Duhamel: A seismic analysis of differential compaction in a Leduc reef

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ABSTRACT

The Duhamel reef is an isolated Frasnian limestone bioherm of the Leduc Formation in south-central Alberta. Although Duhamel has a relatively small basal area (less than 12 km^2), the reef rises some 275 m above the platform facies. The seismic data show what we interpret to be a raised peripheral reef rim, which appears to be elevated about 25 m relative to the interior of the reef. Raised rims are commonly considered to be diagenetic in origin, and attributed to differential compaction within reef complexes. Although late-stage accretionary growth about the periphery of the reef complex may have contributed to its development, we interpret the raised rim at Duhamel to be principally of secondary origin. This thesis is supported by the incorporated seismic and well-top data.

The seismic data also suggest that the facies within the reef rim have a lower seismic velocity than the facies within the structurally lower reef interior, consistent with the observation that raised rims are generally more porous than the encircled and structurally lower lagoon and, therefore, constitute a preferred well-completion site. Optimal hydrocarbon recovery could be realized if all producing wells were drilled into the raised reef rim. Our data for Duhamel show that even relatively small reefs can exhibit raised rims and that these rims may be seismically visible, especially if one can incorporate multicomponent and/or 3-D data. Such data should be acquired prior to drilling across similar reefs with a view to imaging and locating the complete raised rim, not simply its updip side, so that all parts of the rim can be targeted for the drill.

INTRODUCTION

Within the Frasnian-age Woodbend Group, the Leduc Formation of Alberta (Figures 1 to 3) developed as fringing reef complexes, linear chains of reefs, and isolated reefs of various shapes and sizes (Klovan, 1964; Mountjoy, 1980; Stoakes, 1980; Stoakes and Wendte, 1987; Andrews, 1988; Anderson et al., 1989a, b; McNamara and Wardlaw, 1991; Switzer et al., 1994). In central Alberta, the Leduc overlies a regional platform facies, the Cooking Lake Formation and is encased in the impermeable shales of the Duvernay and Ireton Formations.

In a study of the isolated Leduc Formation limestone reef complex at Redwater, Mossop (1972) described raised peripheral rims as primarily the result of the differential compaction of rigid reef-rim facies and central lagoonal facies. The rigid reef-rim facies are sediments deposited in the high-energy environment about the seaward edge of the reef complex, while the central lagoonal facies are fine-grained sediments deposited within the encircled and sheltered, relatively low-energy environment of the reef interior. Mossop (1972) concluded that, at the time of deposition, the interior of Redwater was about 12 m higher than the encircling rim. He

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further pointed out that compaction by stylolitization through pressure-solution of carbonate mineral matter is an important process resulting in volume loss in carbonate rocks. As a result of such postdepositional differential compaction, the Redwater rim is now structurally elevated by some 34 m. Mossop estimated that the rigid reef-rim facies and the interior lagoonal facies were compacted by at least 13% and 24%, respectively. He cautioned that these percentages were likely minimum estimates and that numerous factors bias their reliability as precise indicators of the amount of carbonate removed. These different values in Mossop's (1972) estimates of compaction are also attributable to the differences in susceptibility to compaction of the rigid reef-rim and interior lagoonal facies.

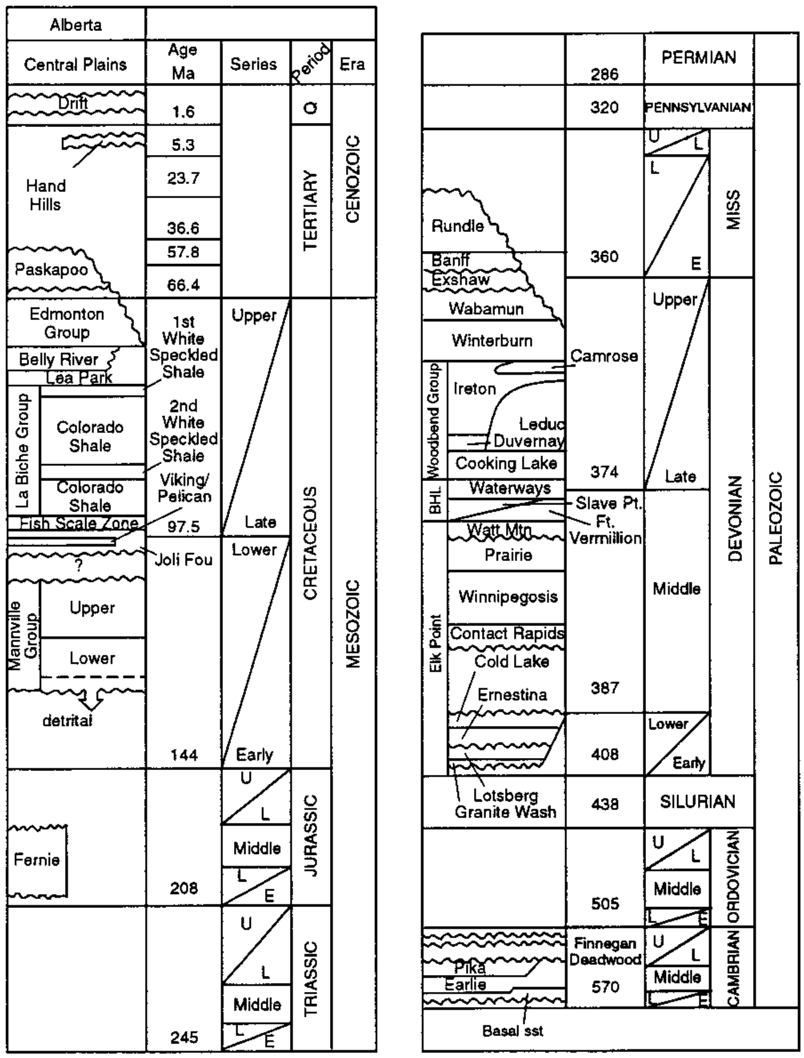

Fig. 1. Stratigraphic chart for south-central Alberta (modified after AGAT Laboratories, 1988).

