848	4848	4849	4849	4849	4849
ΔPS	Isochron	148.8	148.4	148.6	148.4	147.6	146.6	146.3	146.5	146.7	147.2	147.7	147.7	147.3	147.0	146.9	147.1	147.3	146.8	143.8	141.8	141.3	141.3	141.4	141.7	142.0
6/12-20/35	200.9	1.70	1.71	1.70	1.71	1.72	1.74	1.75	1.74	1.74	1.73	1.72	1.72	1.73	1.73	1.74	1.73	1.73	1.74	1.79	1.83	1.84	1.84	1.84	1.84	1.83
6/12-22/37	197.7	1.66	1.66	1.66	1.66	1.68	1.70	1.70	1.70	1.70	1.69	1.68	1.68	1.68	1.69	1.69	1.69	1.68	1.69	1.75	1.79	1.80	1.80	1.80	1.79	1.78
6/12-24/39	198.7	1.67	1.68	1.67	1.68	1.69	1.71	1.72	1.71	1.71	1.70	1.69	1.69	1.70	1.70	1.71	1.70	1.70	1.71	1.76	1.80	1.81	1.81	1.81	1.80	1.80
6/12-26/41	198.6	1.67	1.68	1.67	1.68	1.69	1.71	1.71	1.71	1.71	1.70	1.69	1.69	1.70	1.70	1.70	1.70	1.70	1.71	1.76	1.80	1.81	1.81	1.81	1.80	1.80
6/12-28/43	198.0	1.66	1.67	1.66	1.67	1.68	1.70	1.71	1.70	1.70	1.69	1.68	1.68	1.69	1.69	1.70	1.69	1.69	1.70	1.75	1.79	1.80	1.80	1.80	1.79	1.79
6/12-30/45	197.7	1.66	1.66	1.66	1.66	1.68	1.70	1.70	1.70	1.70	1.69	1.68	1.68	1.68	1.69	1.69	1.69	1.68	1.69	1.75	1.79	1.80	1.80	1.80	1.79	1.78
6/12-32/47	197.8		1.67	1.66	1.67	1.68	1.70	1.70	1.70	1.70	1.69	1.68	1.68	1.69	1.69	1.69	1.69	1.69	1.69	1.75	1.79	1.80	1.80	1.80	1.79	1.79
6/12-34/49	198.3			1.67	1.67	1.69	1.71	1.71	1.71	1.70	1.69	1.69	1.69	1.69	1.70	1.70	1.70	1.69	1.70	1.76	1.80	1.81	1.81	1.80	1.80	1.79
6/12-36/51	199.1				1.68	1.70	1.72	1.72	1.72	1.71	1.71	1.70	1.70	1.70	1.71	1.71	1.71	1.70	1.71	1.77	1.81	1.82	1.82	1.82	1.81	1.80
6/12-38/53	199.4					1.70	1.72	1.73	1.72	1.72	1.71	1.70	1.70	1.71	1.71	1.71	1.71	1.71	1.72	1.77	1.81	1.82	1.82	1.82	1.81	1.81
6/12-40/55	199.8						1.73	1.73	1.73	1.72	1.71	1.71	1.71	1.71	1.72	1.72	1.72	1.71	1.72	1.78	1.82	1.83	1.83	1.83	1.82	1.81
6/12-42/57	197.2							1.70	1.69	1.69	1.68	1.67	1.67	1.68	1.68	1.68	1.68	1.68	1.69	1.74	1.78	1.79	1.79	1.79	1.78	1.78
6/12-44/59	196.3								1.68	1.68	1.67	1.66	1.66	1.67	1.67	1.67	1.67	1.67	1.67	1.73	1.77	1.78	1.78	1.78	1.77	1.76
6/12-46/61	195.4									1.66	1.65	1.65	1.65	1.65	1.66	1.66	1.66	1.65	1.66	1.72	1.76	1.77	1.77	1.76	1.76	1.75
6/12-48/63	193.7										1.63	1.62	1.62	1.63	1.64	1.64	1.63	1.63	1.64	1.69	1.73	1.74	1.74	1.74	1.73	1.73
6/12-50/65	192.8											1.61	1.61	1.62	1.62	1.62	1.62	1.62	1.63	1.68	1.72	1.73	1.73	1.73	1.72	1.72
6/12-52/67	192.8												1.61	1.62	1.62	1.62	1.62	1.62	1.63	1.68	1.72	1.73	1.73	1.73	1.72	1.72
6/12-54/69	192.8													1.62	1.62	1.62	1.62	1.62	1.63	1.68	1.72	1.73	1.73	1.73	1.72	1.72
6/12-56/71	193.3														1.63	1.63	1.63	1.62	1.63	1.69	1.73	1.74	1.74	1.73	1.73	1.72
6/12-58/73	194.2															1.64	1.64	1.64	1.65	1.70	1.74	1.75	1.75	1.75	1.74	1.74
6/12-60/75	195.2																1.65	1.65	1.66	1.71	1.75	1.76	1.76	1.76	1.76	1.75
6/12-62/77	195.8																	1.66	1.67	1.72	1.76	1.77	1.77	1.77	1.76	1.76
6/12-64/79	196.3																		1.67	1.73	1.77	1.78	1.78	1.78	1.77	1.76
6/12-66/81	196.8																			1.74	1.78	1.79	1.79	1.78	1.78	1.77
6/12-68/83	197.4																				1.78	1.79	1.79	1.79	1.79	1.78

Vp/Vs determined from logs 1.65

Vp/Vs diff: ± 5 % ; ± 10 % ; ± 15 %

Min 1.61
Avg 1.72
Max 1.84
SD 0.05

Type section well from White Rose L08 2818-3120 m MD (302 m)

FIG. 10. Vp/Vs analysis for the Ben Nevis Formation (White Rose L-08 2818-3120 m MD). The reservoir has a thickness of 302 m with an average porosity of 14% and an expected Vp/Vs of 1.65. Tuning effects with the overlying Nautilus formation cause difficulty in picking top reservoir reflector on the PS synthetic.

