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ON THE QUESTION OF LATERAL VELOCITY VARIATIONS OVER LEDUC AND RAINBOW REEFS

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Abstract

We have examined sonic-log and seismic data recorded in the vicinity of several Leduc Fm and Rainbow Mbr reefs in Alberta. Our results show that interval velocities derived from sonic logs recorded in closely spaced wells of the same status (i.e., onreef or offreef) can differ significantly (~10%) without any apparent corresponding seismogeologic differences. The interval velocities determined seismically, on the other hand, differ by much less (~2 1/2 %). This large scatter in sonic-log velocities, especially on older logs, is apparently a reflection of the large uncertainties accompanying such measurements due to factors such as varying tool design and borehole conditions, and possibly also to very small-scale inhomogeneities that are not seen by the much longer seismic wavelengths. Further, average onreef sonic velocities are not found to differ significantly from average offreef velocities within laterally continuous stratigraphic units for the three Leduc reefs that we have examined. We conclude that large lateral velocity variations of the order of 10%, as have previously been proposed for some Devonian reefs in Alberta, are inconsistent with the seismic data, both in the form of time sections and the depth sections derived from them.

In this paper, we briefly consider some possible explanations for the apparent incongruity among the results of various geophysical studies of Devonian reefs in Alberta. Three factors that probably are significant are the questionable correspondence between interval velocities determined from sonic-log data and surface-seismic data, the large measurement uncertainties involved in the sonic-log data, and the differences in methodologies used in different studies. We conclude that this question is not yet wholly resolved and suggest a future research initiative which ideally would constitute an integrated geophysical and geological investigation of one or more Devonian reefs of Alberta using all practical means to constrain the results as much as possible.

Introduction

The problem of the possible existence of density and/or velocity anomalies in the sedimentary section over carbonate reefs has been a challenging one for many years. It has been difficult, for example, to account for the gravity anomalies observed over some reefs simply on the basis of the anomalous mass of the reef and overlying draping strata without the inclusion of some density variation within stratigraphic units (Yungul, 1961; Haye, 1967; Gretener, 1970). However, the actual existence or nature of such density anomalies, as well as agreement on what mechanisms might have produced them, are still unsettled issues. Trott (1981), on the other hand, has shown for two Leduc reefs in Alberta (Westerose South and Golden Spike) that the observed gravity anomalies are indeed substantially accounted for by consideration of the reef and drape structures, without provision for anomalous density variations, except for a 50-kg/m^3 (2%) increase in the Ireton Fm over the Golden Spike reef.

The suggestion that density within a particular unit might be higher onreef than offreef has as a natural corollary the proposition that seismic velocity might exhibit a similar variation. Davis (1971, 1972a, b) looked for lateral velocity anomalies over a number of reefs in the Devonian of Alberta (Figure 1) and concluded that such anomalies do indeed exist. In a pioneering study of six Leduc Fm reefs in a 20 000-km^2 area of central Alberta incorporating 130 borehole sonic logs, Davis (1971, 1972a) concluded that the offreef-to-onreef increase of velocity amounts on average to about 11% in the reef-encasing Ireton Fm, decreases to about 2 1/2% at the top of the Paleozoic section (Mississippian Series) and increases again to about 5% above the pre-Cretaceous unconformity in the basal Cretaceous, above which it disappears.

In a subsequent study of Keg River Fm (Rainbow Mbr) reefs incorporating 134 sonic logs over a 300-km^2 area of northwestern

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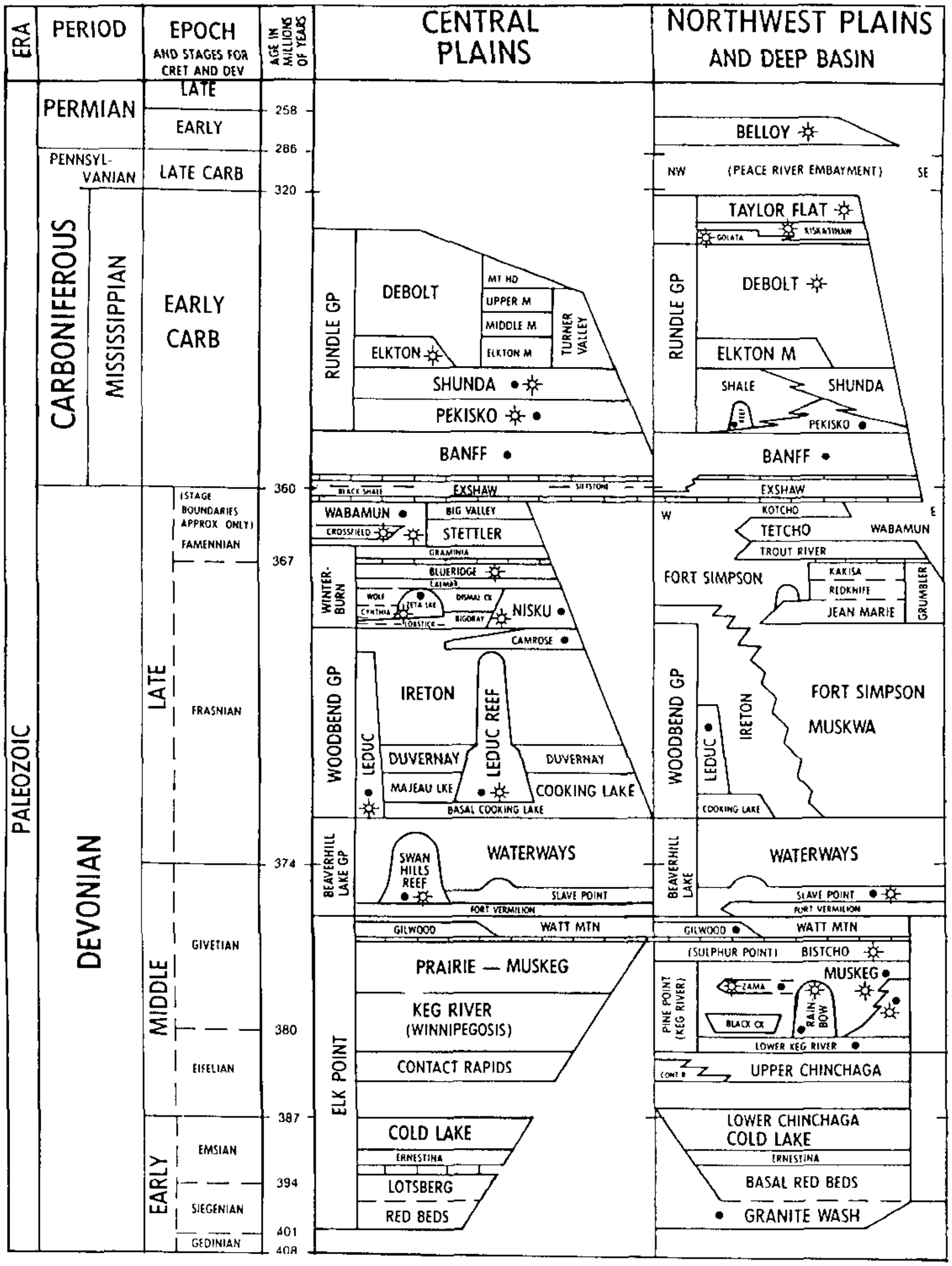


