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GEOPHYSICAL ASPECTS OF WABAMUN SALT DISTRIBUTION IN SOUTHERN ALBERTA

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ABSTRACT

We have mapped the thickness of the Wabamun Group salts in the Stettler area of southern Alberta from well-log data. Prominent collapse features are seen to be associated with many of the edges of these salt remnants suggesting that the salts were probably, at one time, uniformly distributed throughout much of southern Alberta and subjected to extensive postdepositional dissolution. The original distribution of these salts and the timing and extent of their dissolution is critically important to the explorationist for several reasons: (1) structural traps can form where reservoir facies are draped across salt remnants or collapse features; (2) stratigraphic traps can form where reservoir facies were either preferentially deposited or preserved in salt-dissolution lows; (3) reservoir facies can develop in high-energy environments like topographic highs that are controlled by salt-dissolution edges or remnants; (4) closure across Wabamun salt remnants can be misinterpreted as drape over a nonexistent reef, or can distort the drape across an actual underlying Leduc Formation reef, or it may be falsely indicative of deep-seated structure; and (5) Wabamun salts can be erroneously interpreted as Nisku porosity on seismic data.

In this paper, an isopach map of the Wabamun salts in the Stettler area and a suite of geologic cross-sections are presented. These data help to elucidate the timing and extent of the dissolution of these salts and to illustrate some associated potential trapping mechanisms. In addition, seismic and gravity models are presented which indicate that these techniques can be used to advantage in the mapping of salts in areas of partial removal.

INTRODUCTION

The regional work of Belyea (1964) and Meijer Drees (1986), among others, shows that the Wabamun Group and its equivalents (Figures 1 and 2) are present over a large areal extent of the western Canada basin and that residual Wabamun Group/Stettler Formation salts cover a considerable area of southern Alberta. We have carried out a more detailed mapping of Wabamun salt thickness in the Stettler area of Alberta (Figures 2 and 3) from about 500 well logs (the control points of Figure 3). We intend, in this paper, to consider the present Wabamun salt distribution and any collapse features associated with the dissolutional salt edges to try to gain at least a preliminary understanding of the original depositional salt distribution and how dissolution, or leaching, proceeded through time. In doing this, we apply the simple principle that, over a dissolutional edge, those overlying units that are undisturbed, i.e., exhibit no collapse features, must have been deposited after cessation of salt removal. In the present paper, we discuss several possible salt-related effects that one might look for in seismic and gravity data, but we defer to future publications the presentation of real examples thereof.

The timing and the extent of salt leaching is important as both structural and stratigraphic traps can form as a result. For example, reservoir facies can be structurally closed across salt remnants and, stratigraphically, could have been either preferentially preserved or preferentially deposited in dissolutional lows or highs. An understanding of the overall salt history — deposition and dissolution — is also important because of the risk of erroneous interpretation of drape across a salt remnant as closure on an underlying Leduc reef, or of salt itself as porosity within the Nisku Formation, schematic examples of which are presented in the next section.

Recent work on salt-dissolution features in Alberta includes studies by Oliver and Cowper (1983) of salt removal in the Rumsey area; Meijer Drees (1986) and Anderson et al. (1989a) on salts in western Canada generally; Hopkins (1987) on salt dissolution and subsidence at the Berry field; and Anderson et al. (1989b) on the exploration-related effects of salt dissolution.

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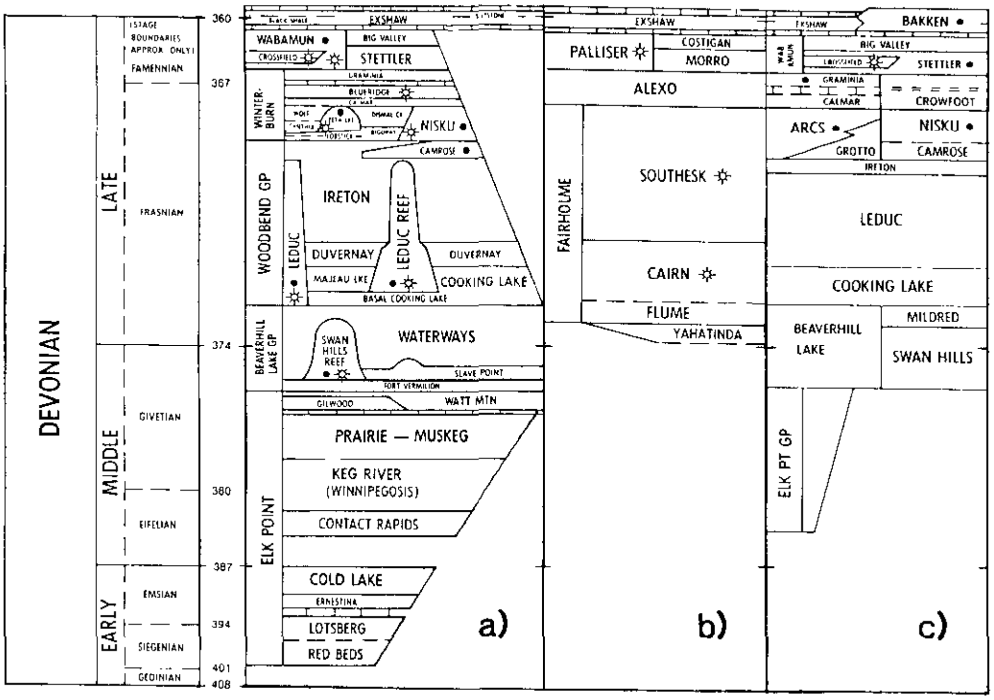