Jaramillo (2002; ibid, 2003; ibid, 2005) has done extensive work on the multi-component seismic data at White Rose L-08. Using the 2002 Mariprobe OBS survey, acquired over White Rose L-08 by CREWES, Jaramillo was able to conclude that the converted-wave (PS) data should be useful in mapping the Avalon reservoir (recently redefined as Ben Nevis). In addition to the structural value of the PS data, Jaramillo's Vp/Vs analysis closely agrees with the synthetic work of this paper with an average value of ~1.75 with a range from 1.51 to 1.91. Jaramillo associated the low values to the gas cap and the higher values to locations with significantly higher shale content. Alternatively, as will be described shortly, the range of values could simply be from wavelet effects on the top and base reflectors.

HIBERNIA FORMATION

The Hibernia formation (McAlpine, 1990) is a light grey, clean quartz sandstone that is generally fine at the base, grading to medium, to coarse grained at its top. The Hibernia sequence is composed of alternating thick sandstones and thinner interbedded shale and is believed to be the result of a large fluvial system draining the Avalon Uplift to the south and west. The type section for the Hibernia formation is Hibernia K-14 from 3839 to 4062m and the reference log section is from Hebron I-13 from 2887-3490 m.

Hebron M-04, which is close to Hebron I-13, was selected to represent the type section as Hibernia B16-1, along with being highly deviated, it was also missing log information. The Hibernia Formation at Hebron M-04 has five significant sandstone bodies defined as the Upper, Mid, Mid2, Lower and Basal Hibernia sandstones. The reservoir thicknesses are 22, 61, 38, 22, and 80 m, and assuming ¼ wavelength resolution limit, would require 47, 16, 28, 47, 13 Hz frequency data to define top and base reflectors.

The broad bandwidth Hibernia PP and PS seismic section (right side of FIG. 11) indicates a fair separation of top and base reflectors. By the time the PP and PS data bandwidth has decreased to 6/12-56/71 and 6/12-46/61 (middle of FIG. 11), reflectors are starting to tune together or disappear. When the PP and PS seismic bandwidth has been reduced to 6/12-30/45 and 6/12-20/35 (left side of FIG. 11) several of the reflectors are impossible to interpret.

As reported earlier, the overall Vp/Vs for the Hibernia Formation was 1.72 with a range of ±0.03 (Base of B Marker to Top of Fortune Bay). The individual sandstone bodies have Vp/Vs from logs of between 1.65 and 1.72 while the intra-formational shales have values between 1.71 and 1.81. The Vp/Vs for the five sandstone bodies as calculated from the synthetic seismic data are 0.55 ±0.48, 1.78 ±0.25, 2.24 ±0.84, 2.45 ±0.84 and 4.32 ±0.86 (> ¼ λ resolution limit). FIG. 12 is the Vp/Vs matrix plot for the Mid Hibernia SS, a relatively blocky sandstone with a bed thickness of 61 m. By the time the PS seismic frequency has been reduced to less than 40 Hz (2X resolution), tuning effect has caused the top reflector to disappear. Even for the calculations above this limit, the resulting Vp/Vs varies from below a pure quartz crystal (1.6) to values one would expect for a shale (2.01).

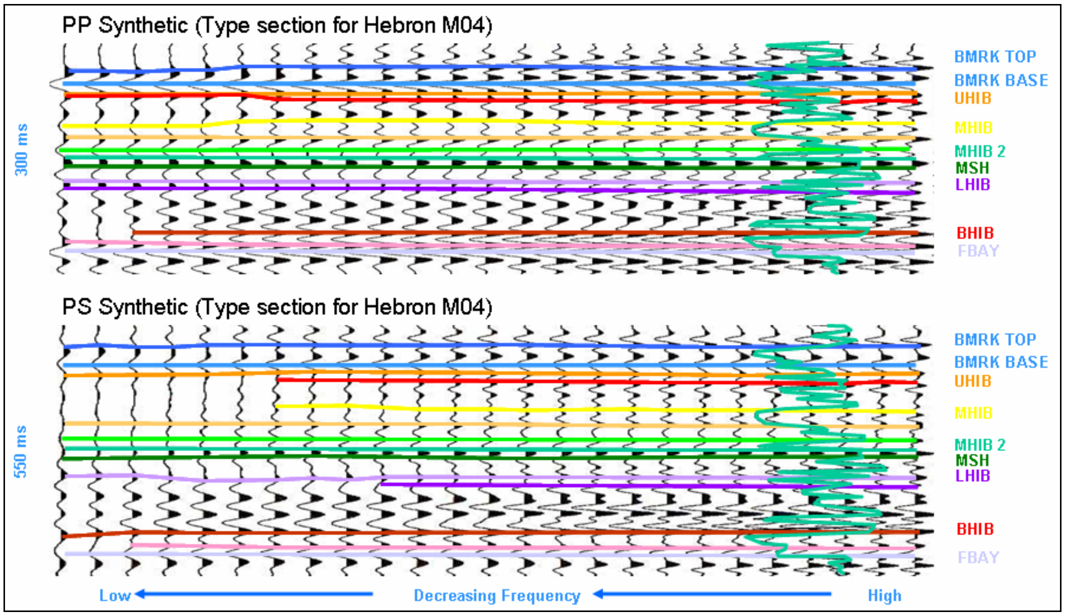

FIG. 11. Hibernia Formation PP (top) and PS (bottom) synthetic response with gamma ray log and horizon interpretation.