Fig. 1. Stratigraphy from the base of the Devonian to the top of the Paleozoic for the central plains and northwest plains of Alberta (after AGAT Laboratories, 1988).

Alberta, Davis (1972b) found that the velocity anomalies were less significant in magnitude, vertical extent, and correlation with reef occurrence than in the Leduc case. For the Rainbow Lake area, velocity anomalies were reported over some but not all of the reefs with magnitudes ranging from about - 4% (i.e., a decrease) in the reef-encasing Muskeg Fm to about + 6% in the Middle Devonian Watt Mountain Fm to about zero in the Upper Devonian Fort Simpson Fm.

In these studies, two quite different methods were used to determine the regional velocity variations. The implications of this will be further touched upon below. It should also be mentioned that around 1970 there were far fewer sonic logs available than is the case today, and many of those were not borehole-compensated, this advance having appeared around 1965.

In a recent study of western Canadian Devonian reefs, Anderson (1986) found that incorporation of velocity variations of up to 10% within laterally continuous units overlying Leduc reefs leads to geologically implausible results in transforming from time or seismic section to geologic or depth section, such as topographic lows on prereef platforms. On the other hand, the assumption of laterally constant interval velocities within units throughout the entire section leads to geologic interpretations that seem more reasonable in that reef growth on topographic lows is not implied.

The upper portion of the Ireton Fm, generally present both offreef and onreef, has higher average *P*-wave velocity than the lower portion, which is thin or absent onreef (Davis, 1971, 1972a; Anderson et al., 1989b, c). Thus, for the Ireton interval as a whole, there is an increase in average *P*-wave velocity over the reef; and probably, in accord with Trott's (1981) Golden Spike model, a corresponding increase in density as well. However, within each of these units separately, our interpretations have not required the introduction of any lateral velocity variation (Anderson, 1986; Anderson et al., 1986, 1989b, c; Anderson and Brown, 1987).

This apparent incongruity in the findings of different studies on this topic prompts us to consider the matter further. In this paper, we critically examine the suitability of borehole sonic logs in providing sufficiently accurate data to resolve offreef-to-onreef velocity variations and the consequences to geologic interpretation of laterally varying versus constant interval velocities. In addition, we consider some of the different methods that have been used and are available for future investigations of this problem.

Sonic-Log Velocities

Reliability of sonic-log velocities

P-wave interval velocities determined by means of borehole sonic logs can differ significantly from those determined using surface-seismic data as a result of dispersion, short-path multiples, variations in borehole environments, and different sonic-log measuring tools and techniques. Due to dispersion alone, sonic-log velocities can exceed seismic velocities by ~10% while short-path multiples can produce differences of the same sense of ~3% (Stewart et al., 1984). Differences among closely spaced individual sonic logs themselves may also exist due to variations in tool design and borehole conditions. Such differences are shown below, in an analysis of two suites of closely spaced wells, to be as much as ~17%. This large data scatter for sonic-log velocities is thus very significant in relation to the differences between sonic-log and surface-seismic velocities.

The first suite of sonic logs examined is from three onreef wells, all located within 1 km of each other and drilled into a common Keg River (Rainbow Mbr) reef. Sonic-log velocities for selected intervals (Table 1) were determined by measuring transit times and corresponding thicknesses directly on the sonic logs. The sonic-log velocities for the Wabamun/Fort Simpson and the Fort Simpson/Slave Point intervals (i.e., between the respective tops) are seen to be 8% and 7% higher, respectively, in the 12-3 well than in the 3-3 well. The higher velocities in the 12-3 well translate into a 35-ms decrease in two-way traveltime (relative to the 3-3 location) on the integrated velocity logs for the Wabamun/Slave Point interval, in spite of the fact that this interval at the two locations differs in thickness by only about 3 m, according to the formation tops derived from well-log data. Such a large traveltime difference (35 ms) over such a short onreef distance (1 km) is simply not observed on the seismic data and is put into perspective by the fact that one of the principal criteria for delineating Rainbow Mbr reefs is a decrease of 15 ms or more in the Wabamun/Slave Point time-thickness, onreef relative to offreef (McQuillin et al., 1984; Anderson, 1986; Anderson et al., 1989a).

