01 Jan 1991

Differential Compaction of Winnipegosis Reefs: A Seismic Perspective

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Recommended Citation

N. L. Anderson and E. K. Franseen, "Differential Compaction of Winnipegosis Reefs: A Seismic Perspective," *Geophysics*, vol. 56, no. 1, pp. 142-147, Society of Exploration Geophysicists, Jan 1991.
The definitive version is available at https://doi.org/10.1190/1.1442951

GEOPHYSICS, VOL. 56, NO. 1 (JANUARY 1991); P. 142–147, 8 FIGS.

Differential compaction of Winnipegosis reefs: A seismic perspective

N. L. Anderson* and E. K. Franseen*

ABSTRACT

Winnipegosis Formation reefs in southern Saskatchewan are typically encased in the thick, apparently incompressible salts of the Prairie Evaporite. These reefs are characterized by raised rims and reverse drape along the top of the salt. Both features, clearly visible on seismic data, are primarily due to postdepositional compaction. The rims developed principally as a result of differential compaction within the different reef environments; the structural low at the Prairie Evaporite level is attributed to differential compaction between the reef and the encasing salt. If these salts are effectively incompressible, the rim and lagoonal facies are estimated to have been compacted by at least 30 and 44 percent, respectively.

This paper illustrates the usefulness of seismic data to separate postdepositional compaction features from primary features to determine the primary morphology of a reef better and to determine the relative amounts of postdepositional compaction within the different reef environments. The degree to which the reef rim and interior areas were compacted can be estimated based on interpretation of the example seismic line. The methods and results of this paper allow for better definition of prime target areas for potential hydrocarbon reservoirs within the reef proper.

INTRODUCTION

Upper Winnipegosis Formation buildups are scattered throughout the Middle Devonian Elk Point basin (Figure 1). These dolomitized carbonates have been variously described as reefs or as mounds, due to an apparent absence of framebuilding or binding organisms in cores (Gendzwill, 1978; Gendzwill and Lundberg, 1989; Gendzwill and Wilson, 1987; Walter, 1969; Jones, 1965; Perrin, 1982; Precht, 1983; Reinson and Wardlaw, 1972; Wardlaw and Reinson, 1971; and Wilson, 1984). The Upper Winnipegosis buildup (herein referred to as a reef) exhibits a raised rim on the example seismic data, mostly a secondary compaction characteristic of Devonian reefs in western Canada (Anderson and Brown, 1987; Anderson et al., 1986; Anderson et al., 1989; Brown et al., 1990; Mossop, 1972; and Wirnkar and Anderson, 1989). The raised rim could also reflect an original buildup morphology with a margin topographically higher than the interior, possibly due to framebuilding organisms and/or submarine cementation.

The Winnipegosis reef example is encased in the salts of the

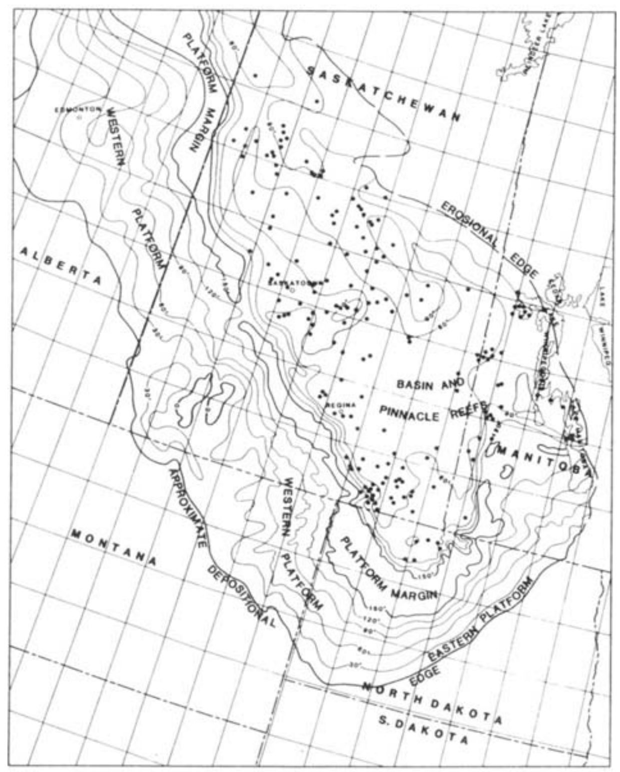

FIG. 1. Regional map showing the Elk Point basin, the thickness of the Winnipegosis, and some known mounds (dots). Contour interval, 30 ft (9.1 m) (Ehrets and Kissling, 1987).