Mid Hibernia SS - Vp/Vs (Horizon Time Pick)

PP	Top	3348	3346	3346	3344	3344	3350	3348	3347	3347	3347	3347	3347	3347	3348	3349	3348	3347	3347	3347	3348	3347	3347	3347	3347	3347
PP	Base	3379	3380	3380	3380	3380	3380	3380	3379	3379	3379	3380	3380	3380	3379	3379	3378	3378	3378	3378	3377	3378	3378	3378	3378	3378
PS	Top	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	5678	5678	5677	5677	5677	5677	5677	5677	5678	5678	5679	5680	5680	5680	5680
PS	Base	5718	5720	5719	5720	5720	5721	5722	5722	5723	5723	5723	5722	5721	5721	5721	5721	5721	5720	5720	5719	5719	5719	5720	5722	5717
	ΔPP	6/12-30/45	6/12-32/47	6/12-34/49	6/12-36/51	6/12-38/53	6/12-40/55	6/12-42/57	6/12-44/59	6/12-46/61	6/12-48/63	6/12-50/65	6/12-52/67	6/12-54/69	6/12-56/71	6/12-58/73	6/12-60/75	6/12-62/77	6/12-64/79	6/12-66/81	6/12-68/83	6/12-70/85	6/12-72/87	6/12-74/89	6/12-76/91	6/12-78/93
ΔPS	Isochron	31.2	33.8	33.5	35.6	35.8	29.9	32.1	32.4	32.5	32.8	32.5	32.5	32.4	31.2	29.7	30.3	31.0	30.9	30.3	29.9	30.1	30.5	30.7	30.9	31.0
6/12-20/35	44.7																									
6/12-22/37	44.7																									
6/12-24/39	44.7																									
6/12-26/41	44.7																									
6/12-28/43	44.7																									
6/12-30/45	44.7																									
6/12-32/47	44.7																									
6/12-34/49	44.7																									
6/12-36/51	44.7																									
6/12-38/53	44.7																									
6/12-40/55	44.7						1.99	1.79	1.76	1.75	1.73	1.75	1.75	1.76	1.87	2.01	1.95	1.88	1.89	1.95	1.99	1.97	1.93	1.91	1.89	1.88
6/12-42/57	44.2							1.75	1.73	1.72	1.70	1.72	1.72	1.73	1.83	1.98	1.92	1.85	1.86	1.92	1.96	1.94	1.90	1.88	1.86	1.85
6/12-44/59	44.2								1.73	1.72	1.70	1.72	1.72	1.73	1.83	1.98	1.92	1.85	1.86	1.92	1.96	1.94	1.90	1.88	1.86	1.85
6/12-46/61	43.9									1.70	1.68	1.70	1.70	1.71	1.81	1.96	1.90	1.83	1.84	1.90	1.94	1.92	1.88	1.86	1.84	1.83
6/12-48/63	43.7										1.66	1.69	1.69	1.70	1.80	1.94	1.88	1.82	1.83	1.88	1.92	1.90	1.87	1.85	1.83	1.82
6/12-50/65	43.8											1.70	1.70	1.70	1.81	1.95	1.89	1.83	1.83	1.89	1.93	1.91	1.87	1.85	1.83	1.83
6/12-52/67	43.7												1.69	1.70	1.80	1.94	1.88	1.82	1.83	1.88	1.92	1.90	1.87	1.85	1.83	1.82
6/12-54/69	43.1													1.66	1.76	1.90	1.84	1.78	1.79	1.84	1.88	1.86	1.83	1.81	1.79	1.78
6/12-56/71	41.9														1.69	1.82	1.77	1.70	1.71	1.77	1.80	1.78	1.75	1.73	1.71	1.70
6/12-58/73	40.6															1.73	1.68	1.62	1.63	1.68	1.72	1.70	1.66	1.64	1.63	1.62
6/12-60/75	39.9																1.63	1.57	1.58	1.63	1.67	1.65	1.62	1.60	1.58	1.57
6/12-62/77	39.9																	1.57	1.58	1.63	1.67	1.65	1.62	1.60	1.58	1.57
6/12-64/79	40.7																		1.63	1.69	1.72	1.70	1.67	1.65	1.63	1.63
6/12-66/81	41.9																			1.77	1.80	1.78	1.75	1.73	1.71	1.70
6/12-68/83	37.3																				1.49	1.48	1.45	1.43	1.41	1.41

Could not pick the PS reflector for the top of the Mid Hibernia SS

Vp/Vs determined from logs 1.70

Vp/Vs diff		
± 5 %	Min	1.41
± 10 %	Avg	1.78
± 15 %	Max	2.01
	SD	0.12

Type section well from Hebron M04 3207-3269 m MD (62 m)

FIG. 12. Vp/Vs analysis for a Mid Hibernia Reservoir (Hebron M-04 4223-4285 m MD). Formation thickness is 62 m thick with a 14% average porosity and a 1.7 Vp/Vs. The formation has an overall blocky appearance with moderate grading into the adjacent shale at both the top and base. Top reflector on the PS section could not be interpreted below a 6/13-40/45 bandwidth.

JEANNE D'ARC FORMATION

The Jeanne d'Arc Formation is the third and final example to be discussed in this paper. The Jeanne d'Arc formation is characterized as an overall upward- fining sequence of sandstones that are interbedded with silty shales and lime mudstones. Lithofacies are highly variable within the formation and several locally correlatable units can be recognized (McAlpine, 1980). Sandstone beds commonly contain a basal-pebble to cobble-sized conglomerate that grades into thin to thick beds of fine to very fine coarse-grained, moderately well-sorted sandstones.

Terra Nova L98-3 contains all 6 major sandstone beds found in the Jeanne d'Arc Formation type section at Terra Nova K-18, the two Basal sandstones (A, B), the Terra Nova member (C, D) and the upper Beothuk member (E, F). The largest of these sandstone members is the C Sandstone, a 38 m bed which, along with the D Sandstone, makeup the productive units at Terra Nova.

FIG. 13 is the PP and PS seismic section from the Terra Nova L-98 well. Seismic frequencies are the same as for the Ben Nevis/Avalon (Figure 9) and Hibernia (FIG. 11) formations. The overall formation thickness is smaller and the sandstone beds are substantially thinner than the Hibernia Formation at Hebron M-04 with reservoir thicknesses of 8, 24, 25, 28, 13 and 25 meters. Again assuming that a ¼ wavelength resolution limit is adequate to clearly image the respective beds, the PP and PS seismic section would need bandwidths greater than 130, 44, 42, 28, 80 and 42 Hz frequencies.

The Vp/Vs calculated for the total Jeanne d'Arc formation from the Base of the Fortune Bay to the Mid Kimmeridigan Unc has a Vp/Vs of 1.82 only 0.01 higher than from the well logs (FIG. 8). By selecting two of the more consistent reflector pairs across the sandstone prone interval base of the F sand to the Top of the A sand, the calculation becomes 1.78 ±0.14 (FIG. 14), again extremely close to the expected value from the well logs. The variance across the formations as a function of seismic frequency is a concern. The Vp/Vs values ranging from 1.57 to 1.97 with the variance being most significant as the PS bandwidth falls.

