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GEOPHYSICS, VOL. 54, NO. 2 (FEBRUARY 1989); P. 148-157, 14 FIGS.

Seismic signature of a Swan Hills (Frasnian) reef reservoir, Snipe Lake, Alberta

N. L. Anderson*, R. J. Brown‡, R. C. Hinds§, and L. V. Hills‡

ABSTRACT

Swan Hills formation (Frasnian stage) carbonate buildups of the Beaverhill Lake group are generally of low relief and considerable areal extent and are overlain by and encased within the relatively high-velocity shale of the Waterways formation, which thins but does not drape across the reefs. Consistent with this picture, prereef seismic events are not significantly pulled up beneath the reefs nor are postreef events draped across them. Indeed, the seismic images of these reefs are effectively masked by the high-amplitude reflections from the overlying top of the Beaverhill Lake group and underlying Gilwood member and cannot be distinguished from those of the basin fill. However, it is possible to identify the reefs indirectly on conventionally processed seismic sections because the image of the encompassing Beaverhill Lake/Gilwood interval varies significantly from onreef to offreef positions.

One such Swan Hills formation field at Snipe Lake has an areal extent of about 90 km^2 and typical reef relief of some 50 m above the platform facies. This reef is shown to be recognizable on three example seismic lines from interference phenomena that vary laterally in association with the lateral variations in thickness of the Swan Hills formation. These phenomena include an offreef peak that is one half-cycle below the Beaverhill Lake reflection trough and that dies out laterally going onreef, a tendency for the amplitude of the Gilwood event to decrease beneath the reef, and thinning of the order of 5 ms of the onreef section relative to the offreef section. Through seismic modeling, these seismic-image characteristics are seen to be predictable geophysical manifestations of the inherent geologic variations.

INTRODUCTION

Western Canadian Devonian reefs fall into two broad categories based on their environment of deposition: evaporitic-basin types and shale-basin types. Typically, significant time-structural relief due to drape (frequently accentuated by reef-focused salt dissolution) and lateral variations in average velocity (causing pullup or pushdown) are associated with both evaporitic-basin and shale-basin reef types. In addition, reefs and basin fill can often be differentiated on the basis of their respective seismic images. For example, anomalies in the otherwise laterally uniform seismic images of basin fill are diagnostic of most western Canadian Devonian reefs. However, the seismic signatures of Swan Hills reefs are much subtler (Bubb and Hatlelid, 1977; Anderson, 1986; Anderson and Brown, 1987; Bower et al., 1987), and conventional seismic indicators are essentially useless in Swan Hills reef exploration. The Snipe Lake field (Figures 1 and 2) provides us with a typical example of the roughly ten major Swan Hills reef complexes of west-central Alberta. Time-structural relief is not a very significant component of the seismic signature of this reef nor can the seismic image be differentiated readily from that of the basin fill (Anderson, 1986; Anderson and Brown, 1987).

Nevertheless, we intend to show that at least some Swan Hills reefs may be recognized on conventionally processed seismic sections if one knows what distinguishing characteristics to look for. We use knowledge of the geology to model what should be seen on seismic sections, onreef and offreef, and use the resulting seismic image as justification for the interpretation.

Throughout this paper, references of the type "the Beaverhill Lake reflection or event" will always imply the reflection

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from the top of the specified unit, in this example, the Beaverhill Lake group—which also happens to be the top of the Waterways formation in the study area.

GEOLOGIC BACKGROUND

The stratigraphy (Figure 3), sedimentology, and paleontology of the Beaverhill Lake group in the central plains of Alberta have been discussed by Fischbuch (1968a, b), Hemphill et al. (1970), Mountjoy (1980), Wendte and Stoakes (1982), Walls and Burrowes (1985), and Craig (1987). The Beaverhill Lake group of the Frasnian stage consists of marine carbonates, evaporites, and fine clastics and in the vicinity of the Snipe Lake reef has been divided into four formations: Fort Vermilion, Slave Point, Swan Hills, and Waterways. The Beaverhill Lake group overlies the Gilwood member of the Watt Mountain formation (Elk Point group) in the study area.

The Gilwood member, a poorly sorted coarse-grained sandstone, is typically 5 to 10 m thick in the vicinity of the Snipe Lake reef. These clastics are underlain by Watt Mountain formation shales and overlain throughout the area by 5 to 10 m of the limy shales and anhydrites of the Fort Vermilion

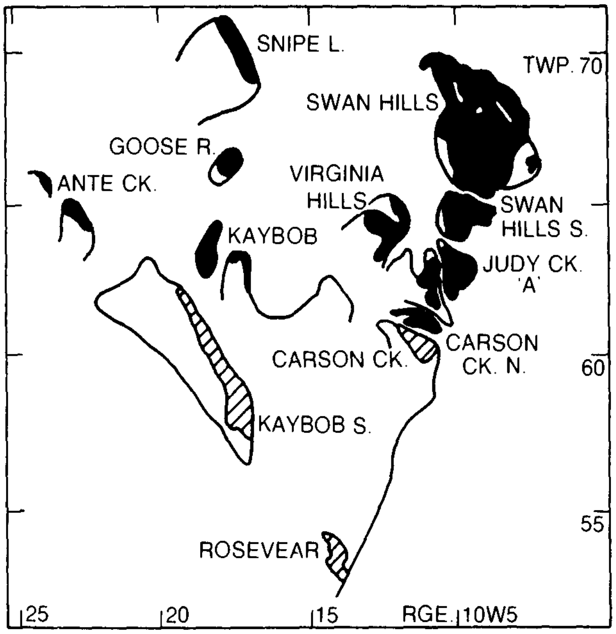

FIG. 2. The boxed area of Figure 1 showing Swan Hills formation reservoirs (after Walls and Burrowes, 1985): limestone (solid black shading) and dolostone (diagonal shading). Not shown are three or four additional dolostone gas reservoirs in the Swan Hills bank south of the area shown.