Manuscript received by the Editor March 9, 1990; revised manuscript received June 20, 1990.
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Prairie Evaporite Formation (Figure 2) which appear to be relatively incompressible compared to carbonates. The top of these salts, on the example seismic line, is structurally lower on top of the reef than in the adjacent offreef areas. This structural low and the pattern of relief as the beds are traced across the top of the reef itself are consistent with the thesis of postdepositional compaction of the reef.

If the Prairie Evaporite was uniformly deposited in the study area, as appears to be the case, then the relief observed across the tops of the reef and the salts are estimates of differential compaction within the different reef environments, and between the reef and the salts, respectively. If the salts are assumed to be effectively incompressible (as a minimizing assumption), then the extent to which this reef was compacted can be estimated quantitatively.

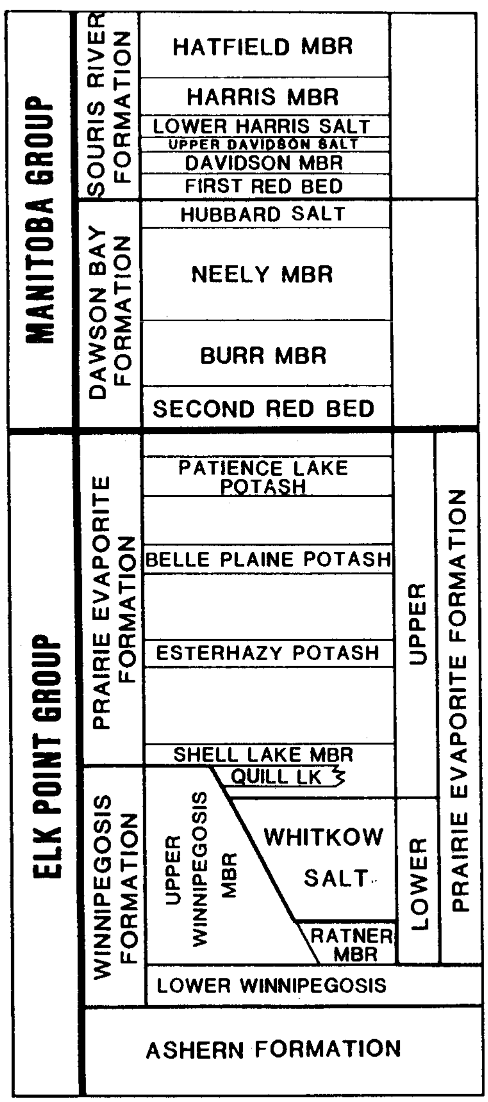

FIG. 2. Detailed stratigraphy of the Elk Point group of southern Saskatchewan (modified after Gendzwill and Lundberg, 1989).

THE ELK POINT GROUP

The Elk Point Group in Saskatchewan (Figure 2) is subdivided into three formations: (1) the Ashern, a basal shale unit; (2) the Winnipegosis, a dolomitized carbonate unit; and (3) the Prairie Evaporite, a thick unit of rock salt.

The Ashern is typically composed of thin-bedded red, green, and grey shale, dolomitic siltstone, and argillaceous dolomite. This unit was deposited unconformably above Silurian strata in a shallow marine environment during the initial transgression of the Devonian sea across southern Saskatchewan. The Ashern has an unconformable contact with the overlying Winnipegosis (Perrin, 1982).

The Winnipegosis consists of platform (lower Winnipegosis), reef (upper Winnipegosis), and interreef (Ratner member) carbonates (Figure 2). The lower Winnipegosis is described as a dolomitized fossiliferous packstone (Jones, 1965) that has a gradational upper contact. The overlying upper Winnipegosis reefs are composed of dolomitized carbonates (Gendzwill and Wilson, 1987) that Wilson (1984) subdivided into four main units from base to top: (1) peloidal grainstone; (2) laminated carbonate mudstone; (3) an "organic" unit; and (4) a fringing cap unit (Figure 3). The organic (stromatoporoids, oncolites, and shell fragments) and fringing cap (pisolites, peloids, and intraclasts in micrite matrix) units are thought to have been deposited as reef-margin facies in relatively high-energy environments around the outer edge of the reef. The laminated carbonate mudstone (locally with anhydrite in the upper portion) was deposited in an interior (lagoon to sabkha?) environment, behind and likely sheltered by the organic and fringing cap units.