Fig. 1. Stratigraphic chart for the Devonian of southern and central Alberta (modified after AGAT Laboratories, 1988): a) central plains; b) south-central mountains and foothills; c) southern plains.

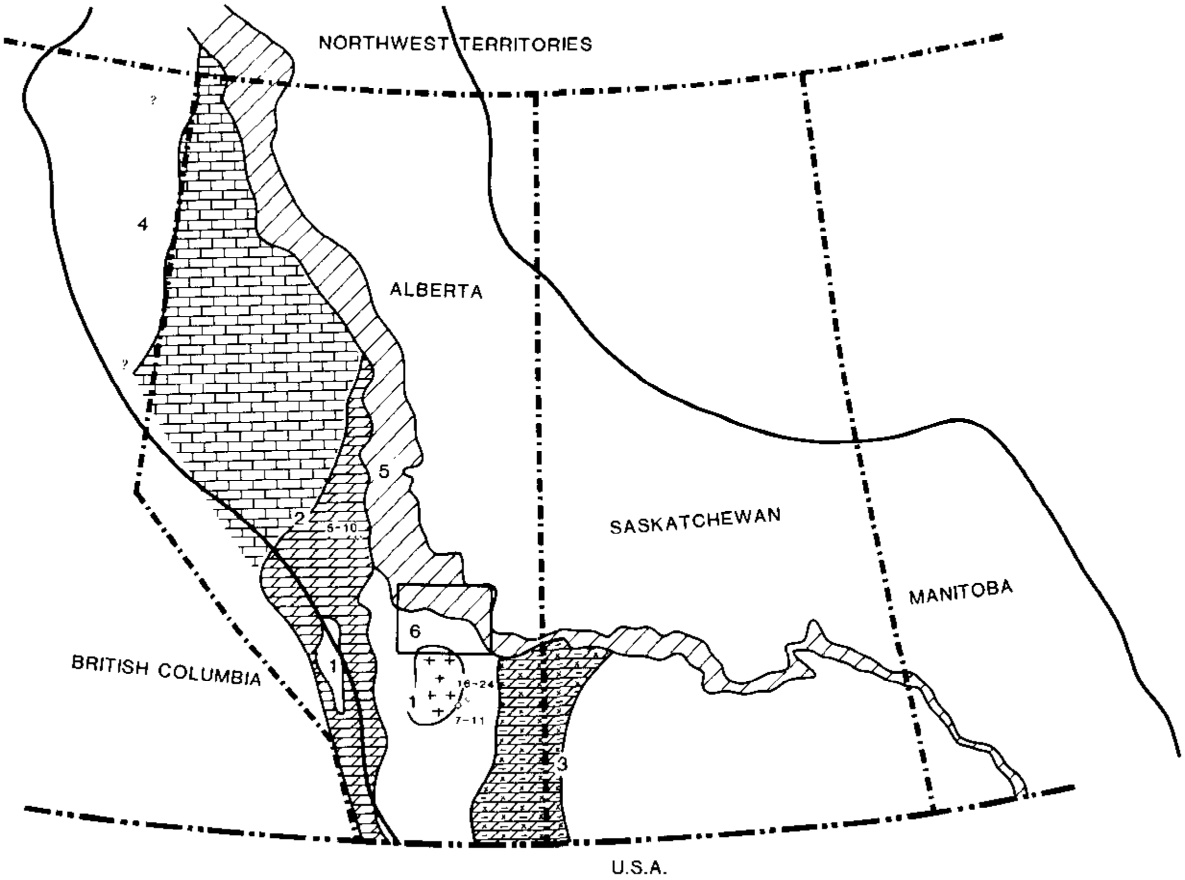


Fig. 2. Distribution of the Stettler Formation (Wabamun Group) and its equivalents within the western Canadian interior plains (modified after Belyea, 1964; Meijer Drees, 1986). The approximate time equivalents are: 1 = Stettler Formation (white: anhydrite; crosses: halite and anhydrite); 2 = Wabamun Group (diagonal hatching: dolomite; vertical hatching: limestone); 3 = Torquay Formation (white: redbeds; hatching: dolomite, anhydrite and shale) and 4 = Kotcho Formation (fossilliferous shale). In addition: 5 = the Wabamun (and equivalents) subcrop area and 6 = the study area of Figure 3. Also shown are the locations of the two wells of Figure 4 (7-11 and 16-24) and the Wabamun type-section well (5-10).