Anderson and Franseen (1991), in a seismic study of a relatively small western Canadian reef (~1.5 km wide) of the Givetian Elk Point Group, report higher compaction values, 30% and 44% for the rigid reef-rim and interior lagoon, respectively, than for Redwater. They conclude that the raised rim is essentially a secondary compactional feature, characteristic of Devonian Elk Point and Woodbend reefs in western Canada (Anderson and Brown, 1987; Andrews, 1988; Anderson et al., 1989a,b,c; Brown and Anderson, 1991; Brown et al., 1990) and at least partly due to the cementation or lithification history (early cements being more likely in the reef-rim facies), selective dolomitization (possibly more dolomite in the interior reef area), and/or the presence of relatively more noncarbonate mud (or other insoluble material) in the reef-interior facies. Anderson and Franseen (1991) acknowledge that the raised rim could also reflect an original buildup morphology with a margin that was topographically higher than the interior, possibly due to frame-building organisms and possibly preserved by submarine cementation.

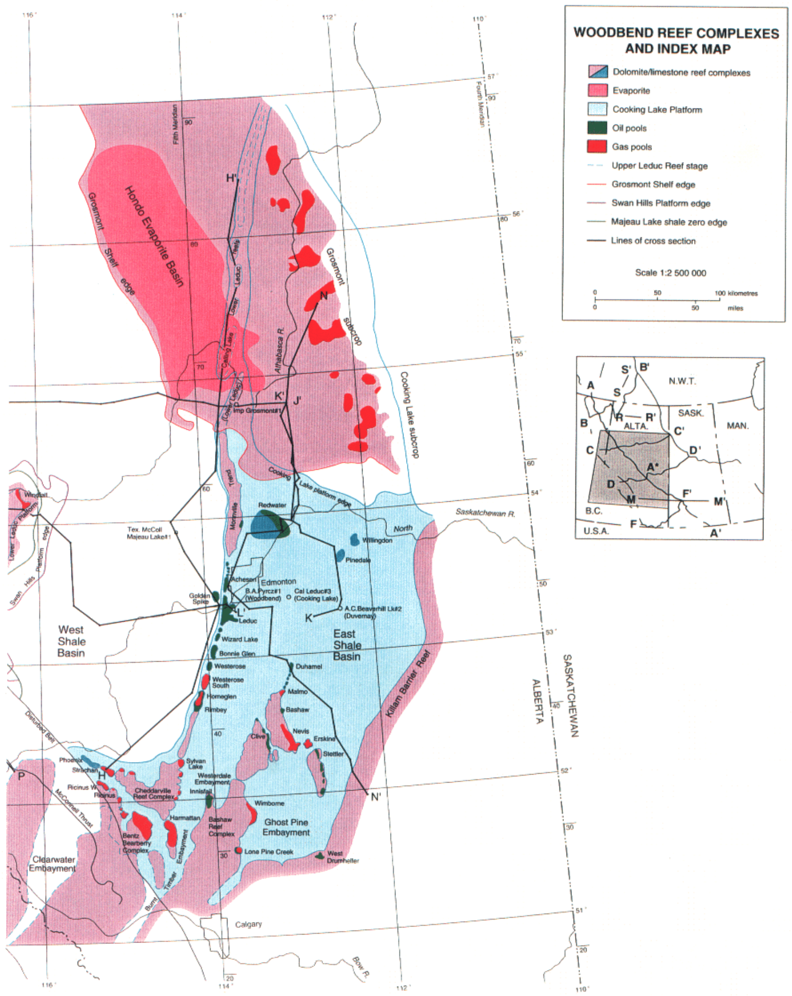

Fig. 2. Distribution of Upper Devonian Woodbend Group (Frasnian) reef complexes, intervening shale basins, oil and gas pools, and line of cross-section N-N' (after Switzer et al., 1994, with input from Andrews, 1988). The map has been truncated to the west (cf. inset key). Reproduced by permission of the Canadian Society of Petroleum Geologists and the authors (Switzer et al., 1994)

As a result of differential compaction between the reefal carbonate facies and the off-reef shale facies, overlying strata typically drape across Leduc buildups (Mossop, 1972; O'Connor and Gretener, 1974; Wirnkar and Anderson, 1989). The amount of drape is a function of the thickness of the overlying sedimentary section and of the relative compactabilities of these reef and off-reef facies through all postdepositional volume changes, whether chemical or physical in origin.

In this paper we examine a 2-D seismic line that extends across the Duhamel Leduc reef, geologic cross-sections constructed from well-log formation tops, and take a preliminary look at some 3-D and VSP data. These data appear to illustrate two classic compactional features: (1) relief along postreef strata as a result of the differential compaction of reef and off-reef facies; and (2) a raised peripheral rim.