The structural relief observed across the top of the reef in the seismic line in Figures 4 and 5 is largely a result of the differential compaction of these different reef facies. As evidenced by the example seismic data, the reef in the study area attains a maximum thickness, including the underlying platform facies, of about 95 m and is about 1.4 km wide. The interreef Ratner member (Figure 3), described as carbonate mudstone and/or anhydrite, is about 45 m thick (including the thickness of the underlying platform facies).

The Prairie evaporite overlies the Winnipegosis formation and, in the study area, attains maximum thicknesses of about 140 m in areas adjacent to the reefs (Gendzwill and Lundberg, 1989).

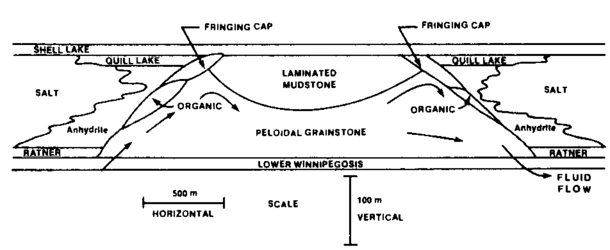

FIG. 3. Conceptual model of a Winnipegosis mound showing the four principal units of the upper Winnipegosis: peloidal grainstone, laminated mudstone, an organic unit, and fringing cap unit (Gendzwill and Lundberg, 1989).

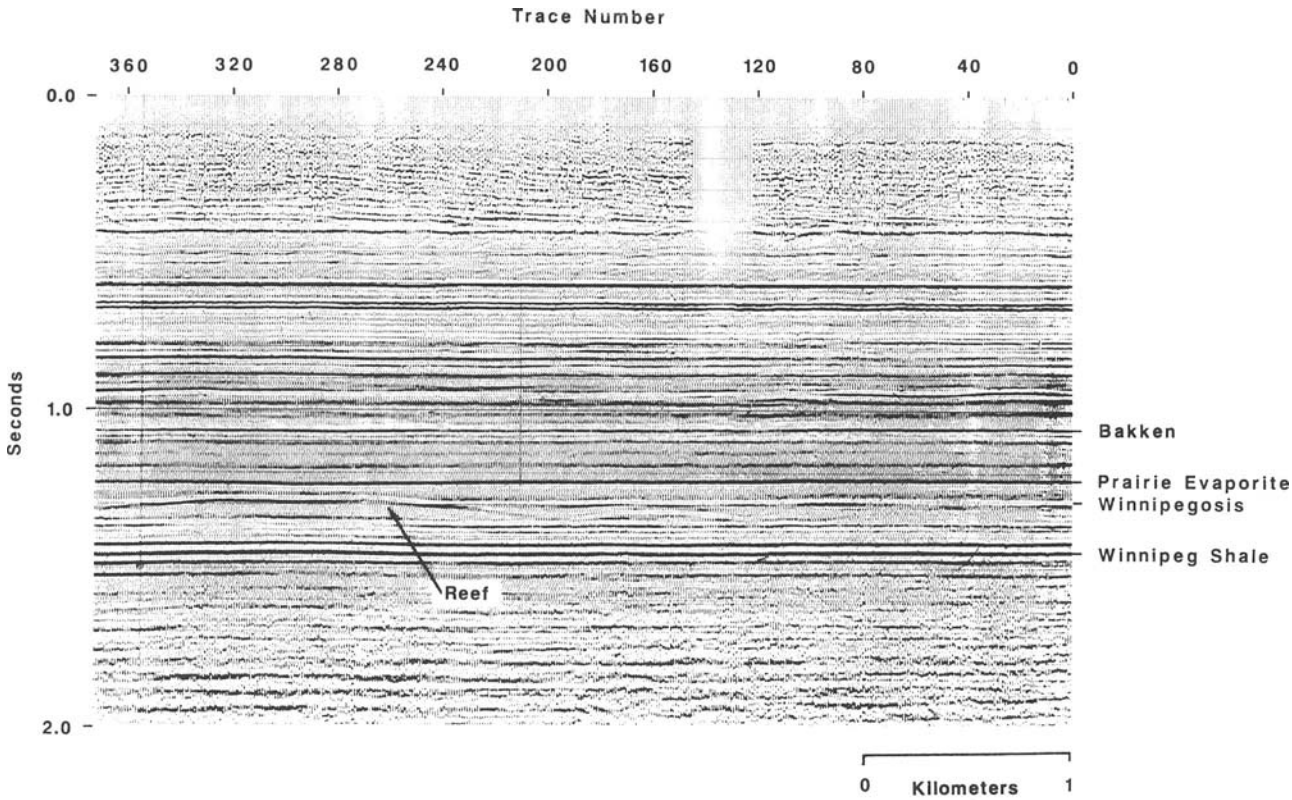

FIG. 4. Seismic line across a Winnipegosis reef (traces 240–360 at about 1.3 s).