FIG. 15 is the Vp/Vs matrix plot for the C sand, as mentioned earlier, the larger of the two producing zones at the Terra Nova Field. The ¼ wavelength resolution limit would indicate we only need 28 Hz seismic data to distinguish between the reflectors. Both the PP and PS seismic sections (FIG. 13) have a strong peak-trough-peak signature. Nevertheless, the calculated Vp/Vs values varied from 0.99 to 3.22, with the lowest values resulting from higher frequency PP/PS pairs, with the highest Vp/Vs values occurring when high PP frequencies are paired with low PS frequencies.

This is surprising! The frequencies should be sufficient to image both the top and base reflectors. The seismic wavelet appears to be well behaved, without any doublet tuning, and even at seismic levels seen on VSP's (right side of FIG. 15), the estimated Vp/Vs values are well below what is physically possible.

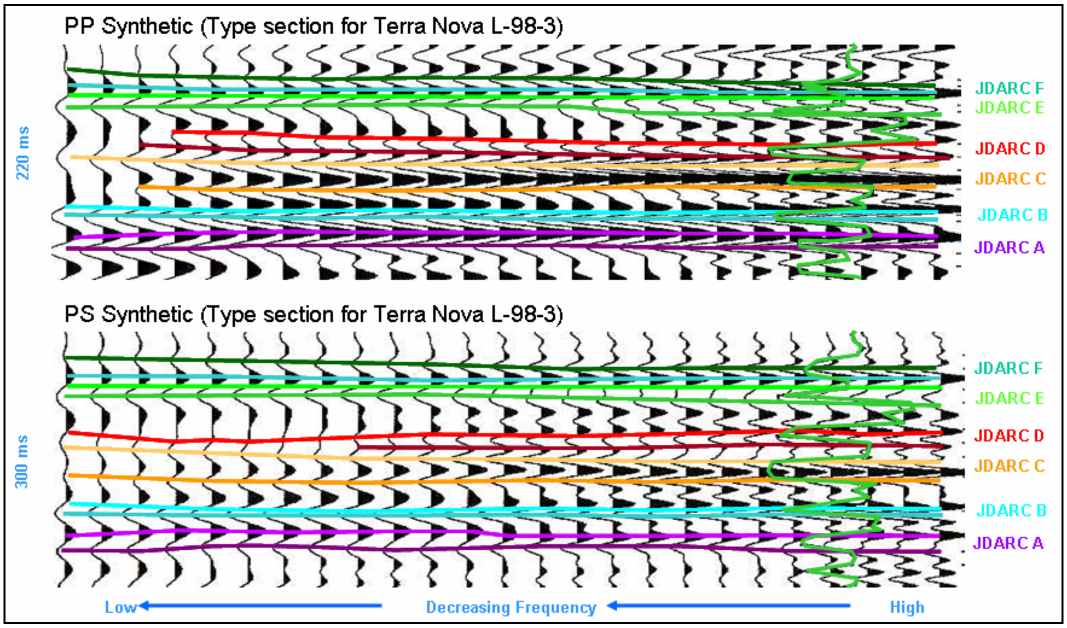

FIG. 13. Terra Nova Formation PP (top) and PS (bottom) synthetic response with gamma ray log and horizon interpretation.