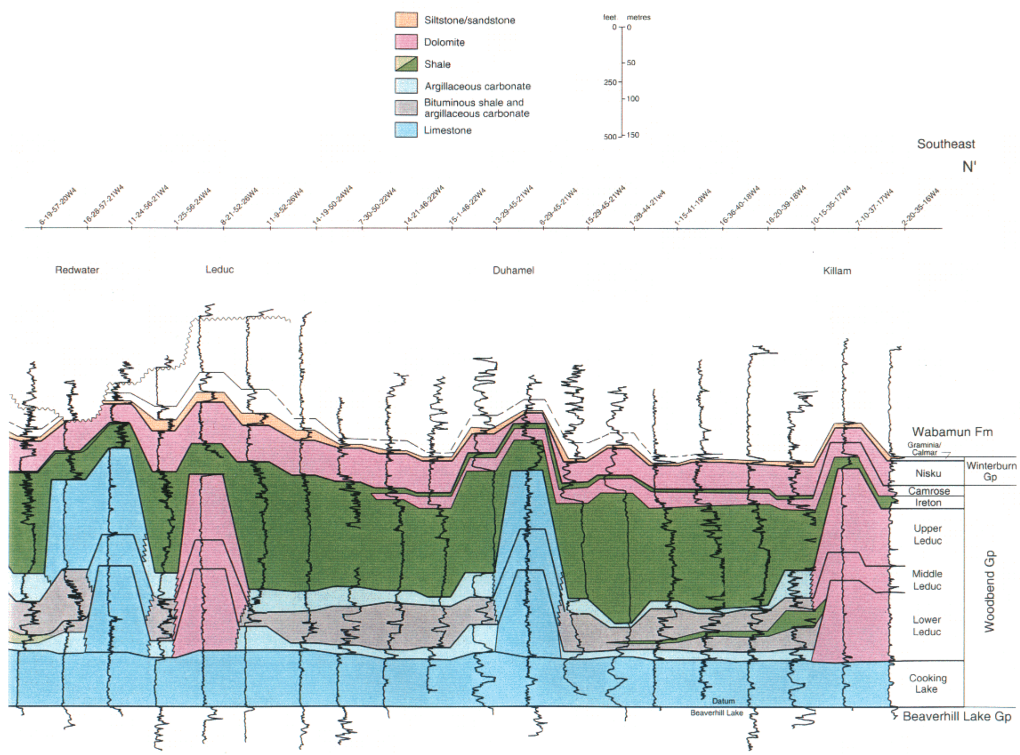

Fig. 3. Cross-section N-N' (Figure 2) showing Woodbend–Winterburn strata from Redwater to the Killam barrier (after Switzer et al., 1994). Log traces are gamma ray. The cross-section has been truncated to the north (cf. Figure 2). Reproduced by permission of the Canadian Society of Petroleum Geologists and the authors (Switzer et al., 1994)

THE DUHAMEL REEF

Relatively little has appeared in the literature on the Duhamel reef. The earliest published information seems to be a routine oilfield report by Wallace (1960), a geochemical study by Haites (1960) espousing the concept of basement-fault control on growth of Duhamel and neighbouring Leduc reefs, and a preprint of a study by Andrichuk (1960) focused mainly on the conditions responsible for initiation of reef growth. Andrichuk (1961) then published the full text of this pioneering study, in which he interpreted a strong connection between observed anomalous thickness and facies changes that preceded and accompanied reef growth and a tectonic hinge line caused by basement fault movement. Kirmani (1962, 1965), who carried out a facies analysis of the Duhamel reef, was also interested chiefly in evidence pertaining to the environment at the time of deposition. None of these studies were concerned with the question of a raised peripheral rim; neither did they make any mention of such a feature.

Duhamel is a relatively small, isolated, undolomitized Leduc Formation reef, located about 15 km north-northeast of the Bashaw reef complex of the East Ireton Shale Basin (Figures 2 and 3). The reef is roughly elliptical in plan view, about 1.5 by 7.5 km, and