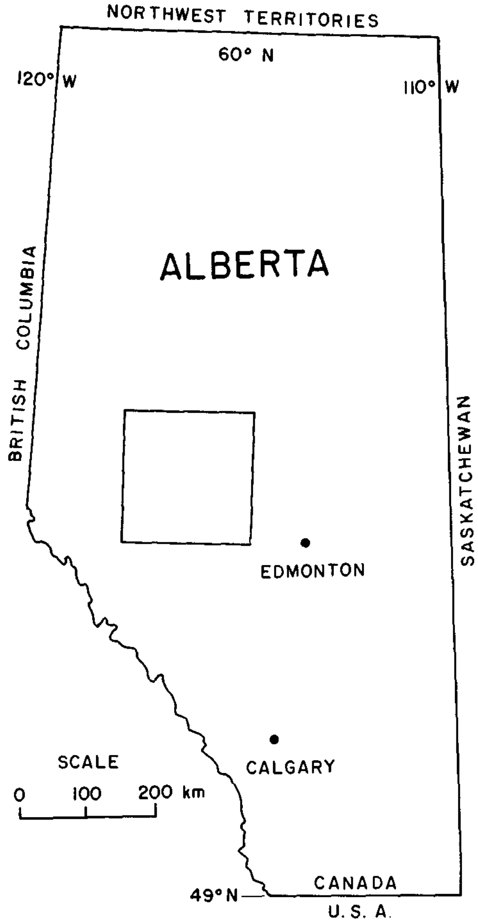

FIG. 1. Location map of Alberta, Canada, showing the general area of Swan Hills reef reservoirs.

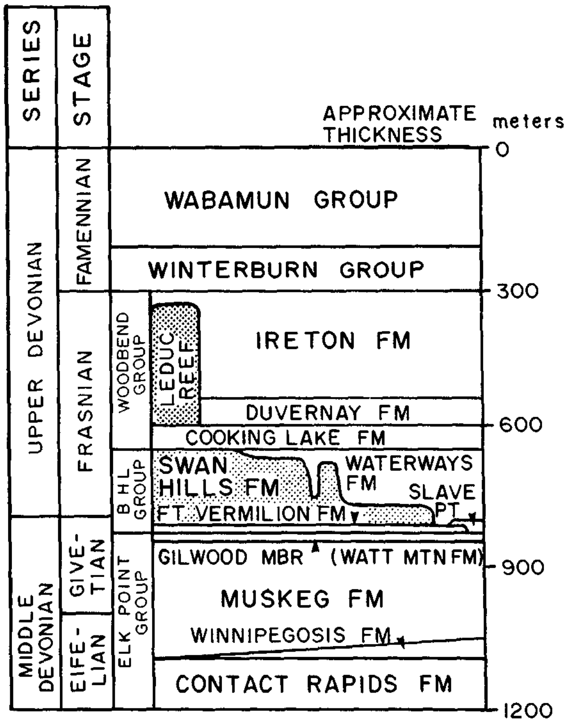

FIG. 3. Devonian stratigraphy of the Swan Hills area of west-central Alberta (modified after Hemphill et al., 1970; Klovan, 1974; Mountjoy, 1980; Craig, 1987, and AGAT Laboratories, 1988); BHL = Beaverhill Lake.

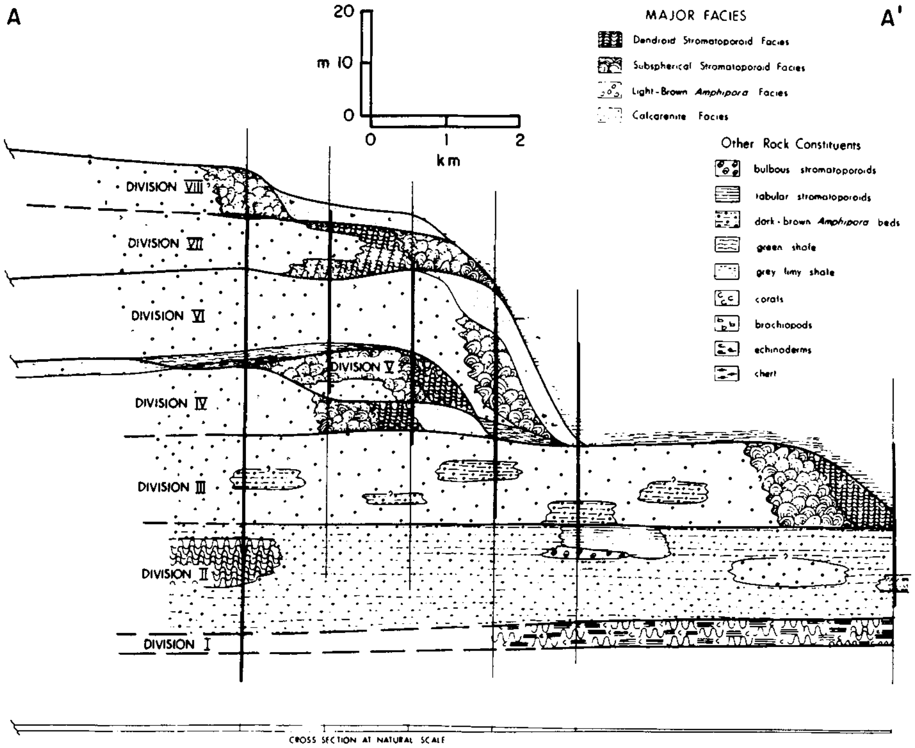

FIG. 4. Stratigraphic cross-section along AA′ (Figure 5) showing Snipe Lake reef complex with the top of the Gilwood member as a datum (modified after Fischbuch, 1968a); thicker vertical lines represent cored sections of wells. From left to right these wells are 10-21-70-18W5, 4-27-70-18W5, 10-27-70-18W5, 4-35-70-18W5, 10-35-70-18W5, and 12-18-71-17W5.

formation (Fischbuch, 1968a, b), the evaporites having formed during an earlier phase of Frasnian regression. During the subsequent marine transgression, conditions conducive to reef growth were established; and the Swan Hills formation carbonate complexes developed on widespread topographic highs.

Fischbuch (1968a, b) described the development of the Snipe Lake reef in five stages: (1) deposition of divisions I to V (Figure 4) with boundaries between divisions representing near termination of reef growth, probably due to shallowing of the sea and submarine erosion; (2) retreat of the sea with erosion of the exposed terrain including the reefs; (3) transgression with deposition of muds around the eroded mounds of divisions I to V; (4) resumption of reef growth (divisions VI to VIII), reefs growing to the southwest over the muds; and (5) reef-growth termination at the end of division VIII following shallowing of the sea.