The second suite of sonic logs (Table 2) is from four closely spaced onreef wells (within a radius of 1 km) drilled into a common Leduc reef in the Penhold area and tied to a seismic line (Figure 2). For the Mannville/Banff, Banff/Wabamun and Wabamun/Ireton intervals, the sonic-log velocities (Table 2) are 17%, 17% and 11% higher in the 16-29 well than in the 9-28 well, respectively. The net effect is that the two-way traveltime through the Mannville/Ireton interval on the 9-28 synthetic seismogram is 22 ms greater than on the 16-29 synthetic (Figure 3), despite the fact that this interval is about 30 m thicker in the 16-29 well. No such 22-ms difference is seen on the seismic

Table 1. Average interval velocities (m/s) calculated from sonic logs for three wells in the Rainbow field (T.109, R.8W6) drilled into a common Keg River reef.

Stratigraphic interval	Well 3-3	Well 13-2	Well 12-3	Mean value	Standard deviation
Banff-Wabamun	3234	3306	3139	3226	84
Wabamun-Fort Simpson	4736	5038	5121	4965	203
Fort Simpson-Slave Point	3391	3859	3614	3621	234
Slave Point-Watt Mountain	5716	5615	5564	5632	77

Table 2. Average interval velocities (m/s) calculated from sonic logs for four wells in the Penhold field (T.36, R.27W4) drilled into a common Leduc reef.

Stratigraphic interval	Well 9-28	Well 13-28	Well 15-29	Well 16-29	Mean value	Standard deviation
Mannville-Banff	3551	4141	4132	4170	3999	299
Banff-Wabamun	4726	5377	5438	5545	5272	370
Wabamun-Ireton	5522	6010	5966	6139	5909	268

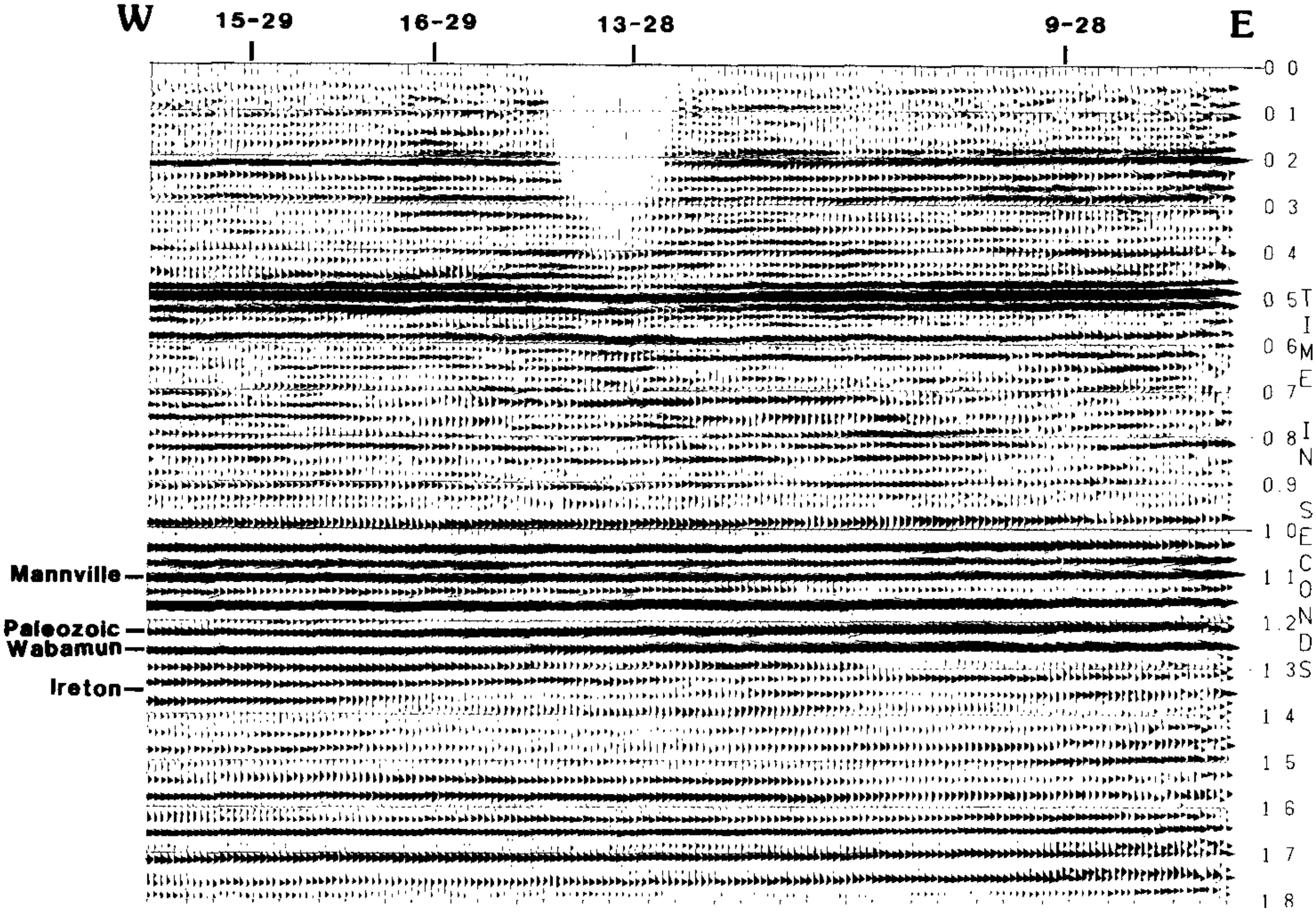


Fig. 2. Seismic section from a line that ties to the four wells of Table 2, which penetrate a common Leduc Fm reef in the Penhold field (T.36, R.27W4). A detailed interpretation of this line (Anderson et al., 1989c) shows that the reef edge is just west of the 15-29 well and that the reef has reached full thickness at the 16-29 location. Both of these, as well as the 13-28 well, are within about 200 m of the seismic line, while the 9-28 well (full reef thickness) is within about 500 m of the line.