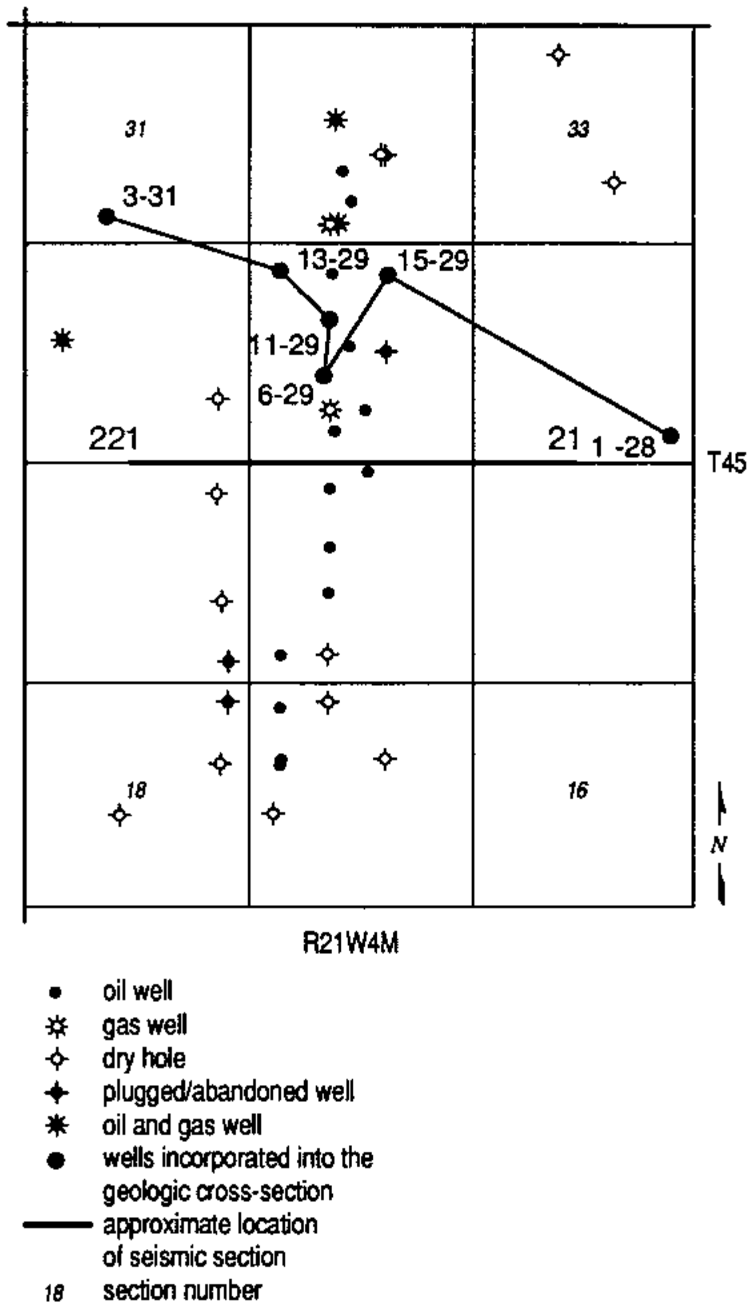

Fig. 4. Map of the study area showing the approximate location of the example seismic line (trace numbers 21 to 221 indicated) and the wells used in the geologic cross-section (zigzag line). Township and range numbers, as well as a few section numbers, are shown. Each section measures 1 mile (1.609 km) on a side.

stands some 275 m above the regionally planar platformal carbonates of the Cooking Lake Formation (Andrichuk, 1961; Moore, 1988) (Figures 4 and 5). Duhamel is believed to be somewhat analogous to the much larger Redwater reef complex; however, there is insufficient core control at Duhamel to confirm or refute the presence of the interior lagoonal facies as described by Mossop (1972) for Redwater. In their study of the small (~1.6 by 5.5 km) dolomitized Leduc reef at Westerose reservoir, McNamara and Wardlaw (1991) report a noticeable absence of stratified lagoonal mudstones and tidal flat sediment, both of which are unique reef interior facies, suggesting that the facies variations within the limestone Duhamel complex may not be as distinct as those identified at Redwater.

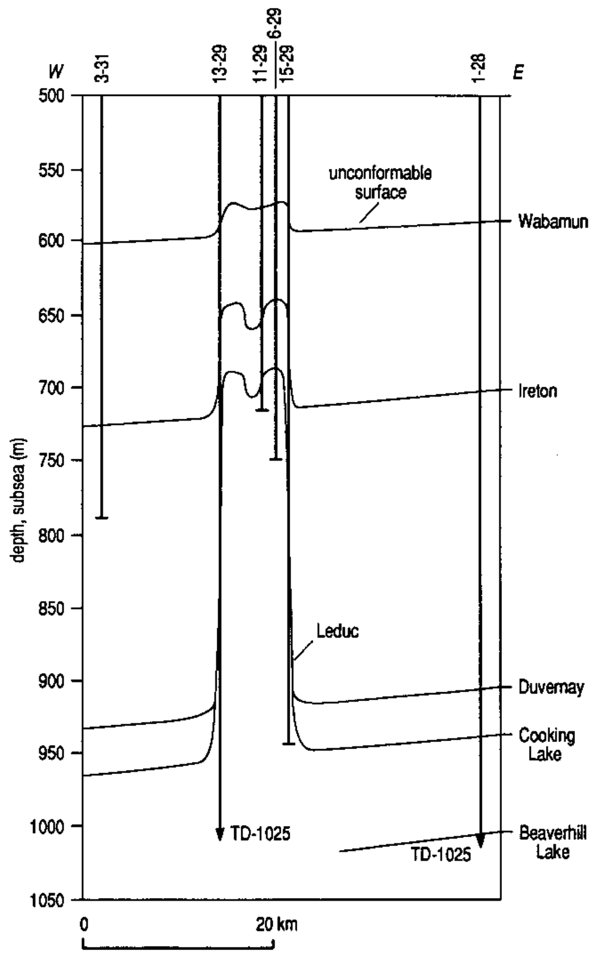

Fig. 5. Geological cross-section illustrating postulated structural relationships among platform, onreef, offreef and postreef strata. The western edge of the raised rim is defined only on the basis of seismic data (Figures 7 and 8) as there is no well control there (Figure 6).

In Figures 5 and 6a, Duhamel is mapped as having a raised rim and a structurally lower interior; relief is on the order of 25 m. The interpretation of the morphology of the western edge of the reef is based on the example seismic data and is, as yet, not confirmed by well control. None of the reef wells in the study area are situated along what seismic control suggests is the western part of the raised rim (Figures 5 and 6a). The distribution of these wells is not unexpected in that the Duhamel reef was discovered and developed in the early 1950s, prior to Klovan's (1964) paper establishing raised rims as morphological features typically associated with Leduc reefs and Mossop's (1972) paper which described the development of the raised rim at the Redwater reef complex. The exploration philosophy at the time Duhamel was discovered was to drill as close as possible to the updip edge of the carbonate buildup as defined on single-fold seismic data. Raised rims were not understood and operators would not have considered intentionally spudding a well along the western, downdip margin of a reef.