Wendte and Stoakes (1982) presented an alternative viewpoint, disagreeing particularly with Fischbuch's stage 2, and proposed periodic increases in the rate of transgression to account for the observed changes in reef growth. Regardless of whether there was overall transgression or transgressive events punctuated by periods of regression and exposure of the reefs, Fischbuch's (1968a, b) work provides a model of the reef suitable for evaluating its seismic image.

Figures 4 and 5 are a cross-section and a plan view, respectively, of the Snipe Lake reef. The platform facies (divisions 1 to 3; Fischbuch, 1968a, b) is generally 30 to 35 m thick. The

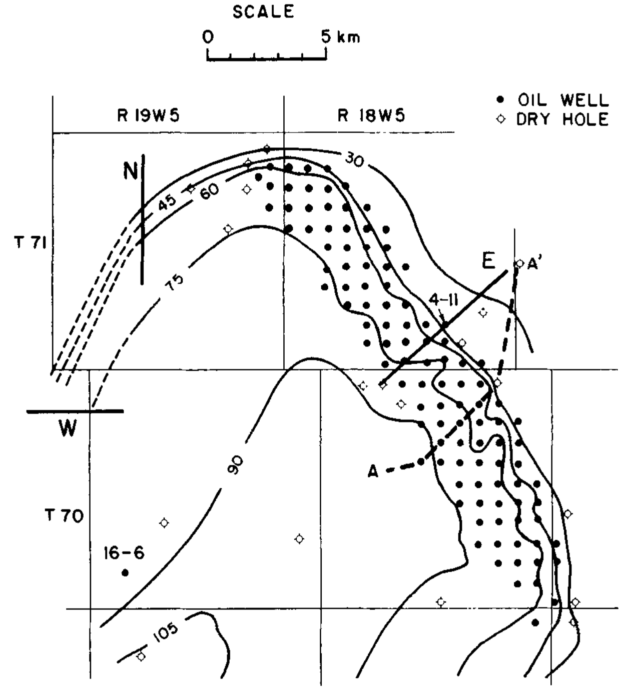

FIG. 5. Isopach map of the Snipe Lake reef complex (modified after Fischbuch, 1968a); the isopach interval is 15 m. The approximate positions of the three example seismic lines of this paper are plotted as E (east), N (north), and W (west). The wells used in the synthetic seismograms (Figures 6, 7, and 11) are labeled as 16–6 (for 16-6-70-19W5) and 4–11 (for 4-11-71-18W5). The 16-6 well was not completed until 1983 and thus was not one of Fischbuch's (1968a, b) control points, accounting for the slight apparent discrepancy in Swan Hills thicknesses.

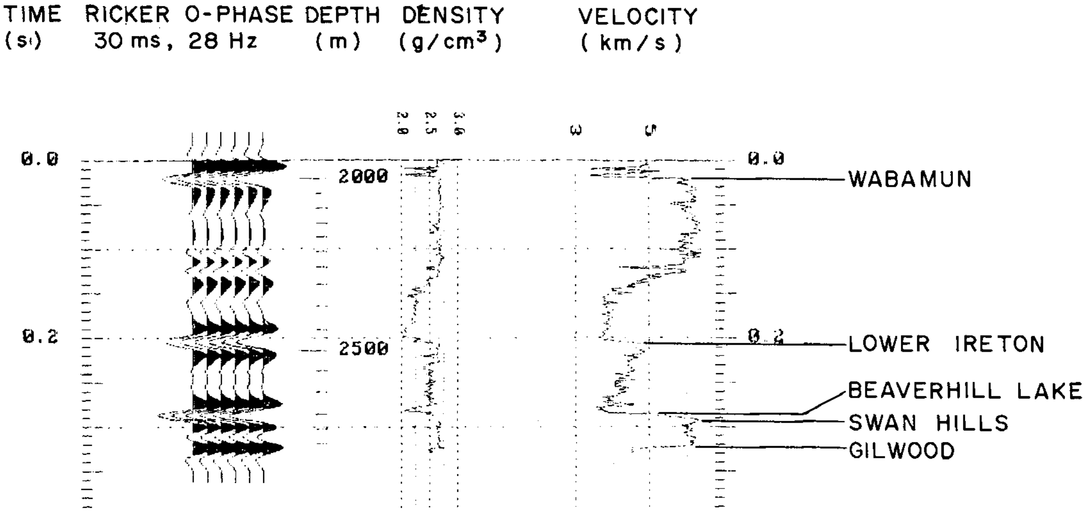

FIG. 6. Velocity log (right), density log (center), and corresponding 1-D synthetic seismogram for the 16-6-70-19W5 well, the location of which is shown in Figure 5 (16-6).

Slave Point (carbonate) formation is considered to be the approximate offreef time-equivalent of the Swan Hills platform facies and may be absent in the vicinity of Swan Hills reefs (Craig, 1987). The reef (including the platform) is seen (Figure 5) to attain a maximum thickness of about 110 m; nearer the reef margins where our three seismic lines are situated (Figure 5), this maximum thickness is more typically 70 to 80 m. The underlying 5 to 10 m of Fort Vermilion limy shales and anhydrites have average interval velocities similar to those of the carbonates. Note also the absence of a reef rim and the broad areal extent of the complex, some 400 km^2. The limy nodular high-velocity shales of the Waterways formation, the deposition of which followed cessation of reef growth, are thinner, but they do not drape over the Snipe Lake reef. The Waterways ranges in thickness from about 100 to 150 m in offreef locations where the Swan Hills formation is absent.

MODELING

As an aid to the interpretation of the example seismic lines, suites of one-dimensional (1-D) and two-dimensional (2-D) synthetic seismograms were assembled using the GMA Stratigraphic Modelling System (Geophysical Micro Computer Applications Ltd., Calgary) and publicly available well logs. (In Canada, virtually all well logs at least one year of age are available.) Figure 6 shows a velocity log and the corresponding 1-D synthetic over more or less full reef thickness. The Beaverhill Lake and Gilwood events have relatively high-amplitude troughs and peaks, respectively, on the reversed-polarity display. Note that in this well the Swan Hills formation is about 95 m thick and the underlying Fort Vermilion formation is 5 to 10 m thick, whereas nearer the reef margins the Swan Hills formation is more typically about 75 m thick (Figure 4).