Table 3. Average interval velocities (m/s) measured on the seismic section (Figure 2) at the tie points to the wells of Table 2. Measured thicknesses (m) and two-way traveltime (s) are also tabled.

Stratigraphic interval	Well 15-29	16-29	13-28	9-28	Mean value	Standard deviation
Mannville-Banff	2x231.3/ 0.117 = 3955	2x233.5/ 0.118 = 3957	2x227.7/ 0.116 = 3926	2x221.9/ 0.113 = 3927	3941	17
Banff-Wabamun	2x100.6/ 0.040 = 5029	2x91.7/ 0.036 = 5097	2x88.7/ 0.035 = 5068	2x94.5/ 0.038 = 4973	5042	54
Wabamun-Ireton	2x277.4/ 0.094 = 5901	2x270.0/ 0.088 = 6138	2x252.4/ 0.085 = 5938	2x245.7/ 0.082 = 5992	5992	104

section (Figure 2). Rather, we measure a 9-ms difference of the opposite sense (Table 3), quite consistent with the thickness difference.

At each well-seismic tie point (Figure 2), seismic interval velocities have been calculated for the Mannville/Banff, Banff/Wabamun and Wabamun/Ireton intervals (Table 3). For comparison, the corresponding sonic-log velocities (Table 2) have been plotted against these seismic velocities (Figure 4). In contrast with the sonic-log velocities, the seismic velocities are relatively uniform, varying by an average of 2% and by a maximum of 4%, suggesting that differences observed between sonic logs are principally due to the measurement error discussed above and cannot confidently be attributed to real variations in seismic velocity.

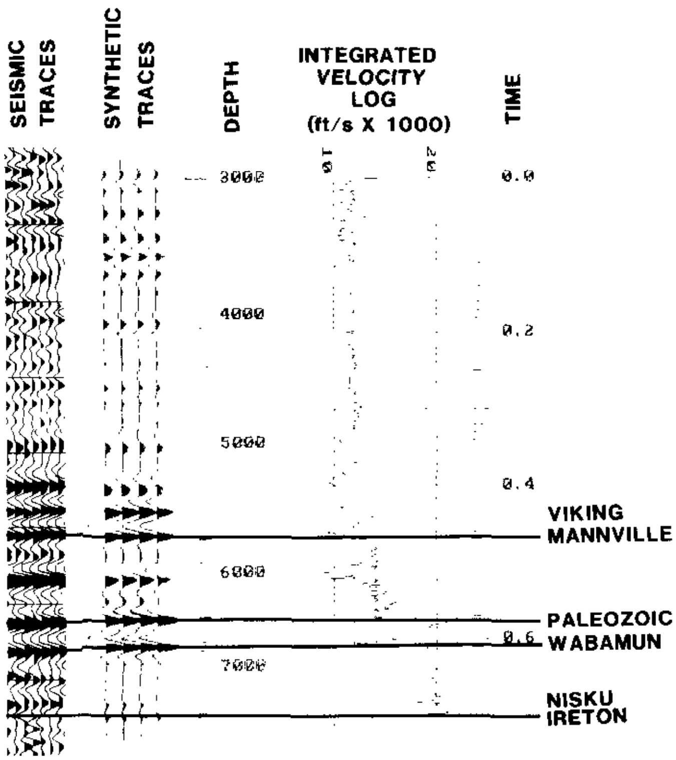


Fig. 3. Integrated velocity log from the 16-29-36-27W4 well (cf. Table 2 and Figure 2), corresponding synthetic seismic traces, and seismic traces recorded near the 16-29 well.

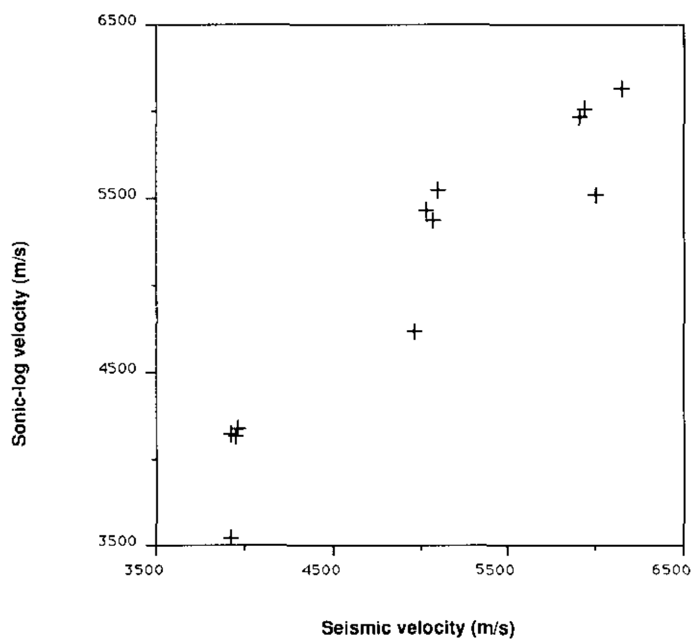


Fig. 4. The sonic-log interval velocities of Table 2 (Penhold area) plotted against the corresponding seismic interval velocities of Table 3. The three groups of points, corresponding to the three stratigraphic intervals, are seen to be much more scattered vertically (sonic-log) than horizontally (seismic). Collectively, the points scatter about an imaginary line drawn from corner to corner: the line of equality of the two velocities.

Sonic-log velocities: onreef and offreef

Sonic-log interval velocities are calculated for three separate suites of well logs: from the Strachan area (Table 4, Figure 5), the Rumsey-Stettler area (Table 5, Figure 6) and the Obed area (Table 6). Each suite consists of both onreef and offreef wells within a common area (although for Obed only one onreef well was available in our data base). Comparison of these interval velocities reveals that, although they vary from well to well, there is no recognizable correlation between the average velocities in these intervals and the presence or absence of Leduc Fm reef. Table 7 compares these results with those of Davis (1971, 1972a).