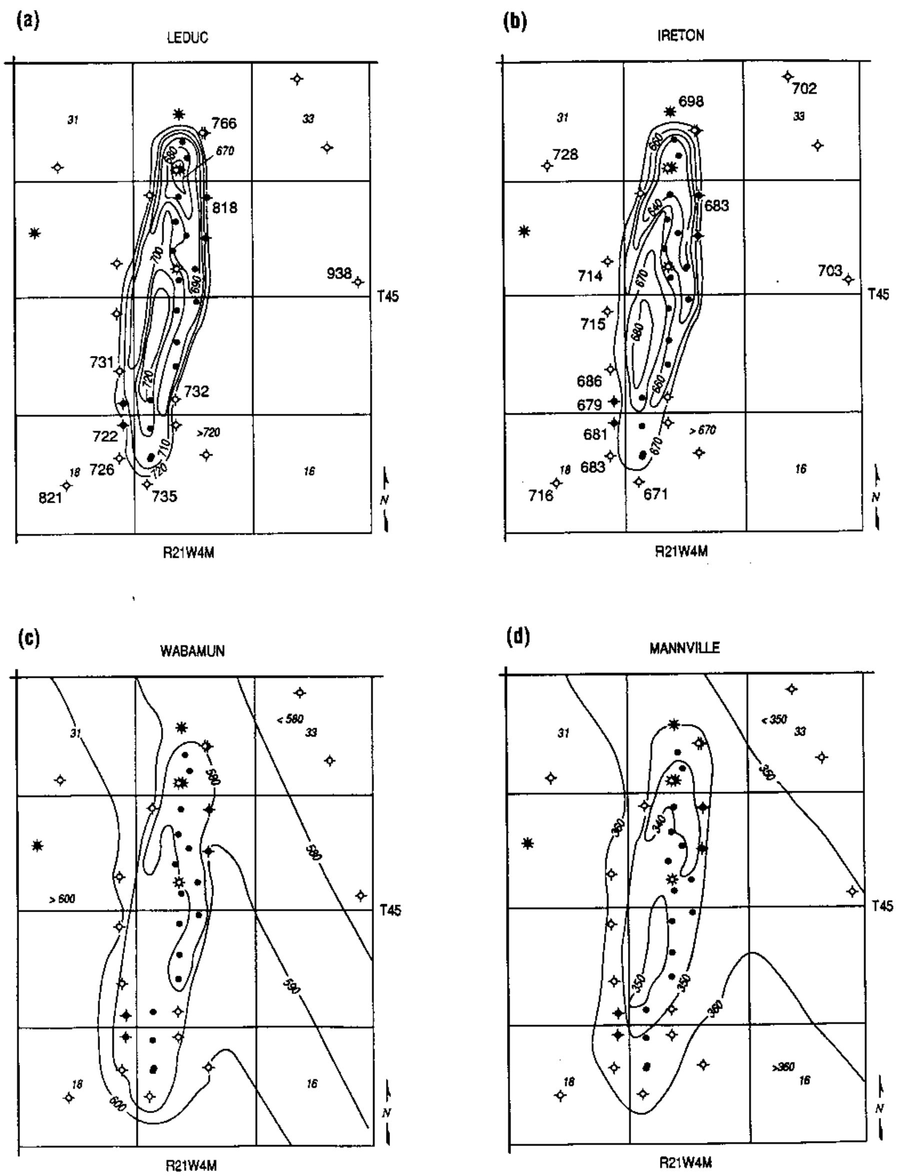

Fig. 6. Structural contour maps showing subsea depths in metres of the tops of (a) the Leduc Formation (Duhamel reef complex); (b) the Ireton Formation; (c) the Wabamun Group; (d) the Mannville Group. For clarity, depth contours in excess of 720 m (a) and 670 m (b) are not shown. In (a), the contoured and posted values represent the depth to the top of the Leduc, or, in its absence, the Cooking Lake Formation. Note that the Leduc (a) and Ireton (b) tops are more or less parallel as contoured, while the Wabamun and Mannville tops exhibit subdued expressions of these, consistent with the thesis of a raised peripheral rim of secondary origin. Symbols and scale are defined in Figure 4.

From a historical point of view, we note that the first four wells to encounter full Leduc reef at Duhamel, 12-17, 13-17, 4-20 and 14-29, (Figures 4 and 6a) were drilled in either 1950 or the first quarter of 1951. Of these four wells, only 14-29 encountered thick Leduc pay; the other three were marginal Leduc oil wells and currently produce from the overlying Nisku Formation. These latter three wells were thought to define the western limits of economic Leduc production; indeed all of the follow-up reef wells (with the exception of 16-18 and 1-19), were located updip and to the east (Figures 4 and 6). Note that wells 16-18, 1-19 and 8-19 were probably drilled more in order to evaluate land holdings than with high expectations of encountering full Leduc reef.

The top of the Ireton Formation is also about 25 m higher across the raised rim than above the reef interior (Figure 6b). The thickness of the Ireton interval is relatively uniform on-reef, 38 to 44 m, with the exception of a 32-m thickness at the 3-32 well . These relationships suggest that, on the whole, the top of the Duhamel complex was relatively planar at the end of Leduc time and that the postulated raised rim is a secondary compactional feature. The slight variations in the thickness of the Ireton interval could partially reflect the original buildup morphology.

Principally as a consequence of differential compaction between reef and off-reef facies, overlying strata are draped across the Duhamel complex. In Figure 6, the Ireton, Wabamun and Mannville are shown to be up to 75, 20 and 15 m, respectively, higher on-reef than off-reef. Thus, significantly greater drape is observed below the pre-Cretaceous subcrop, that is, below the Wabamun, than above. This relationship is due to the erosion of a thick section of upper Paleozoic and Mesozoic strata prior to the onset of Cretaceous deposition. Significant rates of compaction within the Woodbend Group (which resulted in drape within the Cretaceous section), were not reestablished until the weight of the Cretaceous strata exceeded that of the eroded sediment (O'Connor and Gretener, 1974).

2-D SEISMIC DATA

The approximate location of the normal-polarity seismic line (Figures 7 and 8) is shown in Figure 4. These 12-fold, unmigrated, dynamite data were recorded with a 35-m group interval. In Figure 9, a segment of the data is correlated with the 8-30-45-21W4 synthetic seismogram in support of our interpretation.