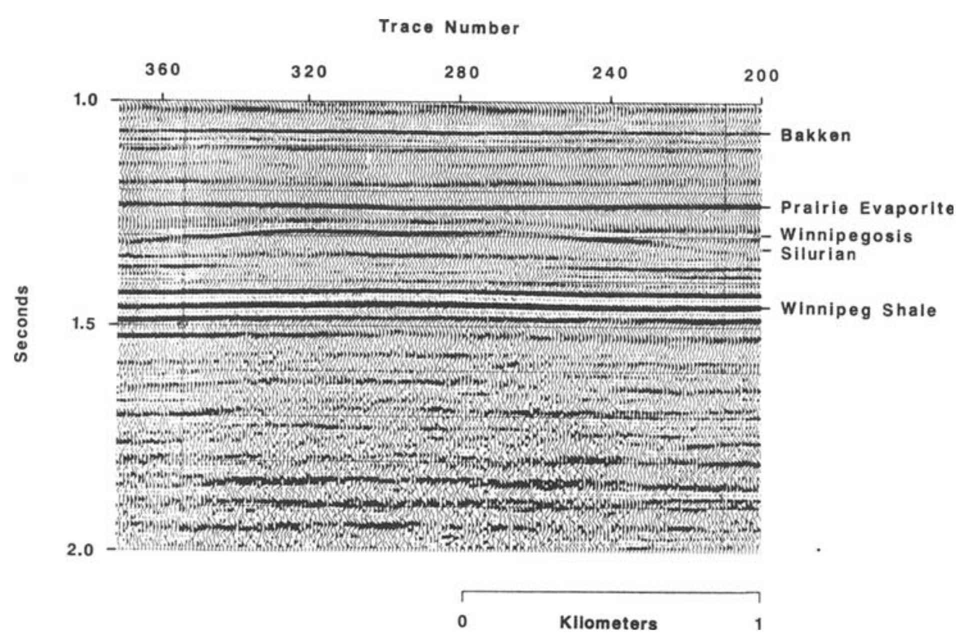

FIG. 5. Enlargement of Figure 4. The raised rim (traces 260–275 and 310–330) and the interior backreef environment (275–310) are clearly visible.

EXAMPLE SEISMIC LINE

The interpreted, reverse polarity, example seismic line and enlargement of the same, are presented as Figures 4 and 5, respectively. These 12-fold, dynamite data were acquired using a 25 m group interval. In Figure 6, these data are correlated to a 1-D synthetic seismogram for the 13-24-02-3W217 well (about 6 km off-line). These data have been hand inverted and a compatible depth-velocity cross-section has been created (Figure 7). The model in Figure 7 also supports the thesis of differential compaction within the reef and illustrates many of the interpretational concepts discussed below.

The reflection from the top of the Winnipegosis (base Prairie Evaporite) is high amplitude and can be confidently correlated (Figures 4 and 5). The reflection from the base is not easily correlated, being effectively masked by the Silurian (base Ashern) event. Despite the absence of a reflection from the base of the Winnipegosis, the thickness of the Winnipegosis Formation can be estimated. For example, if the thickness of the Ashern, online, is assumed to be 16 m as in the 13-24-2-3W2M well, then the thicknesses of the Winnipegosis (including the Ratner where present) at traces 266, 296, and 180 are calculated to be 93, 85, and 60 m, respectively. These estimates are based on Winnipegosis-Silurian intervals of 41 ms, 39 ms, and 28 ms, respectively, and average Ashern and Winnipegosis velocities of 5300 m/s. The reef (traces 240 to 360), is characterized by (1) positive relief at the Winnipegosis level (20 ms/45 m at trace 266; 16 ms/36 m at trace 296) relative to adjacent offreef locations; negative relief along the Prairie Evaporite event; and (3) pullup along pre-Devonian horizons (8 ms at trace 296; 5 ms at trace 266). Note that the reef exhibits a well-defined raised rim (traces 260–275 and 310–330) and a 4 ms/9 m structurally lower interior area (traces 275–310).