In Figure 7, a velocity log model and a corresponding 2-D synthetic are shown. The synthetic has been generated using a

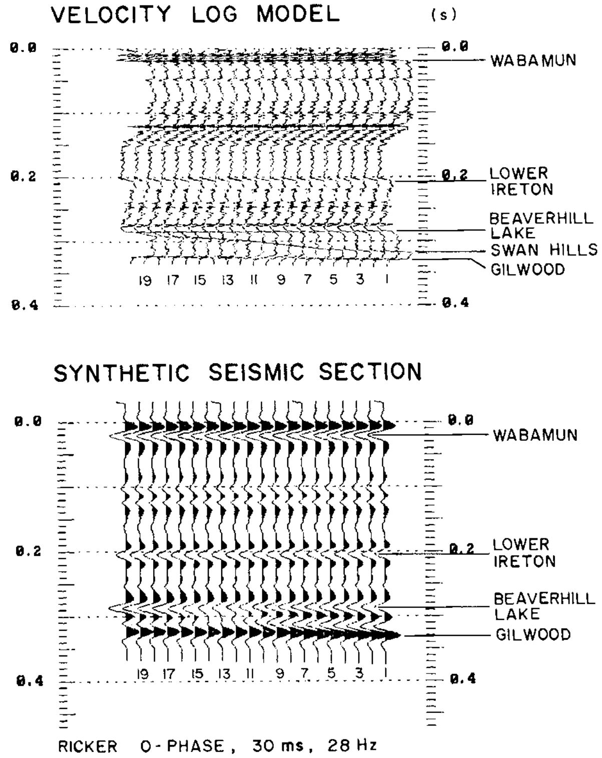

FIG. 7. Velocity log model and corresponding 2-D synthetic seismogram across the margin of the Snipe Lake reef, onreef (left) to offreef (right). The left-hand end-member velocity log is from the 16-6-70-19W5 well (≅95 m of reef); the right-hand end-member log consists of this same 16-6 log edited by the substitution of the Beaverhill Lake portion of the 4-11-71-18W5 well (≅35 m of reef, essentially platform) into the 16-6 log. Between end members, a gradational editing has been carried out such that reef thicknesses at log traces 7 and 13 are about 45 m and 75 m, respectively. Locations of both wells (16-6 and 4-11) are shown in Figure 5.

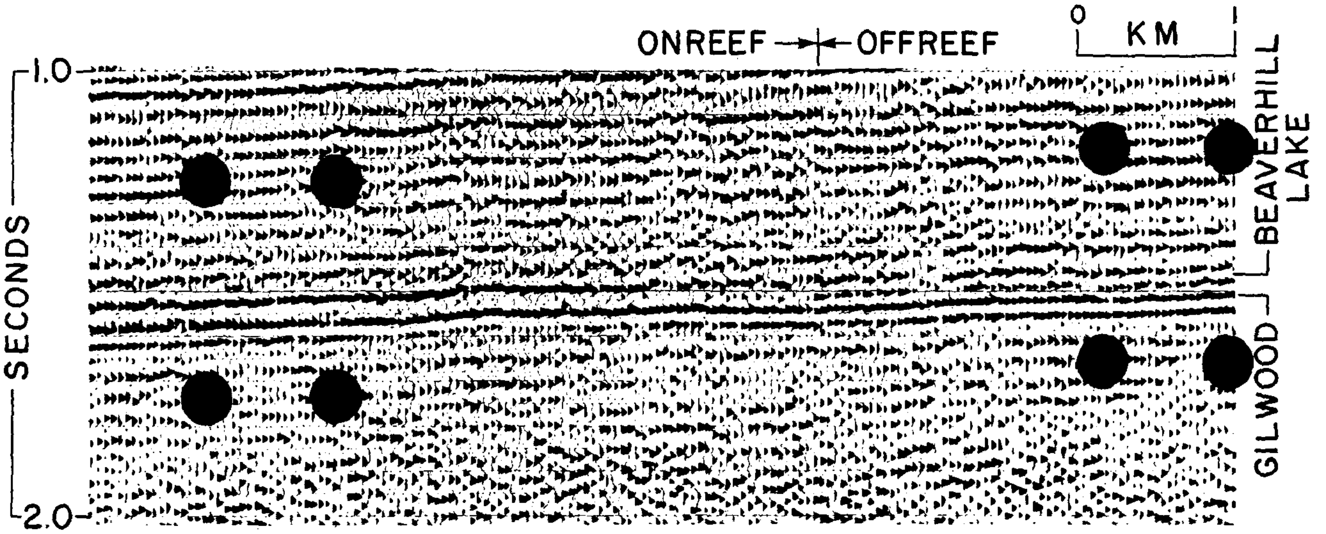

FIG. 8. Example seismic section for the east line (E in Figure 5); rectangular areas (indicated by corner dots) are enlarged in Figure 12.