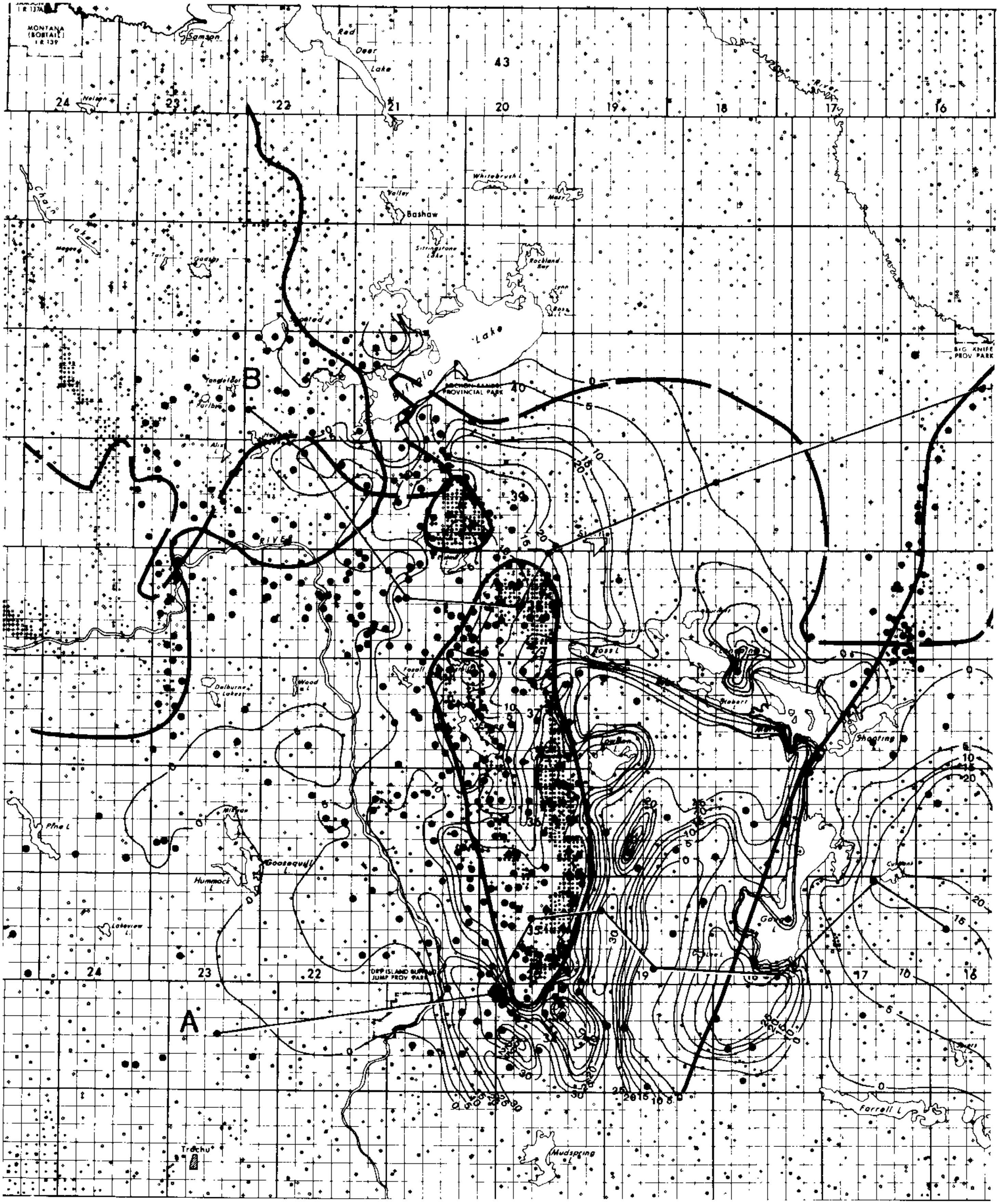
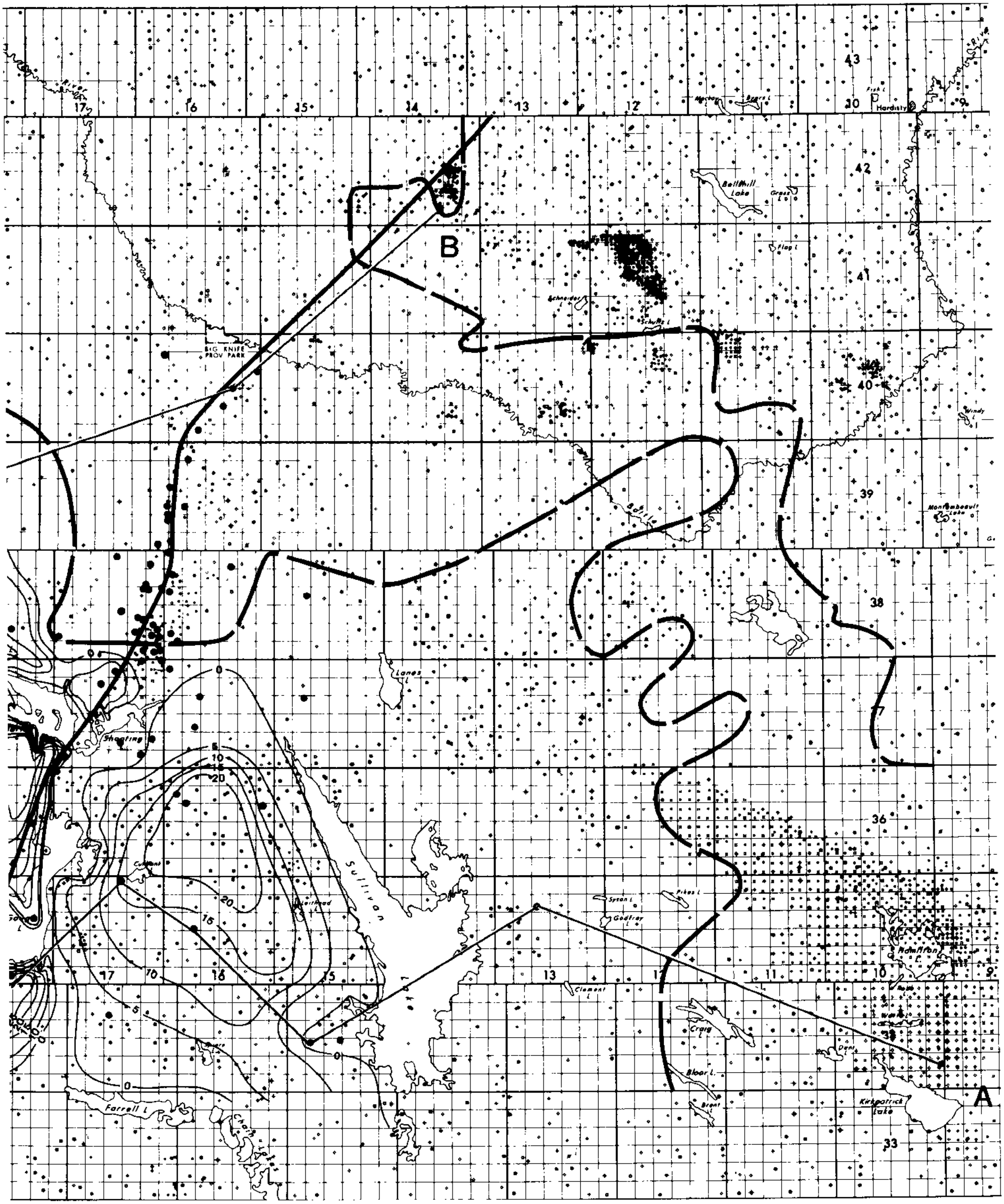


Fig. 3. Net Wabamun salt isopach map of the study area; dots are control points; thicknesses are given in metres. Leduc reefs are delineated the structural cross-sections of those figures.