Interpretation of Seismic Data

We have studied seismic sections over a number of Leduc reefs and attempted to interpret these data with the aid of synthetic sections which incorporate higher interval velocities onreef than offreef (Anderson, 1986; Anderson and Brown, 1987; Anderson et al., 1989b, c; Brown et al., 1990). The results were always inconsistent with prevailing concepts of reef morphology. In particular, on such geologic models, horizons predating the reef were structurally lower onreef than offreef. In contrast, when we input laterally uniform interval velocities the data were satisfactorily modelled in the sense that prereef topography turned out to be either positive or negligible beneath reef buildup.

Table 4. Average interval velocities (m/s) calculated from sonic logs for onreef and offreef wells in the Strachan area (Leduc reef).

WELL	Mannville-Paleozoic	Paleozoic-Wabamun	Wabamun-Ireton
ONREEF (T.37, R.9W5)			
2-21	4327	5977	6236
11-22	4168	5721	6171
11-27	4140	5907	6218
11-28	4328	6021	5795
10-31	4183	5846	6216
7-32	4350	5966	6162
Mean	4249	5906	6148
Standard deviation	95	109	183
OFFREEF (T.38, R.9W5)			
6-10	4383	5824	6098
10-11	4415	5974	6164
6-14	4318	5956	6096
10-17	4255	5688	6015
9-20	4095	5925	6172
9-24	4275	5643	6083
Mean	4290	5835	6105
Standard deviation	114	142	58

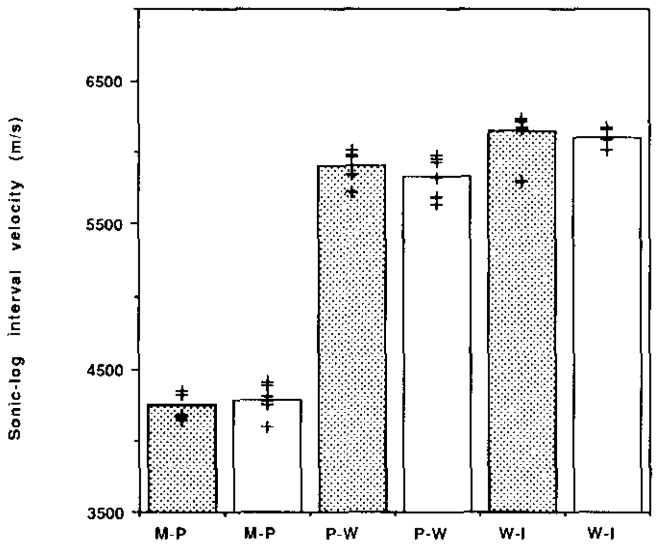


Fig. 5. Onreef/offreef comparison for the Strachan area: for each stratigraphic interval, the two bars indicate mean onreef (stippled) and mean offreef sonic-log interval velocities. Names of stratigraphic units, given in Table 4, are indicated by the first letters of their names, and individual velocity observations are plotted as + signs.

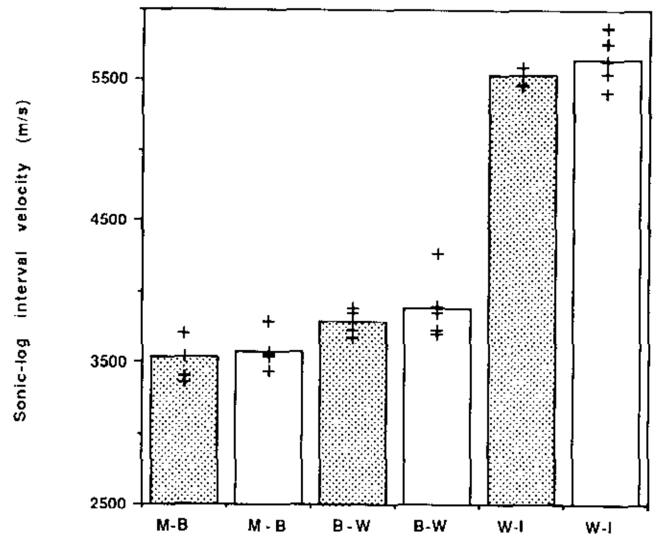


Fig. 6. Onreef/offreef comparison for the Rumsey-Stettler area: for each stratigraphic interval, the two bars indicate mean onreef (stippled) and mean offreef sonic-log interval velocities. Names of stratigraphic units, given in Table 5, are indicated by the first letters of their names, and individual velocity observations are plotted as + signs.

Table 5. Average interval velocities (m/s) calculated from sonic logs for onreef and offreef wells in the Rumsey-Stettler area (Leduc reef).

WELL	Mannville-Banff	Banff-Wabamun	Wabamun-Ireton
ONREEF			
10-34-35-17W4	3397	3885	5473
9-23-35-18W4	3701	3848	5595
14-5-36-20W4	3368	3679	5546
14-31-36-20W4	3695	3723	5543
Mean	3540	3784	5539
Standard deviation	183	98	50
OFFREEF			
2-24-34-21W4	3555	4268	5642
2-1-35-20W4	3434	3894	5550
6-9-36-19W4	3542	3852	5768
16-19-36-21W4	3559	3694	5424
11-7-36-23W4	3792	3721	5877
Mean	3576	3886	5652
Standard deviation	131	230	178

Table 6. Average interval velocities (m/s) calculated from sonic logs for onreef and offreef wells in the Obed area (Leduc reef). The single onreef well also penetrated Leduc reef, whose average interval velocity was determined to be 5842 m/s.