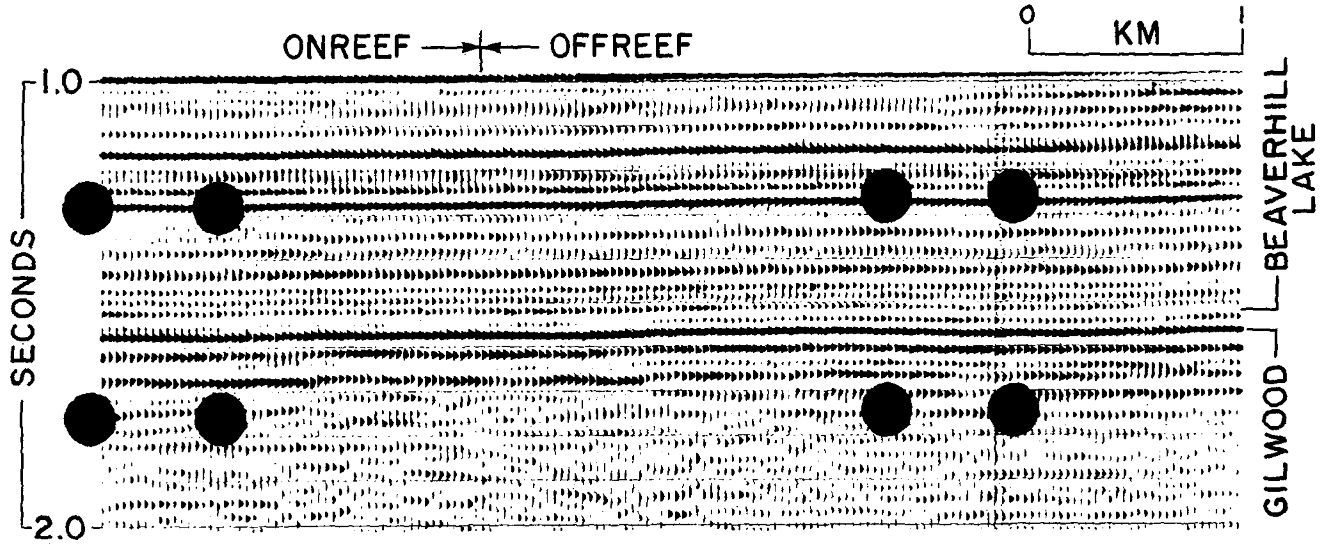

FIG. 9. Example seismic section for the north line (N in Figure 5); rectangular areas are enlarged in Figure 13.

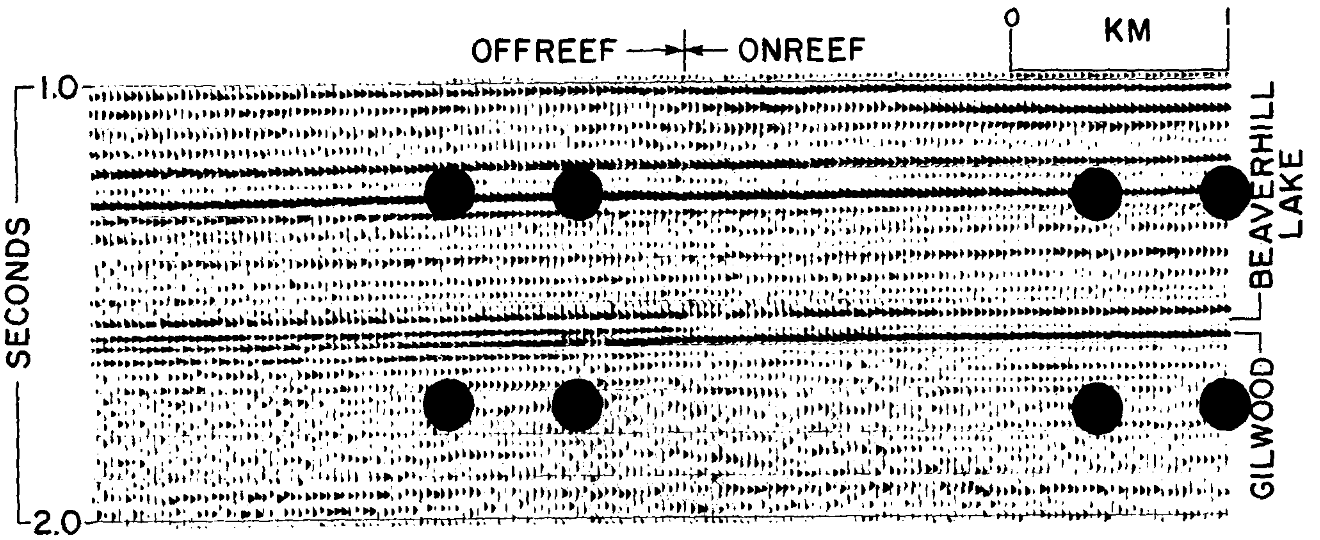

FIG. 10. Example seismic section for the west line (W in Figure 5); rectangular areas are enlarged in Figure 14.

reversed-polarity, zero-phase, Ricker wavelet with a central frequency (determined from the central half-cycle) of 28 Hz and wavelet breadth or central period of 30 ms. [See Ricker (1977, p. 93) for the specification of a Ricker wavelet.] These wavelet parameters were chosen to represent closely those of the processed seismic sections (Figures 8, 9, and 10). A good look at this wavelet itself is provided by the lower Ireton event of Figure 6 or Figure 7.

As anticipated, no significant time-structural relief is observed across the synthetic; the 3 to 4 ms of velocity pullup observed beneath the reef would be difficult to observe on real data. There are, however, significant differences between the signatures of the Beaverhill Lake/Gilwood interval on the offreef and onreef sides of the margin. These differences follow:

(1) The Gilwood event amplitude on the synthetic is higher offreef (Figure 7, traces 1 to 9) than onreef (traces 13 to 20). Qualitatively, this amplitude difference is due to interference of the Gilwood event with the reflection from the Swan Hills formation. The Swan Hills top to Gilwood top interval spans about 13 to 20 ms in two-way time offreef at an average *P*-wave velocity of about 6000 m/s, corresponding to about 40 to 60 m in thickness, including some 5 m of Fort Vermilion formation. For a 30 ms 28 Hz Ricker wavelet and two reflections of opposite polarity, such as those from the Swan Hills and Gilwood, the intervals are close to a quarter-wavelength thick and lead to constructive interference. In contrast, corresponding onreef intervals of about 27 to 33 ms, or about 80 to 105 m, including 5 to 10 m of Fort Vermilion, being close to a half-wavelength in thickness, lead to destructive interference.

(2) The Beaverhill Lake reflection amplitude is lowest over the onreef margin (Figure 7, traces 11 to 13), intermediate offreef (traces 1 to 9), and highest onreef (traces 19 and 20). Again, the amplitude variation is explained qualitatively in terms of interference phenomena, in this case involving the reflections from the top of the Beaverhill Lake group or Waterways formation and the top of the Swan Hills formation. This interval, consisting of the Waterways formation, can be seen by careful comparison of the velocity logs of Figure 6 and Figure 7 (trace 1) to have an average velocity of about 5000 m/s. At trace 12, the Waterways is about 16 ms in two-way time or about 40 m in thickness. 40 m is close to a quarter-wavelength for our Ricker wavelet; for two reflections of the same polarity, such as those from the Beaverhill Lake and the Swan Hills, this leads to destructive interference. For thinner Waterways intervals onreef (10 to 15 m at trace 20) and thicker ones offreef (≅75 m at trace 1), the interference is less destructive or more constructive. However, since wavelets are not harmonic wavetrains, we cannot confidently deduce quantitative differences between these end-member traces by qualitative considerations. Rather, the actual interference effects with respect to the Beaverhill Lake event are best seen by examining the synthetic traces themselves.