Jeanne d'Arc Fm - Interval Vp/Vs

	ΔPP	6/12-30/45	6/12-32/47	6/12-34/49	6/12-36/51	6/12-38/53	6/12-40/55	6/12-42/57	6/12-44/59	6/12-46/61	6/12-48/63	6/12-50/65	6/12-52/67	6/12-54/69	6/12-56/71	6/12-58/73	6/12-60/75	6/12-62/77	6/12-64/79	6/12-66/81	6/12-68/83	6/12-70/85	6/12-72/87	6/12-74/89	6/12-76/91	6/12-78/93
PP	Top	3765	3766	3768	3771	3772	3773	3773	3773	3773	3773	3773	3773	3773	3773	3773	3774	3774	3774	3775	3775	3775	3775	3775	3775	3775
PP	Base	3937	3936	3936	3935	3935	3934	3934	3933	3932	3932	3932	3933	3933	3935	3935	3935	3933	3934	3934	3933	3933	3933	3933	3933	3933
PS	Top	6284	6286	6288	6289	6290	6290	6291	6291	6291	6291	6291	6292	6292	6292	6292	6293	6293	6293	6292	6292	6293	6293	6293	6293	6293
PS	Base	6518	6517	6517	6516	6515	6512	6512	6512	6513	6514	6514	6514	6512	6510	6509	6510	6510	6510	6510	6511	6510	6510	6510	6510	6510
ΔPS	Isochron	172.3	170.3	167.7	164.1	162.5	161.7	161.2	160.4	158.9	158.8	158.8	160.0	160.3	162.3	162.0	161.5	159.0	159.9	158.8	158.2	157.8	157.4	157.2	157.3	157.4
6/12-20/35	233.8	1.71	1.75	1.79	1.85	1.88	1.89	1.90	1.92	1.94	1.94	1.94	1.92	1.92	1.88	1.89	1.90	1.94	1.92	1.94	1.96	1.96	1.97	1.97	1.97	1.97
6/12-22/37	230.7	1.68	1.71	1.75	1.81	1.84	1.85	1.86	1.88	1.90	1.91	1.91	1.88	1.88	1.84	1.85	1.86	1.90	1.89	1.91	1.92	1.92	1.93	1.94	1.93	1.93
6/12-24/39	228.7	1.65	1.69	1.73	1.79	1.81	1.83	1.84	1.85	1.88	1.88	1.88	1.86	1.85	1.82	1.82	1.83	1.88	1.86	1.88	1.89	1.90	1.91	1.91	1.91	1.91
6/12-26/41	227.1	1.64	1.67	1.71	1.77	1.80	1.81	1.82	1.83	1.86	1.86	1.86	1.84	1.83	1.80	1.80	1.81	1.86	1.84	1.86	1.87	1.88	1.89	1.89	1.89	1.89
6/12-28/43	224.6	1.61	1.64	1.68	1.74	1.76	1.78	1.79	1.80	1.83	1.83	1.83	1.81	1.80	1.77	1.77	1.78	1.83	1.81	1.83	1.84	1.85	1.85	1.86	1.86	1.85
6/12-30/45	221.7	1.57	1.60	1.64	1.70	1.73	1.74	1.75	1.76	1.79	1.79	1.79	1.77	1.77	1.73	1.74	1.75	1.79	1.77	1.79	1.80	1.81	1.82	1.82	1.82	1.82
6/12-32/47	220.8		1.59	1.63	1.69	1.72	1.73	1.74	1.75	1.78	1.78	1.78	1.76	1.75	1.72	1.73	1.73	1.78	1.76	1.78	1.79	1.80	1.81	1.81	1.81	1.81
6/12-34/49	220.7			1.63	1.69	1.72	1.73	1.74	1.75	1.78	1.78	1.78	1.76	1.75	1.72	1.72	1.73	1.78	1.76	1.78	1.79	1.80	1.80	1.81	1.81	1.80
6/12-36/51	221.3				1.70	1.72	1.74	1.75	1.76	1.79	1.79	1.79	1.77	1.76	1.73	1.73	1.74	1.78	1.77	1.79	1.80	1.80	1.81	1.82	1.81	1.81
6/12-38/53	222.2					1.73	1.75	1.76	1.77	1.80	1.80	1.80	1.78	1.77	1.74	1.74	1.75	1.79	1.78	1.80	1.81	1.82	1.82	1.83	1.83	1.82
6/12-40/55	222.6						1.75	1.76	1.78	1.80	1.80	1.80	1.78	1.78	1.74	1.75	1.76	1.80	1.78	1.80	1.81	1.82	1.83	1.83	1.83	1.83
6/12-42/57	221.9							1.75	1.77	1.79	1.79	1.79	1.77	1.77	1.73	1.74	1.75	1.79	1.78	1.79	1.81	1.81	1.82	1.82	1.82	1.82
6/12-44/59	219.6								1.74	1.76	1.77	1.77	1.75	1.74	1.71	1.71	1.72	1.76	1.75	1.77	1.78	1.78	1.79	1.79	1.79	1.79
6/12-46/61	217.4									1.74	1.74	1.74	1.72	1.71	1.68	1.68	1.69	1.73	1.72	1.74	1.75	1.76	1.76	1.77	1.76	1.76
6/12-48/63	216.3										1.72	1.72	1.70	1.70	1.67	1.67	1.68	1.72	1.71	1.72	1.73	1.74	1.75	1.75	1.75	1.75
6/12-50/65	217.5											1.74	1.72	1.71	1.68	1.69	1.69	1.74	1.72	1.74	1.75	1.76	1.76	1.77	1.77	1.76
6/12-52/67	217.4												1.72	1.71	1.68	1.68	1.69	1.73	1.72	1.74	1.75	1.76	1.76	1.77	1.76	1.76
6/12-54/69	217.5													1.71	1.68	1.69	1.69	1.74	1.72	1.74	1.75	1.76	1.76	1.77	1.77	1.76
6/12-56/71	217.2														1.68	1.68	1.69	1.73	1.72	1.74	1.75	1.75	1.76	1.76	1.76	1.76
6/12-58/73	218.9															1.70	1.71	1.75	1.74	1.76	1.77	1.77	1.78	1.78	1.78	1.78
6/12-60/75	217.3																1.69	1.73	1.72	1.74	1.75	1.75	1.76	1.76	1.76	1.76
6/12-62/77	217.0																	1.73	1.71	1.73	1.74	1.75	1.76	1.76	1.76	1.76
6/12-64/79	216.9																		1.71	1.73	1.74	1.75	1.76	1.76	1.76	1.76
6/12-66/81	217.0																			1.73	1.74	1.75	1.76	1.76	1.76	1.76
6/12-68/83	217.2																				1.75	1.75	1.76	1.76	1.76	1.76

Vp/Vs determined from logs 1.81

Vp/Vs diff		
± 5 %	Min	1.57
± 10 %	Avg	1.78
± 15 %	Max	1.97
	SD	0.07

Base of F Sand to Mid Kim Unc. From Terra Nova L98-3 3332-3643 m

FIG. 14. Vp/Vs analysis for the Terra Nova Formation (Terra Nova L98-3). Thickness 335 m with a 1.81 expected Vp/Vs. The average Vp/Vs of 1.78 is interpreted to be the result of the conglomerates within the formation. See Stewart (1997) for discussion on average versus interval velocity on Vp/Vs values.