The reflections from the top and base (top Winnipegosis) of the Prairie Evaporite are high amplitude (Figures 4 and 5). On the basis of this interval, the thicknesses of the Prairie Evaporite at traces 180, 266, and 296 are estimated to be 140, 88, and 95 m, respectively. Note that the Prairie Evaporite event is low across the reef (7 ms/20 m at trace 296 and 4 ms/12 m at trace 266) relative to trace 180 in an offreef area, presumably as a result of differential compaction within the reef and due to the relative incompressibility of the salts.

The two lowest events identified on the seismic section are the reflections from the Winnipeg shale and the underlying Silurian. All three events are pulled up by about 7 ms beneath the reef interior (trace 296) and about 5 ms below the raised rim (trace 266). These estimates are consistent with reef velocities on the order of 5300 m/s, salt velocities on the order of 4200 m/s, and the geologic model of Figure 7.

DISCUSSION

The Winnipegosis reef example of this paper is characterized by (1) a pronounced raised rim and a structurally lower interior lagoon; (2) negative drape along the Prairie Evaporite horizon; and (3) pullup at prereef levels (Figures 4, 5, and 7). The raised rim, the structurally lower lagoon, and the negative drape at the Prairie Evaporite level are attributed mostly to differential compaction within the reef, possibly enhancing original depositional morphologies of the reef environments and/or cementation (or rigid framebuilding) characteristics of the different facies, and to the relatively incompressible nature of the encasing salt. These structural features are illustrated in the depth-velocity cross-section of Figure 7.

Figure 8 is a reconstructed version of the geologic model, created by flattening the top of the Prairie Evaporite. This reconstructed model removes the effects of the post-Elk Point compaction of that portion of the reef above the Ratner member. Several interesting relationships can be deduced by comparing these before- and after-decompaction models.

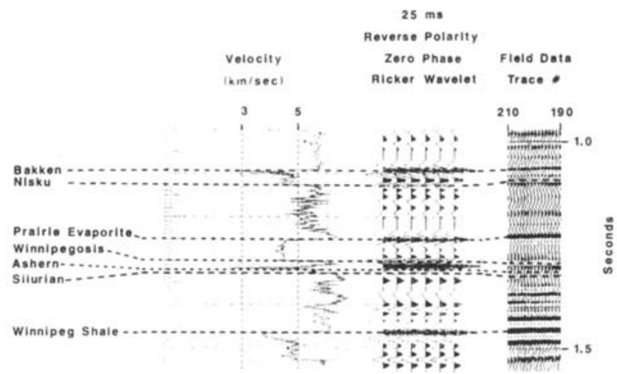

FIG. 6. Correlation of the synthetic seismogram for the 13-24-02-3W2M well and the seismic data.

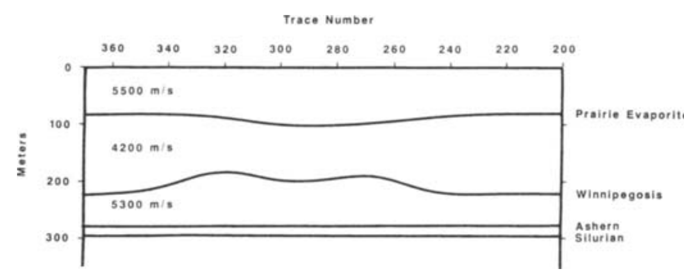

FIG. 7. Geologic model for the Elk Point. This geologic section is an inverted representation of the seismic line of Figure 5. Datum is at 1.2 s.

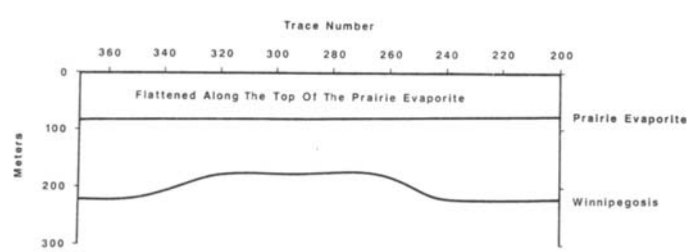

FIG. 8. Reconstructed version of the Elk Point model, created by flattening Figure 7 along the Prairie Evaporite horizon. Ideally this model represents the morphology of the reef at the end of Prairie Evaporite time.

(1) The interior of the reef at the end of Prairie Evaporite time was about 45 m higher than the interreef Winnipegosis (top Ratner). It is now about 25 m higher, indicating that these interior reef facies (laminated carbonate mudstone unit) have been compacted by at least 44 percent. This represents a minimum estimate in that some compaction probably occurred prior to the end of Prairie Evaporite time. Gendzwill (1978) describes differential thickening of salt layers over Winnipegosis mounds and attributes these features to early compaction within the reef.