(3) The Beaverhill Lake/Gilwood interval (Figure 7) is characterized offreef by two distinct peaks with an intervening trough, all of relatively high amplitude. The trough represents the reflection from the top of the Swan Hills platform. The earlier of the two peaks, the constructive interference of first side lobes from the Beaverhill Lake and Swan Hills reflection wavelets, dies out when the recording station moves from offreef to onreef-margin positions (traces 12 to 14) as the Beaverhill Lake/Swan Hills interference grades from constructive to destructive. Approaching full reef thickness, interference again becomes partly constructive but would only be fully constructive for a zero Waterways thickness (≅110 m of Swan Hills reef).

(4) The Beaverhill Lake/Gilwood interval thins by about 4 ms in moving from trace 1 to trace 20 (Figure 7). This thinning is due to the replacement of 60 m of Waterways shale (velocity ≅ 5000 m/s) by 60 m of Beaverhill Lake carbonate (velocity ≅ 6000 m/s). The time thinning between a section of full reef (≅110 m) and a section of no reef or platform (full Waterways section) would then be about 7 ms.

SEISMIC DATA

The three example seismic lines crossing the margin of the Snipe Lake reef are shown in Figures 8, 9, and 10. They are located on the map of Figure 5, where one also sees that the three lines extend onreef only to Swan Hills thicknesses of about 70 to 80 m. Such reef thicknesses correspond to those of traces 12 to 15 on the synthetic of Figure 7, a zone referred to above as the onreef margin. It should also be noted that the Swan Hills formation in the left-hand velocity log of Figure 11 is about 75 m thick. Therefore, the corresponding left-hand synthetic (Figure 11) more faithfully reflects the seismic signature of the Beaverhill Lake/Gilwood interval for onreef-margin locations (hereafter usually termed simply onreef) than does the 1-D synthetic of Figure 6 (identical to trace 20 of Figure 7). The latter should, and does, represent better the situation over nearly full reef thickness. Thus, in comparing the field seismic data (Figures 8 to 10 and 12 to 14) with the synthetic seismic data of Figure 7, we should only consider traces 1 to about 15 of the synthetic.

Examining the three seismic sections (Figures 8 to 10) and the enlarged portions therefrom (Figures 12 to 14) and comparing those sections with the synthetics (Figures 7 and 11) enable us to determine which of the features listed above might be used reliably for reef delineation. For purposes of effective illustration, the enlarged portions (Figures 12 to 14) were deliberately chosen as good, rather than typical, examples of onreef and offreef sections, even if they are somewhat widely separated (Figures 8 to 10).

(1) In visually comparing the onreef and offreef amplitudes of the Gilwood event, one must try not to be influenced by the width of the pulse and to consider just the height of the pulse (or central lobe of the Ricker wavelet). In Figures 12 and 13 (east and north lines) the Gilwood amplitude is definitely larger offreef. However, the generally wider pulses onreef, as well as the fact that nearly all the tops of these peaks are lost in the adjacent-trace peaks, makes it difficult to ascertain where the amplitude is greater. On the full sections, it is not clear for the east line (Figure 8) where the amplitude is generally greater; while for the north line (Figure 9), it is fairly easy to discern a higher Gilwood amplitude offreef. For the west line (Figures 10 and 14), the Gilwood amplitude appears greater onreef than offreef. Relative Gilwood event amplitude does not appear to be a reliable diagnostic for reef delineation—at least not by itself.

(2) The Beaverhill Lake event is a reflection trough. Looking at Figures 12 to 14, we cannot discern any clear difference between the onreef and offreef amplitudes of this trough.