Jeanne d'Arc C SS																										
PP	Top	3843	3846	3847	3847	3848	3849	3849	3850	3850	3850	3850	3850	3850	3850	3850	3850	3850	3850	3850	3851	3851	3851	3851	3852	3852
PP	Base	3872	3873	3872	3874	3874	3874	3874	3875	3874	3874	3874	3873	3873	3872	3871	3871	3870	3869	3869	3869	3869	3869	3869	3869	3869
PS	Top	6383	6385	6387	6388	6389	6391	6393	6394	6395	6395	6395	6395	6396	6396	6396	6397	6397	6398	6399	6399	6399	6399	6400	6400	6400
PS	Base	6418	6422	6422	6423	6423	6424	6424	6424	6424	6424	6423	6422	6421	6420	6420	6421	6421	6421	6421	6421	6420	6420	6419	6419	6419
	ΔPP	6/12-30/45	6/12-32/47	6/12-34/49	6/12-36/51	6/12-38/53	6/12-40/55	6/12-42/57	6/12-44/59	6/12-46/61	6/12-48/63	6/12-50/65	6/12-52/67	6/12-54/69	6/12-56/71	6/12-58/73	6/12-60/75	6/12-62/77	6/12-64/79	6/12-66/81	6/12-68/83	6/12-70/85	6/12-72/87	6/12-74/89	6/12-76/91	6/12-78/93
ΔPS	Isochron	28.8	27.8	25.5	26.5	25.9	25.4	25.0	24.7	24.5	24.1	23.7	23.4	22.7	21.9	21.1	20.5	19.8	19.0	18.6	18.4	18.1	17.7	17.6	17.4	17.5
6/12-20/35	35.4	1.46	1.55	1.78	1.67	1.73	1.79	1.83	1.87	1.89	1.94	1.99	2.03	2.12	2.23	2.36	2.45	2.58	2.73	2.81	2.85	2.91	3.00	3.02	3.07	3.05
6/12-22/37	36.7	1.55	1.64	1.88	1.77	1.83	1.89	1.94	1.97	2.00	2.05	2.10	2.14	2.23	2.35	2.48	2.58	2.71	2.86	2.95	2.99	3.06	3.15	3.17	3.22	3.19
6/12-24/39	35.3	1.45	1.54	1.77	1.66	1.73	1.78	1.82	1.86	1.88	1.93	1.98	2.02	2.11	2.22	2.35	2.44	2.57	2.72	2.80	2.84	2.90	2.99	3.01	3.06	3.03
6/12-26/41	34.4	1.39	1.47	1.70	1.60	1.66	1.71	1.75	1.79	1.81	1.85	1.90	1.94	2.03	2.14	2.26	2.36	2.47	2.62	2.70	2.74	2.80	2.89	2.91	2.95	2.93
6/12-28/43	34.1	1.37	1.45	1.67	1.57	1.63	1.69	1.73	1.76	1.78	1.83	1.88	1.91	2.00	2.11	2.23	2.33	2.44	2.59	2.67	2.71	2.77	2.85	2.87	2.92	2.90
6/12-30/45	33.4	1.32	1.40	1.62	1.52	1.58	1.63	1.67	1.70	1.73	1.77	1.82	1.85	1.94	2.05	2.17	2.26	2.37	2.52	2.59	2.63	2.69	2.77	2.80	2.84	2.82
6/12-32/47	31.6		1.27	1.48	1.38	1.44	1.49	1.53	1.56	1.58	1.62	1.67	1.70	1.78	1.89	2.00	2.08	2.19	2.33	2.40	2.43	2.49	2.57	2.59	2.63	2.61
6/12-34/49	30.5			1.39	1.30	1.36	1.40	1.44	1.47	1.49	1.53	1.57	1.61	1.69	1.79	1.89	1.98	2.08	2.21	2.28	2.32	2.37	2.46	2.47	2.51	2.49
6/12-36/51	29.8				1.25	1.30	1.35	1.38	1.41	1.43	1.47	1.51	1.55	1.63	1.72	1.82	1.91	2.01	2.14	2.20	2.24	2.29	2.37	2.39	2.43	2.41
6/12-38/53	29.5					1.28	1.32	1.36	1.39	1.41	1.46	1.49	1.52	1.60	1.69	1.80	1.88	1.98	2.11	2.17	2.21	2.26	2.33	2.35	2.39	2.37
6/12-40/55	28.0						1.20	1.24	1.27	1.29	1.32	1.36	1.39	1.47	1.56	1.65	1.73	1.83	1.95	2.01	2.04	2.09	2.16	2.18	2.22	2.20
6/12-42/57	26.5							1.12	1.15	1.16	1.20	1.24	1.26	1.33	1.42	1.51	1.59	1.68	1.79	1.85	1.88	1.93	1.99	2.01	2.05	2.03
6/12-44/59	25.2								1.04	1.06	1.09	1.13	1.15	1.22	1.30	1.39	1.46	1.55	1.65	1.71	1.74	1.78	1.85	1.86	1.90	1.88
6/12-46/61	24.5									1.00	1.03	1.07	1.09	1.16	1.24	1.32	1.39	1.47	1.58	1.63	1.66	1.71	1.77	1.78	1.82	1.80
6/12-48/63	24.1										1.00	1.03	1.06	1.12	1.20	1.28	1.35	1.43	1.54	1.59	1.62	1.66	1.72	1.74	1.77	1.75
6/12-50/65	23.7											1.00	1.03	1.09	1.16	1.25	1.31	1.39	1.49	1.55	1.58	1.62	1.68	1.69	1.72	1.71
6/12-52/67	23.3												0.99	1.05	1.13	1.21	1.27	1.35	1.46	1.51	1.53	1.57	1.63	1.65	1.68	1.66
6/12-54/69	22.8	Vp/Vs determined from logs					1.74							1.01	1.08	1.16	1.22	1.30	1.40	1.45	1.48	1.52	1.58	1.59	1.62	1.61
6/12-56/71	22.1														1.02	1.09	1.16	1.23	1.33	1.38	1.40	1.44	1.50	1.51	1.54	1.53
6/12-58/73	21.5		Vp/Vs diff			Min	0.99									1.04	1.10	1.17	1.26	1.31	1.34	1.38	1.43	1.44	1.47	1.46
6/12-60/75	21.1		± 5 %			Avg	1.79										1.06	1.13	1.22	1.27	1.29	1.33	1.38	1.40	1.43	1.41
6/12-62/77	20.5		± 10 %			Max	3.22											1.07	1.16	1.20	1.23	1.27	1.32	1.33	1.36	1.34
6/12-64/79	19.7		± 15 %			SD	0.55												1.07	1.12	1.14	1.18	1.23	1.24	1.26	1.25
6/12-66/81	19.0																			1.04	1.07	1.10	1.15	1.16	1.18	1.17
6/12-68/83	18.5	Type section well from Terra Nova L98-3 3521-3483 m (38 metres)																			1.01	1.04	1.09	1.10	1.13	1.11

FIG. 15. Vp/Vs analysis for the Terra Nova C Sand (Terra Nova L98-3). Reservoir is 38 m thick with a 12% average porosity. A 1.62 Vp/Vs was expected. Actual range was from 0.99 to 3.22 and is believed to be the result of wavelet tuning causing the calculation to become unstable.

PITFALLS WITH V_P/V_S ANALYSIS

The problems with estimated Vp/Vs values based solely on the travel times are two fold. First, unless formation boundaries are sharp contacts with the overlying and underlying lithology, the bounding reflectors are generally a tuned response. FIG. 16 demonstrates the net affect on the reflector shape for three standard geological bed forms using frequencies generally found on 3D streamers (5/10-40/65) and VSP (5/10-80/95) seismic data in the Jeanne d’Arc Basin. Improving the frequency content when the formation has a blocky character sharpens the reflector but doesn’t change the time of the maximum or minimum excursions (peak and trough). When the formation is either coarsing or fining upwards, changing the seismic bandwidth has a marked effect on the maximum or minimum excursion and effectively changes the isochron thickness

Fortunately, on actual field seismic, the bandwidth generally changes slowly laterally. The majority of the changes to the seismic bandwidth are the result of changes in overall depth or changes in lithology of the reflector or the overlying geology. The variation resulting from these changes in frequency, as demonstrated on Figure 9-15, may not be apparent on most field seismic data.