The seismic image of the reef (traces 71 to 151), as shown on Figures 7 and 8, is bounded by the Cooking Lake (base of reef) and Leduc events, attaining a maximum

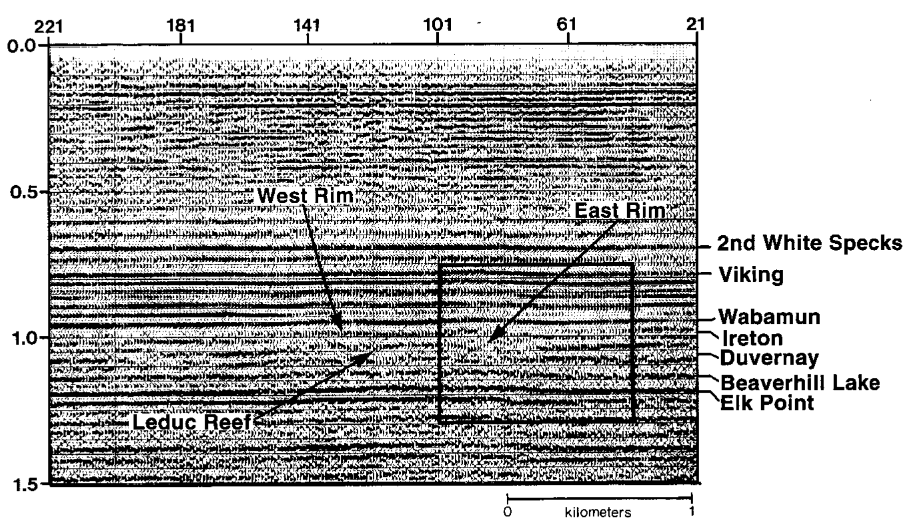

Fig. 7. Normal-polarity seismic section, Duhamel study area. The Leduc appears to exhibit a raised peripheral rim. It is estimated to be about 13 ms (~25 m) higher above the postulated raised rim (traces 85 and 135) than above the structurally low reef interior (trace 110). The Ireton, Wabamun and Viking events are estimated to be higher by about 13 ms (~25 m), 8 ms (~10 m) and 5 ms (~6 m), respectively.

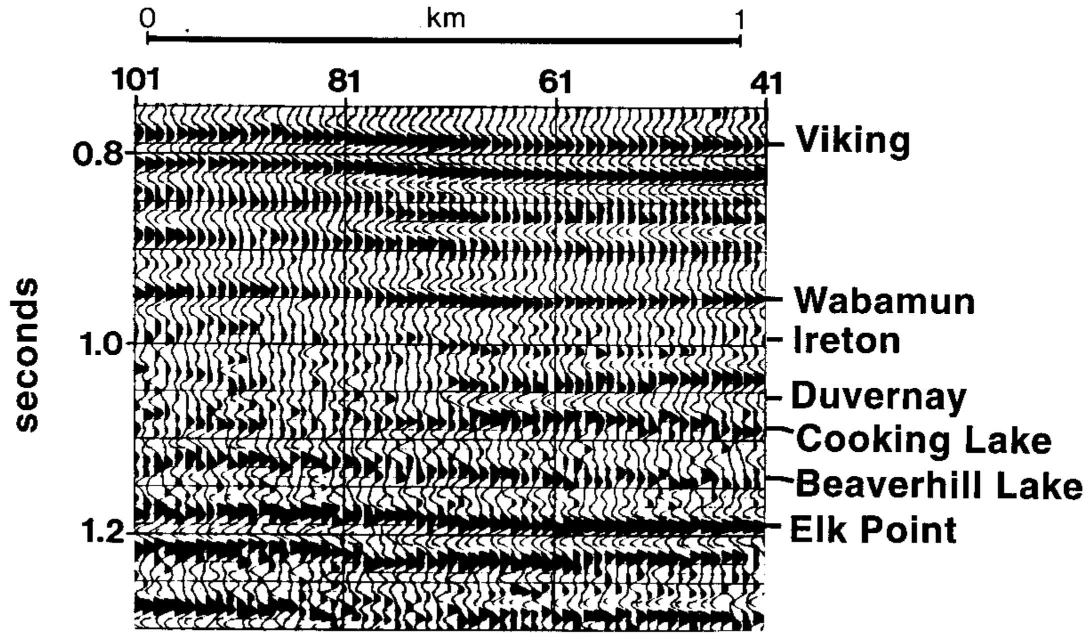

Fig. 8. Blow-up of the boxed portion of Figure 7.

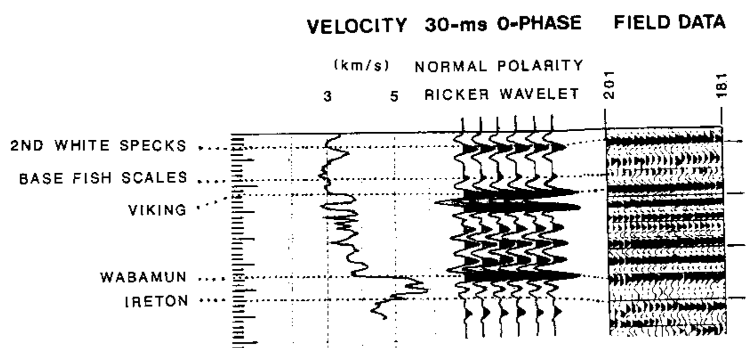

Fig. 9. A comparison of the field data and a 1-D synthetic seismogram for the 8-30-45-21W4M offreef well; courtesy of Geophysical Microcomputer Applications (GMA) Ltd., Calgary.

time-thicknesses on the order of 100 ms (~250 m). Of particular interest are the patterns of relief along these two reflections. More specifically, note that the Leduc is about 13 ms (~25 m) higher above the postulated raised rim (traces 85 and 135) than above the structurally low reef interior (trace 110). The pattern of time-structural relief observed across the top of the Duhamel complex is thought to be indicative of the morphology of the Duhamel complex and is not attributed to lateral velocity variations within the post-reef strata (Brown and Anderson, 1991).