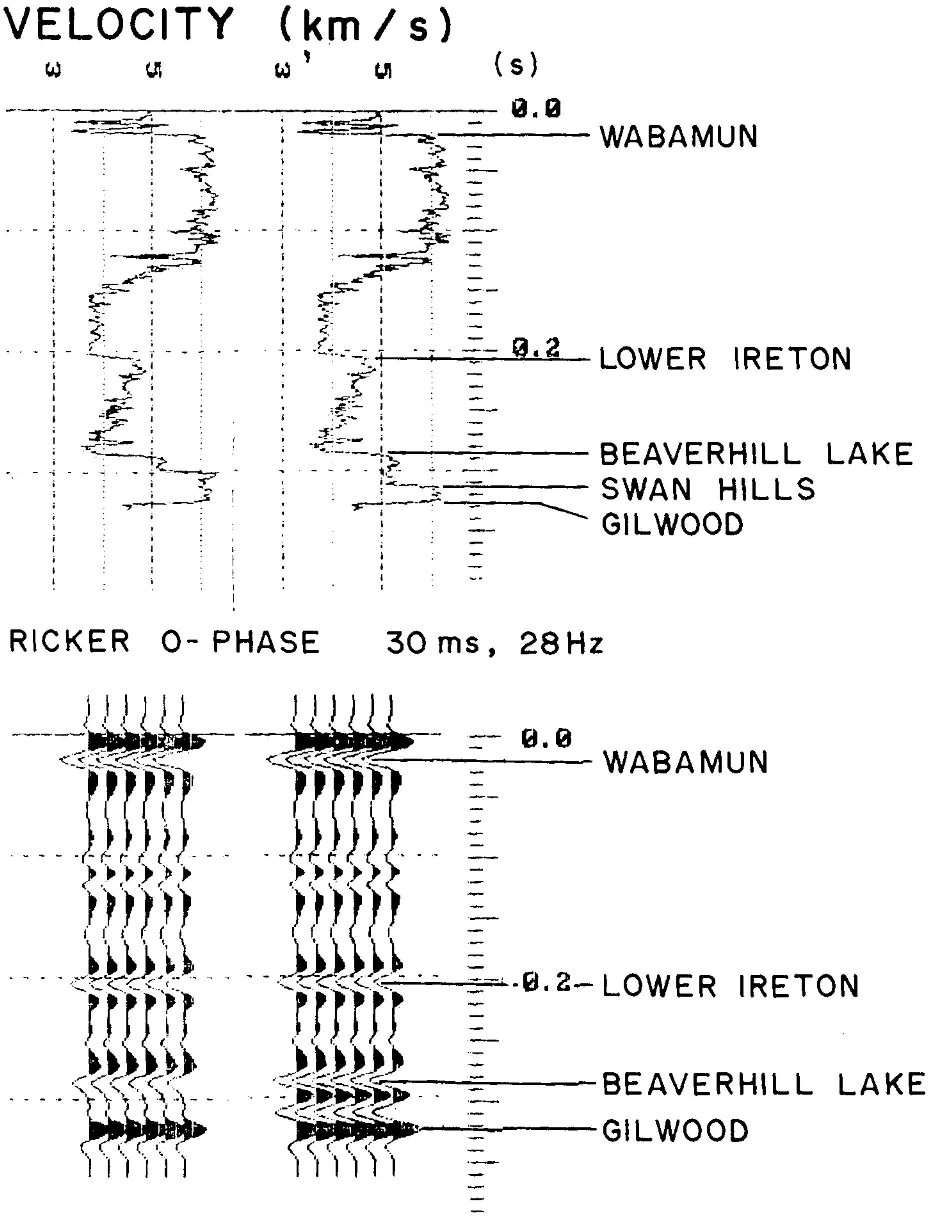

FIG. 11. Comparison of synthetic seismic signatures corresponding to onreef (left) and offreef (right) velocity logs, with typical Swan Hills formation sections of 75 m and 40 m, respectively; these correspond directly to traces 13 and 4, respectively, of Figure 7.

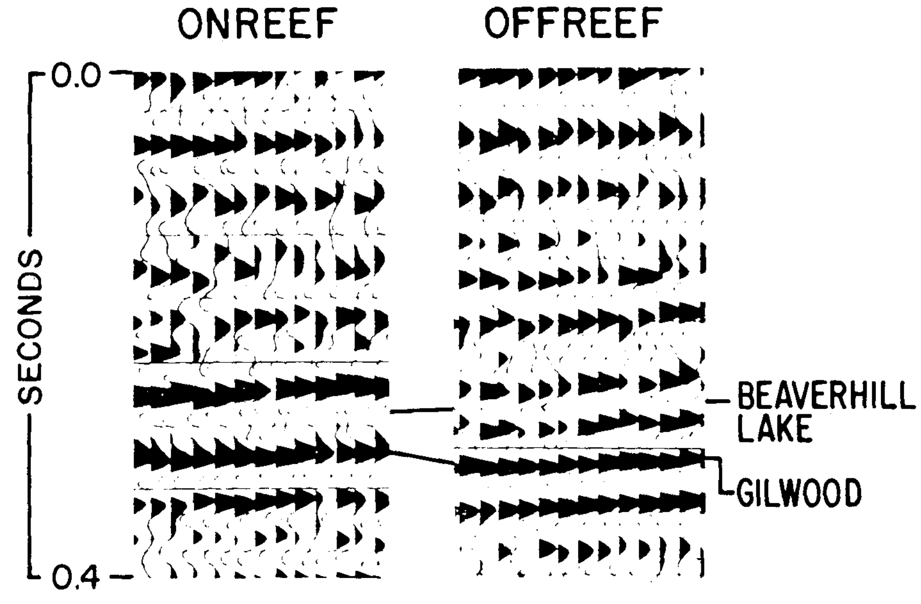

FIG. 12. Comparison of onreef and offreef portions of the east line enlarged from Figure 8.

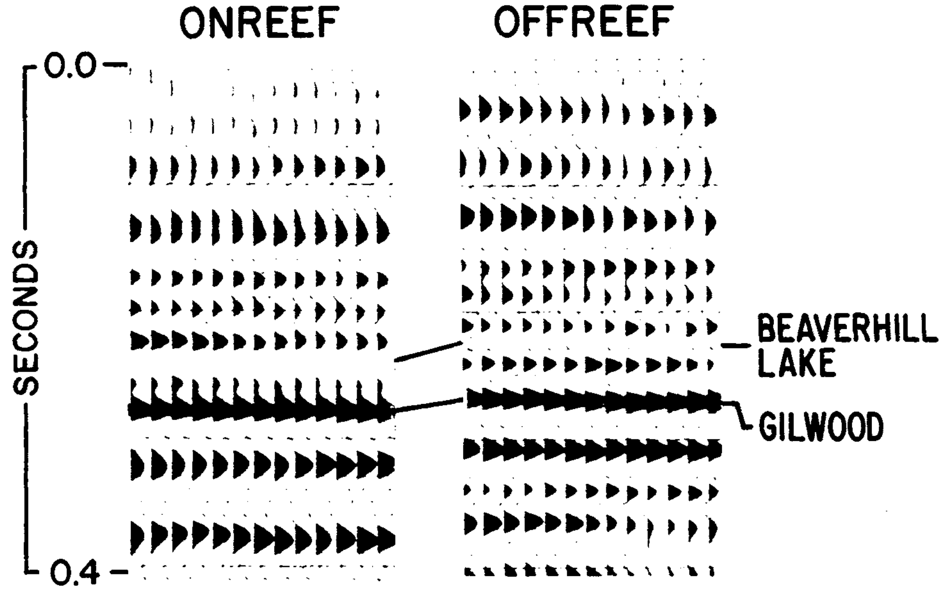

FIG. 13. Comparison of onreef and offreef portions of the north line enlarged from Figure 9.