This brings us to the second significant pitfall of slight correlation errors and their effects on the Vp/Vs calculations. Limiting the horizon picks to peaks, troughs or zero crossings (every ¼ of the wavelength) implies a maximum geological correlation accuracy of only 1/8 of a wavelength. This possible correlation error would equally apply to all four horizons (top and base on the PP and PS sections) and is equivalent, for the average Cretaceous sandstone in the Jeanne d'Arc Basin, to a correlation accuracy of ± 8.9 and 10.6 m, respectively (isochron error ± 3 ms for PP and ± 4 ms for PS).

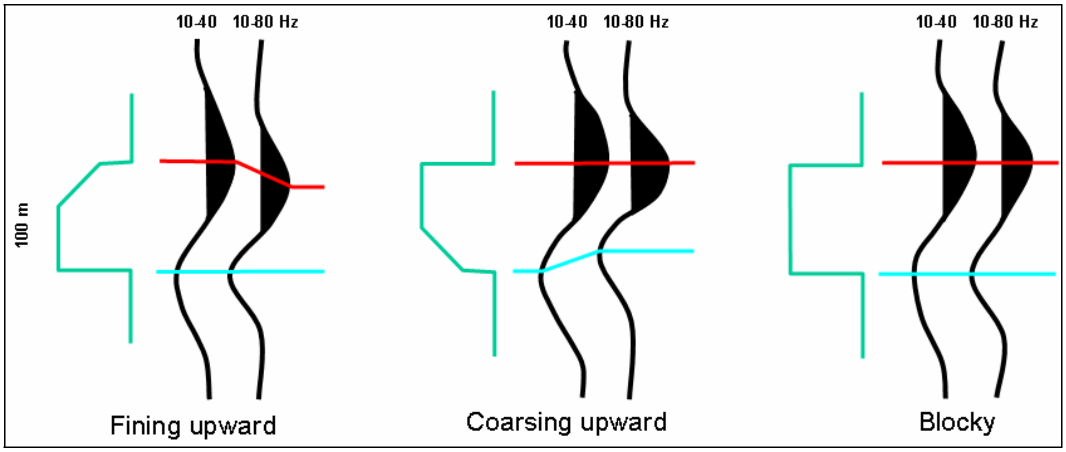

FIG. 16. Effect of formation shape on reflector wavelet. Thickness of upward-fining, upward-coarsing and blocky geology fixed at 100m and convolved with a 5/10-40/65 and a 5/10-80/95 wavelet. The green lines are representative gamma ray log.

As the Garotta (1987) equation involves division, this small picking error can result in large errors in the determined Vp/Vs estimate. FIG. 17 is a summary plot for a Monte-Carlo estimate of the possible Vp/Vs values as a function of the geological bed thickness. The Vp/Vs Monte-Carlo estimate involved taking 10,000 iterations for various bed thicknesses with a constant P-wave velocity of 4260 m/s, S-wave velocity of 2520 m/s with a PP and PS seismic bandwidth of 5/10-60/75 and 5/10-40/55 Hz respectively. The variable in the Monte Carlo simulation was the isochron error assuming an absolute maximum picking error of 1/8 λ.

From the petrophysical analysis, the range of Vp/Vs values for a Cretaceous reservoir varies from a low of 1.64 for 6% porosity sandstone, to a high of 1.73 for 22% porosity sandstone. This represents a variation of Vp/Vs values of only 0.09, which is equivalent to approximately a 5% range/average (red line on FIG. 18). The Monte-Carlo analysis indicates that this degree of accuracy would only be possible when evaluating extremely thick intervals (>2X λ).

Alternatively, the Vp/Vs could be used as a lithology indicator to determine when a formation is predominately quartz rich. The grey line on Figure18 represents the chance the calculated Vp/Vs would exceed 1.8. To achieve a 90% accuracy using Vp/Vs for lithology analysis the bed thickness would need to be greater than 1.5X the seismic wavelength (arrows at base of FIG. 17 and 18).

But what is the statistical accuracy of this method? The orange line on Figure 18 is the more conventional variance measurement, where the estimated value is considered accurate providing it falls within one standard deviation. Using the variance, a statistical prediction of 19 times out of 20 (5% error) would occur if a formation thickness is greater than a half wavelength.