It is interesting to note that the Cooking Lake reflections are pulled up to a greater degree beneath the interior of the reef (15 ms at trace 110) than beneath the structurally elevated rim (10 ms at trace 135). This is entirely consistent with the observation that reef margins are generally more porous than the reef interiors and typically exhibit lower seismic velocities. Indeed given that the reef is on the order of 100 ms thick, the 5 ms difference in time-structural pull-up could be accounted for by an average reef-rim velocity 5% lower than that of the reef interior facies. A similar pattern of time-structural relief is observed along the underlying reflections suggesting that, in the

Duhamel area, the Cooking Lake Formation was relatively planar at the time the Leduc was deposited.

Significant time-structural relief is also observed along post-reef horizons. For example, the Ireton, Wabamun and Viking events are up to 40 ms (~75 m), 12 ms (~20 m) and 10 ms (~15 m), respectively, higher on-reef than off-reef. The Leduc, Ireton, Wabamun, and Viking are interpreted to be respectively 13 ms (~25 m), 13 ms (~25 m), 6 ms (~10 m), and 4 ms (~6 m) higher above the rim than above the interior. The observation that the Leduc and Ireton are effectively time-structurally parallel and lower across the reef interior than above the rim, supports the thesis that the raised rim is mostly a secondary compactional feature. If the rim were mostly a primary feature, the Ireton would be thicker and higher across the reef interior. The example seismic data suggest that on the basis of morphology, Duhamel can be subdivided into a structurally low interior and an elevated periphery. On the example seismic line, the periphery of the reef complex appears to be elevated by about 25 m relative to the interior of the reef.

VSP, CONVERTED-WAVE, AND 3-D SEISMIC DATA

An initial look at some 3-D data and a VSP multicomponent dataset from the Duhamel field seem to confirm the image of a reef with a raised periphery around a structurally lower interior. Study of these datasets has only just begun at this time but they lend preliminary support to our interpretation. A splice of 3-D and VSP P-wave sections (Figure 10) gives a clear indication of a draping Wabamun over peripheral rims on both sides of a lower reef interior. Events that we interpret as Woodbend (Ireton, Leduc, Duvernay) seem to confirm this and deeper reflectors (Beaverhill Lake; Elk Point) appear to show the same differential pull-up pattern mentioned above, i.e., greater pull-up below the reef interior (relatively more compacted) than below the rims. A first look at some converted-wave (P-SV) VSP data from the Duhamel area (Figure 11) shows promise of providing further clarity to the interpretation and we plan to pursue this study in the immediate future.

DISCUSSION AND CONCLUSIONS

The consideration of compaction in carbonate rocks is important and much remains to be learned about it. There is significant disagreement in the literature. Many carbonate sediments, including carbonate mud, have been typically interpreted to be relatively uncompactable (e.g. Pray, 1960; Bathurst, 1975; Ricken, 1986). When restoring sections (backstripping) in some basin-analysis modelling studies, the burial compaction of carbonates is interpreted to be essentially zero, with the reduction of porosity in the carbonates attributed solely to the addition of cement from an outside source (e.g. Bond and Kominz, 1984). However, Shinn et al. (1977) and Shinn and Robbin (1983) showed through experiments that some Recent carbonate sediments (originally mud-supported) could be compacted up to 75% without showing much lithologic evidence thereof. Thus, it is possible that some ancient carbonates could have been similarly compacted prior to lithification without showing much evidence of such compaction.

In this study, the morphology of the Duhamel reef has been described and, on the basis of the 2-D seismic data and geologic (well log) cross-sections, it appeared to us that the relatively small Duhamel exhibits a raised peripheral rim (Brown et al., 1996). A preliminary examination of VSP and 3-D data seems to confirm this view. By analogy with other larger and similar-sized Devonian reefs in western Canada, we suggest that the raised rim at Duhamel is principally attributable to differential compaction of facies within the reef. Other case studies would be desirable in order to add to our knowledge of what types of carbonates are most susceptible to compaction and to provide more details on the timing and mechanisms of compaction. Our intent is to carry out a more extensive analysis of converted-wave, 3-D and VSP data in order to clarify this interpretation further.