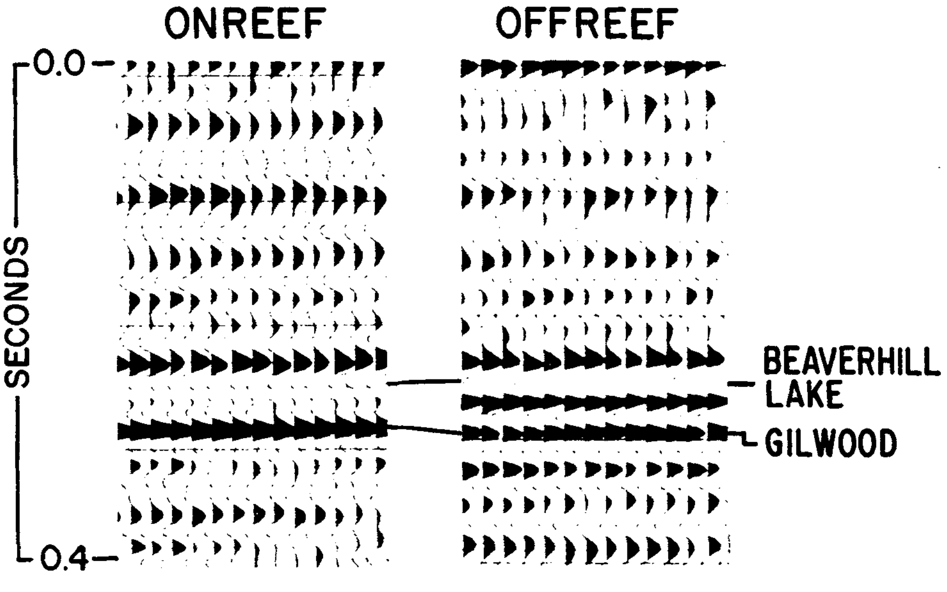

FIG. 14. Comparison of onreef and offreef portions of the west line enlarged from Figure 10; onreef and offreef panels have been reversed, relative to Figure 10, for consistency with Figures 12 and 13.

Indeed, on the synthetic (Figure 7) itself, this variation is quite a subtle one. Amplitude of the Beaverhill Lake event would not appear to be a reliable diagnostic feature for reef delineation either.

(3) The characteristics observed for the synthetics and described under (3) in the previous section are clearly visible on all three of our seismic lines (Figures 12 to 14). In every case, there is a distinct peak between the Beaverhill Lake trough and the Gilwood peak on the offreef section which dies out moving onreef. The representative onreef and offreef synthetics (traces 13 and 4, Figure 7) have been reproduced separately in Figure 11 for easy comparison with the enlargements (Figures 12 to 14). The event resulting from destructive interference between the Beaverhill Lake and Swan Hills wavelets combines with the Gilwood reflection wavelet to give the appearance of a doublet for at least part of the onreef section in each of the field sections (Figures 8 to 10). This doublet can also be seen very clearly on the north-line enlargement (Figure 13), less clearly on the west-line enlargement (Figure 14) and on a single trace of the east-line enlargement (Figure 12). We are using the term "doublet" here in a sense commonly employed by exploration seismologists, namely, of two closely neighboring peaks separated by a low which does not cross the axis significantly, if at all: the definition is not among the definitions given by Sheriff (1984, p. 69). This interference characteristic appears, from the example seismic sections studied here, to be a potentially reliable diagnostic for reef delineation, with or without the appearance of the doublet.

(4) Although the thinning of the Beaverhill Lake/Gilwood interval is very subtle ($\cong 3$ ms) in the synthetics of Figure 11, there appears to be discernible thinning of this interval on the enlargements of each of our three lines (Figures 12 to 14) on the order of 5 ms or more. On the full sections (Figures 8 to 10), this thinning is less consistent and is difficult to measure but, nonetheless, appears to be present. It would be difficult to use thinning of the order of 5 ms as a reliable diagnostic of reef presence on a single seismic section; however, in combination with other indicators and perhaps several lines in an area, such thinning may be useful in reef delineation.

DISCUSSION

The interference phenomena described in the previous two sections [point (3)] appear from the present study to constitute a practicable and reliable diagnostic of the transition from offreef (platform only) to onreef-margin positions. The other three effects are not considered likely to be applicable separately as reliable diagnostics; but, as supporting evidence in combination with point (3), these effects may be helpful in strengthening the intepretation. Particularly useful may be the time thinning onreef relative to offreef. As already mentioned, some thinning is expected due to velocity pullup by the higher velocity of the Swan Hills carbonates relative to that of the Waterways shales. However, since we seem to observe even greater thinning than expected on this basis alone, it may be that other factors intimately associated with the reef contribute to this thinning. For example, the interference phenomena described may also cause some apparent shifting of the Beaverhill Lake reflection trough and Gilwood reflection peak; the uppermost member(s) of the Waterways formation may have higher velocities than the average of the Waterways as a whole; such phenomena as increased content of interbedded limestones in the nodular shales of the Waterways formation in the vicinity of the reef might exist, influencing Waterways onreef versus offreef velocities. In addition, fortuitous causes not related to reef occurrence such as regional thinning may also contribute to the time thinning. These questions are extremely interesting and are worth a separate investigation in themselves; for present purposes, however, they constitute second-order effects. The outcome of such a study would not alter the basic conclusions of this paper.

One other published study has claimed a degree of success in Swan Hills reef delineation. Bubb and Hatlelid (1977, p. 202) report that fair success was achieved in determining the limits of the Judy Creek and other nearby Swan Hills reefs (Figure 2) using "cycle termination" as the diagnostic. They show one example seismic section over the Judy Creek reef of singlefold conventional data, presumably of normal polarity. Although the data quality is not very good, it seems clear to us that this cycle termination is associated with the interference phenomena discussed above and is, in fact, a manifestation thereof. If one looks at the synthetics of Figure 11 and considers what the two would look like in the opposite polarity, one sees that immediately above the Gilwood trough there would be an offreef peak which would die out moving onreef, just as in reversed polarity there is an offreef peak one cycle above the Gilwood peak which dies out moving onreef. It is interesting, however, that Bubb and Hatlelid (1977, p. 203) have listed only one criterion for recognizing carbonate buildup at Judy Creek, namely, the geologic one of basin position, notably omitting amplitude, frequency, or continuity change.

CONCLUSIONS

We conclude that it is possible to delineate the Snipe Lake reef using interference phenomena associated with the lateral variations in thickness of the Swan Hills formation. In view of the fair success reported by Bubb and Hatlelid (1977) using cycle termination—an effect that we believe to be closely related to these interference phenomena—in delineating Swan Hills reefs at Judy Creek and other nearby buildups, it is quite possible that these laterally varying interference phenomena are useful indicators of reef presence not only at Snipe Lake but for other Swan Hills reefs.

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