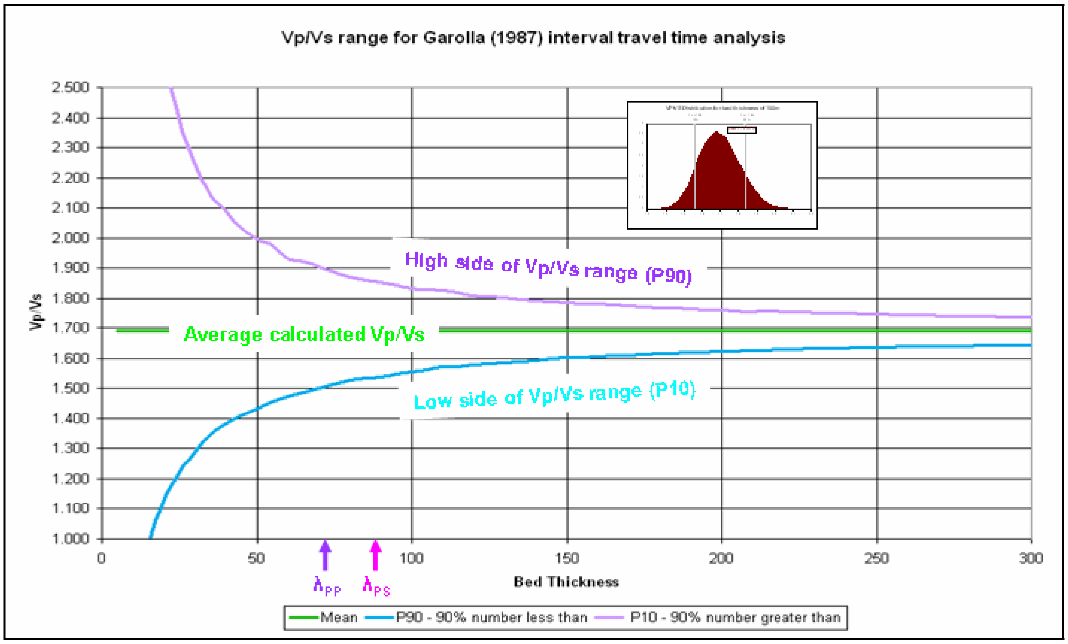

FIG. 17. Resolution limitations on Vp/Vs analysis assuming 1/8 λ picking accuracy. Calculations are for a Cretaceous sandstone bed (Vp = 4260 m/s, Vs = 2520 equivalent to a 15% porosity). Seismic frequencies are for a 10-60 Hz PP and 10-40 Hz PS wavelet. The graph was created using a 10000 simulation Monte-Carlo with a Gaussian distribution to the picking error. The PS and PP wavelength are indicated on the bottom axis.

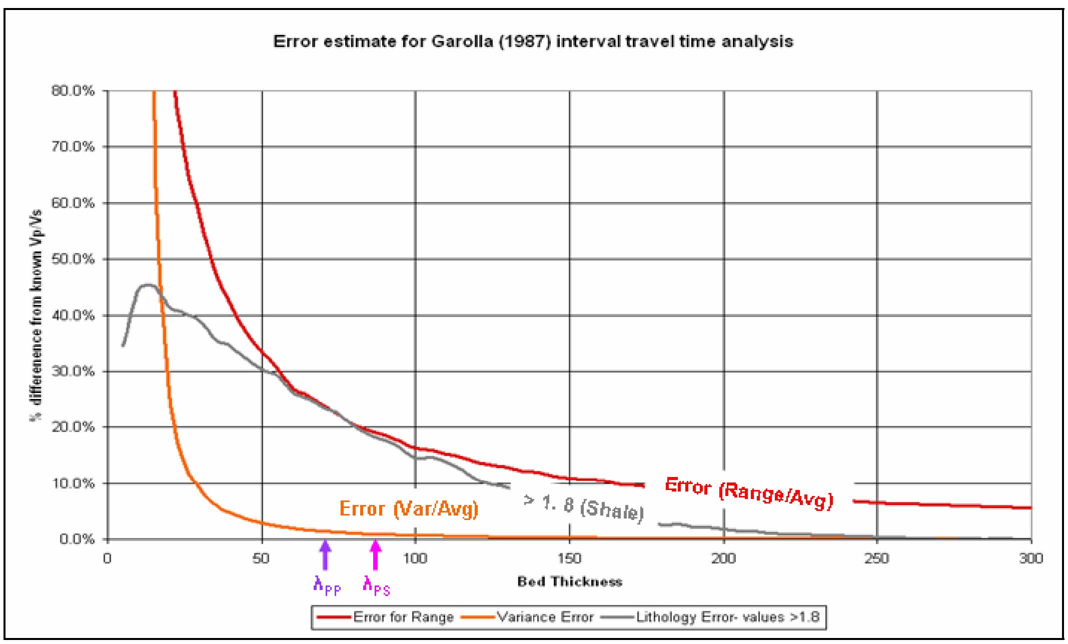

FIG. 18. Vp/Vs analysis error assuming 1/8 λ picking accuracy. Calculations are for a Cretaceous sandstone bed (Vp = 4260 m/s, Vs = 2520 equivalent to a 15% porosity). Seismic frequencies are for a 10-60 Hz PP and 10-40 Hz PS wavelet. The graph was created using a 10000 simulation Monte-Carlo with a Gaussian distribution to the picking error. The PS and PP wavelength are indicated on the bottom axis.

Even if, statistically, the Vp/Vs accuracy could be on par with seismic amplitude resolution (1/4 λ), the narrow range of lithology values (1.6-1.72 sandstones, 1.74-2.5 shale and 1.8-1.85 for carbonates) would indicate that care needs to be taken whenever the formation is less than the seismic wavelength.

CONCLUSIONS

Analysis of multi-component data using the Garotta (1987) interval travel time formula (equation 1) appears to require both the top and base reflectors to be clearly separated and homogeneous. At a formation scale, the analysis will provide a good indication of the relative quantity of quartz and could be used to estimate the change in facies into more distal shales. The stability of the calculation in the presence of picking errors doesn't provide the ability to directly measure porosity. Likewise, differentiating between carbonates and some shales using Vp/Vs would be difficult.

Individual Vp/Vs analysis for the shallower and more massive Nautilus and Ben Nevis Formations tends to give a consistent lithology prediction. The thinner and deeper Hibernia and Jeanne d'Arc Fm appears to be dominated by both tuning effects and resolution effects. As the bed width falls under a seismic wavelength in thickness, the estimated Vp/Vs becomes unstable.

It is recommended that Garotta (1987) interval travel-time analysis be limited to intervals greater than a seismic wavelength. At present we are unsure of the seismic bandwidth that a multi-component survey could achieve in the Jeanne d'Arc Basin but recent land seismic would indicate that seismic bandwidth can actually be better on multi-component data.

FUTURE WORK

Improvements in PP and PS structural interpretation may, on it own, justify an OBS survey (Cary, 2003; Jaromillo, 2005). I would recommend rerunning the CREWES OBS survey with modern OBS nodes prior to undertaking a larger and more costly commercial program. The existing VSP multi-component data in the Jeanne d'Arc Basin has been conducted with the receivers near the base of the Banquereau formations. Running future offset VSP with receivers near the sea floor may provide an alternative method of estimating the PP and PS bandwidth that can be expected from OBS acquisition.

The Garotta (1987) method is only one of many methods to extract lithological information from multi-component seismic. CREWES has initiated work on joint PP and PS AVO inversion using offset data and initial results have been encouraging (Larsen, 1999; Margrave and Stewart, 2001). A study on PP and PS joint AVO inversion would be highly recommended.

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