with solid lines, Wabamun subcrop with broken lines. The red lines AA and BB connect the wells (identified in Figures 5 and 6) contributing to

WABAMUN GROUP SALTS

Geological overview

The type section for the Wabamun Group (Imperial Oil Ltd., 1950) is located between the depths of 1748 and 1919 m (5735 and 6297 ft) in the Anglo Canadian Wabamun Lake No. 1 (5-10-51-4W5) well. This is not very close to our present study area (Figure 2) and so we have used two wells that are closer (Figure 2), 16-24-25-13W4 and 7-11-24-15W4, shown in Figure 4. Of particular interest is the observation that the thick Wabamun salts present in the 16-24 well are absent in the 7-11 well.

The Wabamun Group in the vicinity of the type section, in the Wabamun Lake area of central Alberta, consists predominantly of limestone with dolomitic mottling and local accumulations of dolomite in the lower part. To the south-southeast of the type section, there is a gradual change from limestone to interbedded limestone and dolomite, thence to dolomite and anhydrite with local halite in the Stettler area. Wonfor and Andrichuk (1953) gave the name Stettler Formation to the evaporite sequence; the overlying green shale and fossiliferous limestone are known as the Big Valley Formation (Figure 1; Andrichuk and Wonfor, 1953).

The Wabamun Group in the study area rests on the Winterburn Group (Figure 1). The uppermost unit of the Winterburn Group, the Graminia Formation, cannot be mapped as a distinct unit throughout much of the study area. Consequently, its equivalents are commonly included in the lower part of the Stettler Formation (Belyea and McLaren, 1957; Belyea, 1964). Where erosion has not removed the overlying Mississippian strata, the Wabamun Group is overlain by the Exshaw Formation; elsewhere by the Lower Cretaceous.

Distribution of the Wabamun Group salts

We use the term *distribution* here to imply not only *areal extent* (i.e., salt or no salt) but also *thickness* of salt. For the Wabamun Group salt, this is shown in the salt isopach map of Figure 3. Control values were determined only for those wells in the study area for which caliper logs are available and only one control point was calculated per section. Superposed onto this map are the lines AA and BB of the geologic cross-sections (Figure 5). These data illustrate that the Wabamun salts are laterally discontinuous and that there is a direct correlation between structure at the top of the Wabamun and residual-salt thickness: the Wabamun top is clearly draped across the thicker salts. These observations support the thesis that the Wabamun salts at one time were more or less uniformly distributed throughout the study area and that they subsequently were extensively dissolved. Dissolution of these salts appears to have occurred throughout Mesozoic and Cenozoic time. The evidence for this proposition is threefold:

(1) Wabamun salts have not been encountered along the subcrop area of Figure 3 (except on a limited portion thereof near Buffalo Lake where the salt units themselves do not subcrop), implying some dissolution during the post-Mississippian and pre-Cretaceous hiatuses;
(2) in places, Cretaceous strata drape across salt remnants (Figure 5) implying some post-Cretaceous dissolution; and
(3) present-day drainage patterns appear to correlate to a considerable extent with the present-day edges of the salt remnants (see the lakes in Figure 3), implying some dissolution in Holocene time.

In connection with (3) above, although we have a large number of control points, we still need many more before we can compile a definitive salt isopach map to compare with drainage patterns.

The Wabamun salts in the study area have been extensively dissolved. The timing of this leaching and the distribution of the residual bodies should be extremely significant to the explorationist for a number of reasons:

(1) reservoir facies can be structurally closed over the edge of residual salt bodies (Figure 6);
(2) reservoir facies can be structurally closed over a salt remnant as a result of progressive leaching of salt (Figure 7);
(3) reservoir facies can be stratigraphically trapped where preferentially deposited in salt-dissolution lows (Figure 8) or highs;
(4) reservoir facies can be stratigraphically trapped where preferentially preserved in a salt-dissolution low (Figure 9);
(5) drape across a Wabamun salt remnant can be misinterpreted on seismic data as either drape across a Leduc reef or as being indicative of basement structure (Figure 10);
(6) Wabamun salts can either enhance or degrade the seismic signature of an underlying Leduc reef (Figure 11); and
(7) low-velocity Wabamun salts can be misinterpreted on seismic data as Nisku porosity (Figure 12).

In our continuing research, we intend to assemble a suite of real examples of many or all of these effects.

SEISMIC MODELLING

Suites of one- and two-dimensional synthetic seismograms were generated for selected wells in southern Alberta. Below, both the modelling techniques and the models themselves are briefly discussed. The GMA Stratigraphic Modelling System software was used.