WELL	Mannville-Nordegg	Nordegg-Wabamun	Wabamun-Ireton	Ireton Fm
ONREEF				
2-36-54-23W5	4079	5499	6234	5528
OFFREEF				
6-28-54-21W5	4148	5492	5960	4872
7-6-54-22W5	4059	5518	6189	
Mean	4104	5505	6075	
Standard deviation	63	18	162	
Mean (all wells)	4095	5503	6127	
Standard deviation	47	13	147	

In support of his conclusions, Davis (1971, 1972a) incorporated into his study a seismic section (Figure 7) and a corresponding geologic model (Figure 8) across a particular Leduc reef, namely the Strachan reef, in Township 37, Range 9W5. However, this model does not appear to us to be wholly consistent with the seismic data. For example, both the Blairmore (Mannville) and the Paleozoic are flat in the geologic section of Figure 8a, whereas, as indicated by the well-log data and illustrated by the seismic section (Figure 7), both of these horizons actually drape by about 40 m. This drape generates a significant component of the time-structural relief observed on the seismic section beneath the reef (by velocity pull-up). The introduction of lateral velocity variations into the model leads necessarily to a reduction in the interpreted amount of structural drape so that consistency with the observed seismic pull-up might be preserved.

Table 7. Comparison of percent velocity changes, onreef relative to offreef, *as determined by Davis (1971, 1972a) for a suite of six Leduc* reefs and in this paper for three different Leduc reefs.

Stratigraphic interval	Davis (1971,1972a)	Strachan (Table 4)	Rumsey-Stettler (Table 5)	Obed (Table 6)
Mannville-Paleozoic	5%	2%	1/2%	-1/2%
Paleozoic-Wabamun	2 1/2 to 3 1/2 %	1/2%	-1/4%	0
Wabamun-Ireton	6 to 8 %	-1/2%	-1/2%	3%

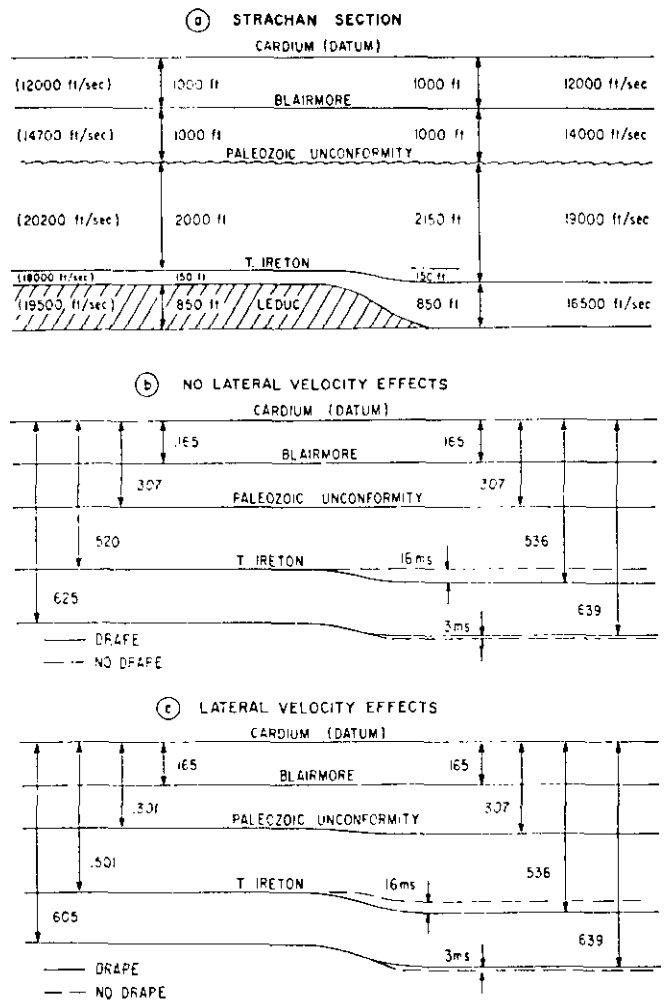


Fig. 8. Representation of **(a)** geologic (depth) section, **(b)** seismic (time) section assuming uniform velocities, and **(c)** seismic section incorporating velocity anomalies over the Strachan reef (after Davis, 1971, 1972a).