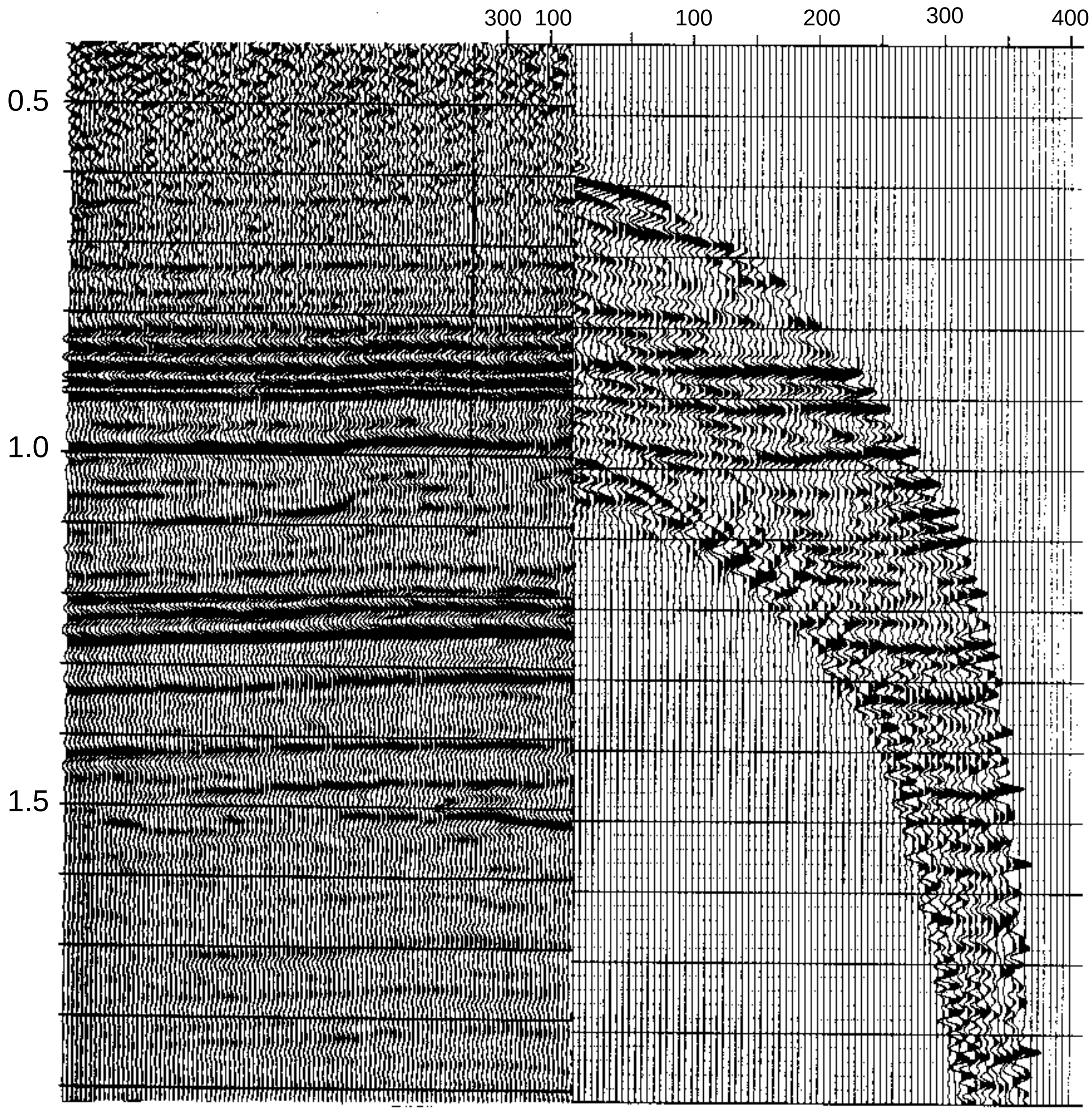

Fig. 10. Tie between 3-D (left) and VSP (right) P-wave sections over Duhamel. Seconds are plotted on the vertical axis and metres on the horizontal axis. The strong event just above 1.0 s, which we interpret as the Wabamun, appears to drape over peripheral rims on both sides of the reef. Woodbend events between 1.0 and 1.1 s also seem to show rims that are higher than the reef interior. Deeper horizons around 1.2 to 1.3 s (Beaverhill Lake; Elk Point) appear pulled up more below the relatively more compacted reef interior than below the rims.

The seismic data also suggest that the facies within the reef rim have lower seismic velocities than those within the structurally lower reef interior. This is wholly consistent with the observation that raised rims are generally more porous than the encircled and

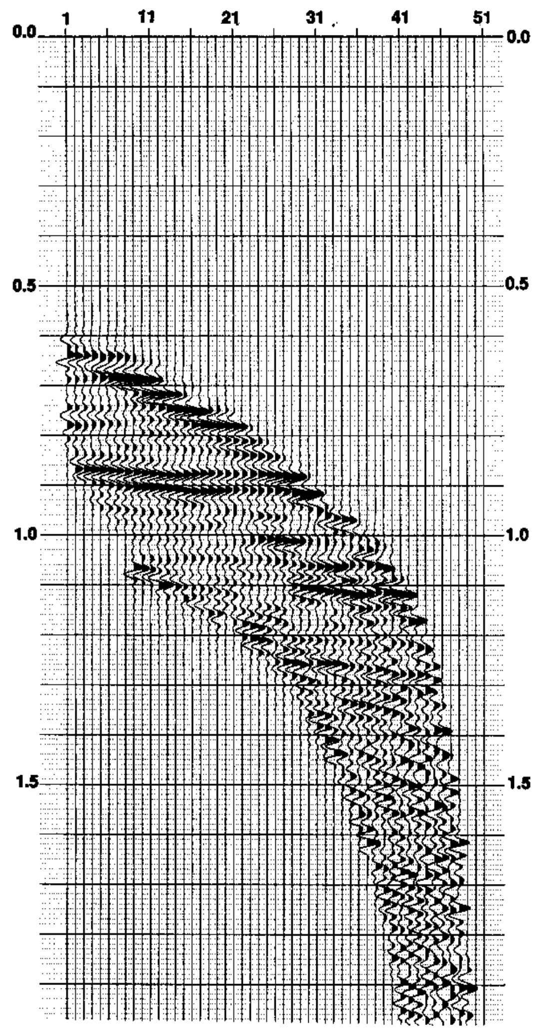

Fig. 11. Common-conversion-point map of the radial component of a VSP from Duhamel processed at a V_P/V_S ratio of 2.0. This represents just a first attempt to incorporate converted-wave (P-SV) data over the reef. Nevertheless, there are indications in the data of some of the features seen above in the P-wave data. The draping events around 0.9 s are initially interpreted as Cretaceous horizons and those around 1.1 s as Woodbend reflectors.

structurally lower lagoon and leads one to conclude that they should constitute a preferred well-completion site. We believe that optimal hydrocarbon recovery from such bioherms would likely be realized if all producing wells were drilled into the raised rims. Data acquisition across similar reefs, prior to drilling, should ideally not stop at 2-D seismic, and should be done with a view to ensuring that the complete raised rim is mapped and could thus be targeted for the drill.

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