(2) The rim of the reef at the end of Prairie Evaporite time stood about 50 m above the interreef Ratner deposits. It is now some 35 m higher than the Ratner, indicating that the rim was compacted by about 30 percent. This is also a minimum estimate, since some compaction probably occurred prior to the end of Prairie Evaporite time.

(3) The decompaction exercise indicates that at the end of Prairie Evaporite time the interior of the reef was slightly lower (5 m or less) than the reef rim, thus illustrating the usefulness of this method to determine original reef morphology. From compaction, the reef interior area is now about 10 m lower than the reef rim.

These estimated compactional factors are probably reasonable estimates of the overall compaction of the reef if the salts are indeed incompressible and have not undergone selective dissolution along their on-reef trace, if the Ratner and basal reef were compacted to a similar degree, and if most of the compaction of the Winnipegosis occurred after the deposition of the Prairie Evaporite. Most likely, some compaction occurred prior to the end of Prairie Evaporite time, meaning that our compaction factors represent minimum estimates.

Mossop (1972), in a study of the Devonian Redwater Leduc reef complex, pointed out that compaction by stylolitization through pressure solution of carbonate mineral matter was an important process resulting in volume loss in carbonate rocks. He reported rim and reef-interior compactional factors of 13 and 24 percent, respectively, based on measurements of stylolites. Mossop (1972) cautioned that the percentages were likely minimum estimates and that numerous factors could bias their reliability to indicate the amount of carbonate removed. The different values in Mossop's estimates of compaction are also attributable to the differences in susceptibility to compaction of the reef rim and reef interior facies. Our study also confirms the differences in compactibility of the reef rim and reef interior facies, probably at least partly due to the cementation or lithification history (early cements are more likely in the reef rim facies), the selective dolomitization (possibly more dolomite in the interior reef area related to the anhydrite), or the presence of relatively more noncarbonate mud (or other insoluble material) in the reef-interior facies (Wilson, 1984). Core examination of the different reef environments may confirm which, if any, of the above were important factors for the compactional differences of the reef environments.

Much remains to be learned about the compaction of carbonate sediments. Many carbonate sediments, including carbonate mud, have been typically interpreted to be relatively noncompactible (e.g., Pray, 1960; Bathurst, 1975; Ricken, 1986). When restoring sections (backstripping) in some basin analysis modeling 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 experimentally that some Recent carbonate sediments (originally mud-supported) could be compacted up to 75 percent without showing much lithologic evidence. Thus, it is possible that some ancient carbonates could have been similarly compacted prior to lithification without revealing much lithologic evidence of such compaction.

The consideration of compaction in carbonate rocks is important, but it may require the integration of several methods to derive an accurate estimate for the amount of compaction in ancient carbonate rocks. Our study, utilizing seismic data, indicates that some carbonates, similar to those of the Redwater reef, were compacted by as much as 45 percent. Other case studies will add to the information on what types of carbonates are most susceptible to compaction and, importantly, more details on the timing and mechanisms of compaction.

SUMMARY

On seismic data, Winnipegosis reefs typically exhibit (1) a raised reef rim and a structurally lower interior; (2) negative drape at the Prairie Evaporite level; and (3) velocity pullup along prereef horizons (Anderson et al., 1986; Anderson and Brown, 1987; Brown et al., 1990; Gendzwill, 1978). Features 1 and 2 are attributed to the postdepositional compaction of the reef and to the relatively incompressible nature of the salt. The compaction is likely enhancing original reef morphology as well as lithologic and cementation differences between the different reef facies. The observed pullup in horizons below the Winnipegosis reef is due to both the velocity contrast between the reef and the encasing salt, and the negative drape along the top of the Prairie Evaporite. As illustrated on our example, velocity pullup beneath the rim is less than beneath the reef interior, probably indicating that the rim facies are more porous. Thus, even though the reef rim areas may have been affected by early cements, the cementation either did not entirely occlude porosity or there was postdepositional dissolution in the reef rim facies that created effective secondary porosity and permeability. Therefore, care should be taken to ensure that wells are drilled into the structurally elevated, relatively more porous and permeable reef rim areas (and possibly forereef areas) that are more likely to be petroleum reservoirs.

ACKNOWLEDGMENTS

We gratefully acknowledge constructive reviews by Don Gendzwill and Paul Enos which led to substantial improvement of the manuscript.

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