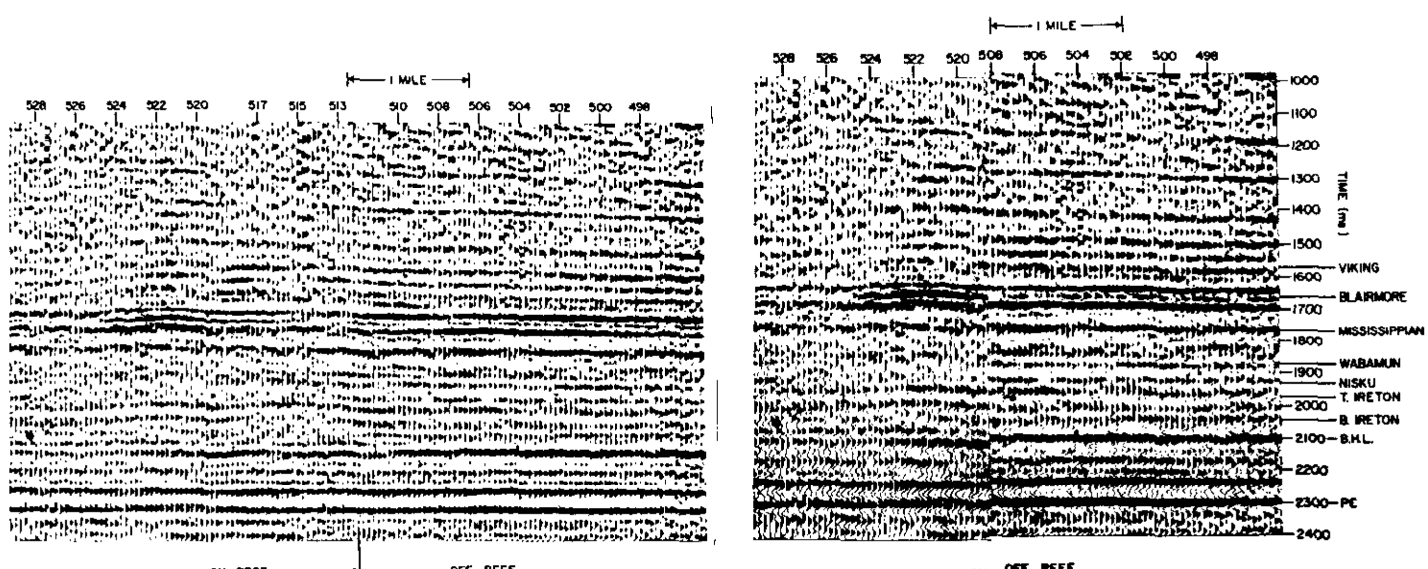


Fig. 7. ***Left:*** *seismic section from the Strachan area (reproduced from Davis, 1972a; with permission).* ***Right:*** *the same section cut and spliced so as to* juxtapose shotpoints 508 (offreef) and 518 (onreef) with the Blairmore top as a datum.

The effect of incorporating lateral velocity variations into the model is demonstrated by comparing the seismic section (Figure 7) with the transformed geologic model (Figure 8). Note that the Blairmore/Ireton intervals (time thicknesses) in Figure 8 are 35 ms greater offreef than onreef. This is inconsistent with the seismic section (Figure 7) where the corresponding two-way traveltime interval is seen to be less than 5 ms greater offreef than onreef. If drape at the Blairmore and the Paleozoic is taken into account, and if laterally invariant interval velocities are used, a geologically sounder and seismically more compatible model is generated (Figure 9).

In summary, Davis's (1971, 1972a) conclusion that average velocity of the upper Paleozoic and lower Mesozoic in the Strachan area is significantly higher onreef than offreef does not appear to be supported either by the data from integrated velocity logs examined in this paper or by the Strachan seismic data.

Discussion

Sonic-log velocities

In an earlier section we mentioned the large uncertainties in sonic-log velocities themselves and their lack of reliability as estimators of seismic velocity. Such errors can easily be larger than the velocity variations in question, although it would seem improbable that such errors would compound so systematically as to produce spurious velocity anomalies of the magnitudes under consideration. Nevertheless, it is conceivable that there is some real lateral anomaly in sonic-log velocity of as much as 10% or more which, however, does not translate into an equally large anomaly in seismic velocity. This would imply the lack of an exact one-to-one correspondence between sonic-log and seismic velocities and perhaps that lithological differences onreef versus offreef translate into different wave-propagation properties (e.g., dispersion) onreef versus offreef.

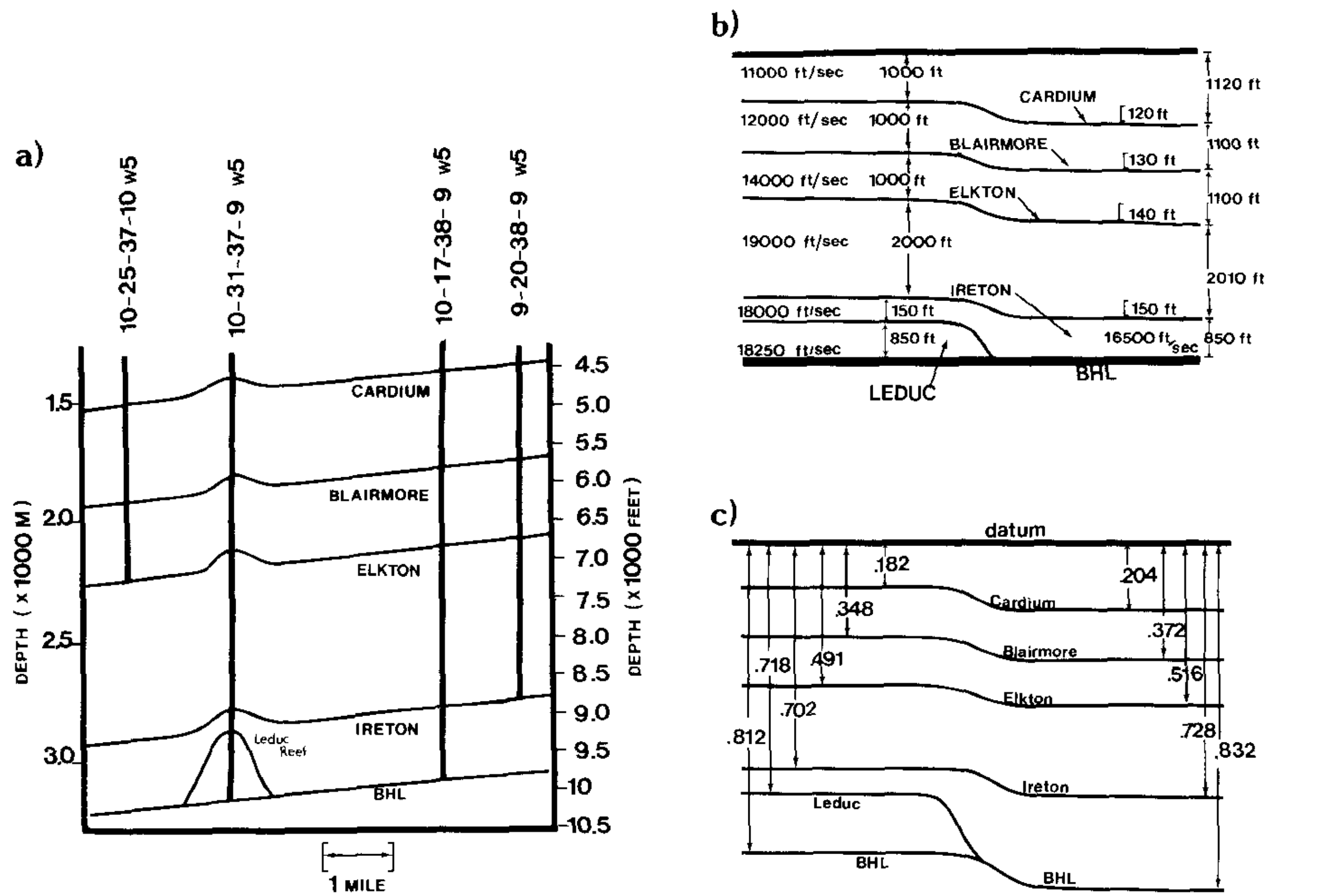


Fig. 9. (a) Subregional geologic cross-section over the Strachan reef, constructed from the wells shown, showing drape as high as the Cardium; **(b)** schematic geologic section over the Strachan-reef edge, expanded from and compatible with the section in (a), incorporating drape on the Cardium top and laterally uniform velocities; and **(c)** the seismic section equivalent to (b). Note that the Blairmore/Ireton interval on the time section is only slightly greater offreef (356 ms) than onreef (354 ms).

Regional velocity computation

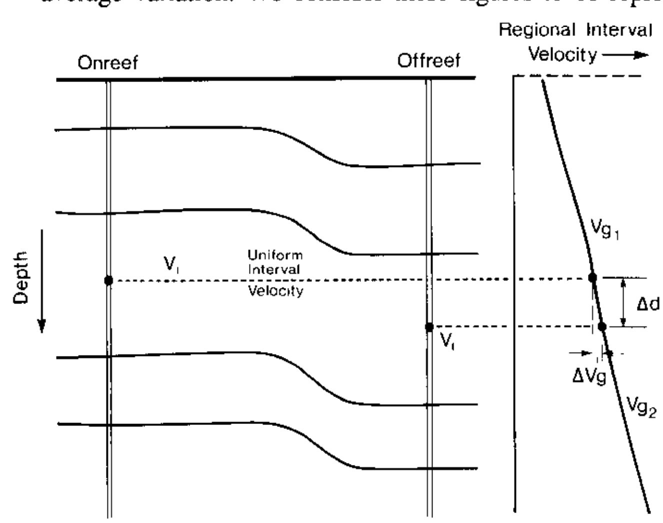
A significant difference in the methodologies applied in past studies appears to lie in the schemes used to determine the regional velocity variations. In the Keg River study (Davis, 1972b), trend-surface analysis was used in fitting the regional variation separately in each of six or seven units, without reference to any explicit depth dependence. However, in determining regional velocities in the Leduc study, Davis (1971, 1972a) applied a velocity-depth relationship due to Acheson (1963, 1981), which yields regional velocity as a function not only of horizontal position but also explicitly of depth. It would be virtually impossible to determine what differences, if any, the two methods would produce, without actually applying both to the same data set. However, one can say that the trend-surface method is conceptually simpler than the velocity-depth-function method, which incorporates a number of subjective refinements. For example, Figure 10 illustrates schematically how a positive onreef anomaly in residual velocity could conceivably be produced as an artifact, even when the interval velocity is constant throughout the unit in question. We have considered such notions in more detail elsewhere (Anderson et al., 1988).

Conclusions and Future Work

Conclusions

1. We found sonic velocities from onreef wells over two different reefs (Keg River and Leduc) to exhibit average variations (over the stratigraphic units considered) of about 10% (Keg River ~7%; Leduc ~14%). Velocities determined seismically over the same Leduc reef showed only about a 2 1/2% average variation. We consider these figures to be representative of the relative uncertainties in the respective methods of velocity determination.
2. Sonic-log interval velocities from both onreef and offreef wells over three Leduc reefs (Strachan, Rumsey and Obed) showed onreef velocities about 1/2% higher, on average, than offreef for the Mannville/Ireton interval.
3. We believe we have shown that the Strachan seismic data support a model with no lateral velocity variation within units.
4. It is possible that errors of ±5% in sonic-log interval velocities could be so systematic as to produce apparent velocity anomalies, especially in older logs.
5. The second computational procedure employed by Davis (1972b), in the Keg River (Rainbow) study, is conceptually simpler than that used in the Leduc study. There is no reason to doubt that the results from the Rainbow area, presented in the residual-velocity contour maps (Davis, 1972b), constitute a faithful representation of the subsurface within the limits of experimental error. In view of this and our other results above, we are led to the conclusion that the actual velocity anomalies over Leduc reefs are probably of the same order of magnitude as those over Rainbow reefs, i.e., no more than about 1% or 2% on average.

We do not believe that we have completely solved the vexing problem of the nature of the *P*-wave velocity variation over Leduc or Keg River reefs. There are still significant incongruities between results that require explanation. The pioneering work of Davis (1971, 1972a, b), at a time when borehole-compensated logs were still in their infancy, shed considerable light on a question that is not only of academic interest but also of considerable practical importance to the explorationist.



$$\Delta V_S = (V_i - Vg_1) - (V_i - Vg_2)$$
$$= Vg_2 - Vg_1 = \Delta Vg > 0$$

Fig. 10. Schematic diagram demonstrating how selection of regional interval velocities, V_g, using an explicit function of depth (e.g., following Acheson, 1963) could conceivably create an apparent onreef/offreef anomaly in residual velocity, V_s, even when the actual interval velocity, V_i, is uniform within each unit.

Future work

The nature of velocity variations over Leduc reefs in western Canada remains today, twenty years after the appearance of Davis's (1971, 1972a) works, something of an enigma. In this paper, we have tried to point this out and document some of the conflicting findings. We believe that reef reservoirs are still a sufficiently important exploration target in Canada, and in the world at large, to warrant further investigation of this problem. A state-of-the-art integrated study of a selected Leduc reef in Alberta, incorporating latest geophysical, borehole and geological techniques, with optimal research results rather than production efficiency as the guiding principle, should be able to resolve these ambiguities once and for all.

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