One-dimensional (1-D) modelling

Two sonic logs (Figure 4) were used to generate synthetics, one of which penetrated a thick salt remnant (16-24), the other of which encountered no salt (7-11). 1-D synthetic seismograms were generated for each of these logs using two different zero-phase Ricker wavelets. The seismograms are displayed (Figures 13 to 14) in both normal and

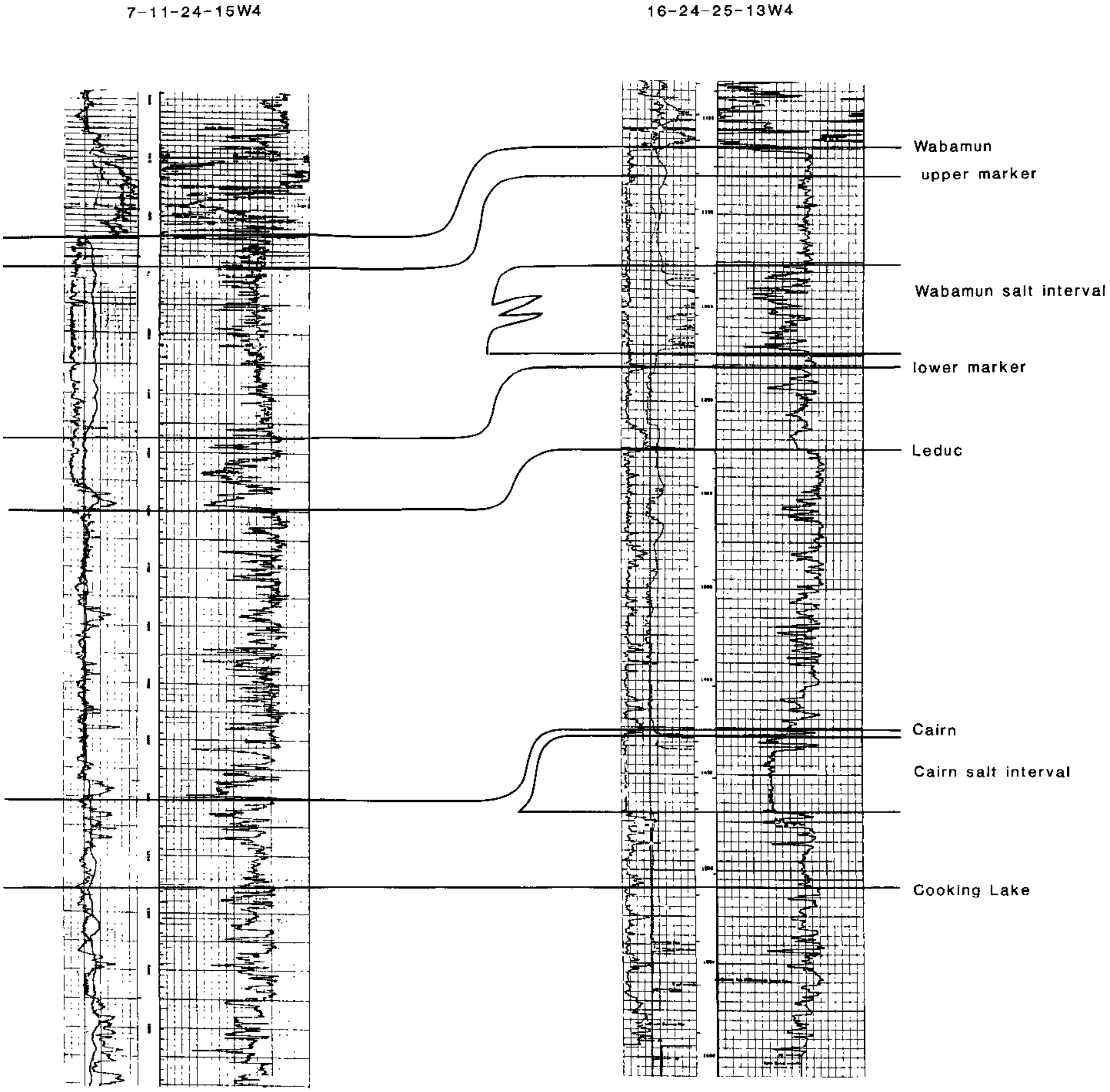


Fig. 4. Gamma-ray and sonic logs for the wells indicated and resulting schematic section for the Wabamun to Cooking Lake interval.

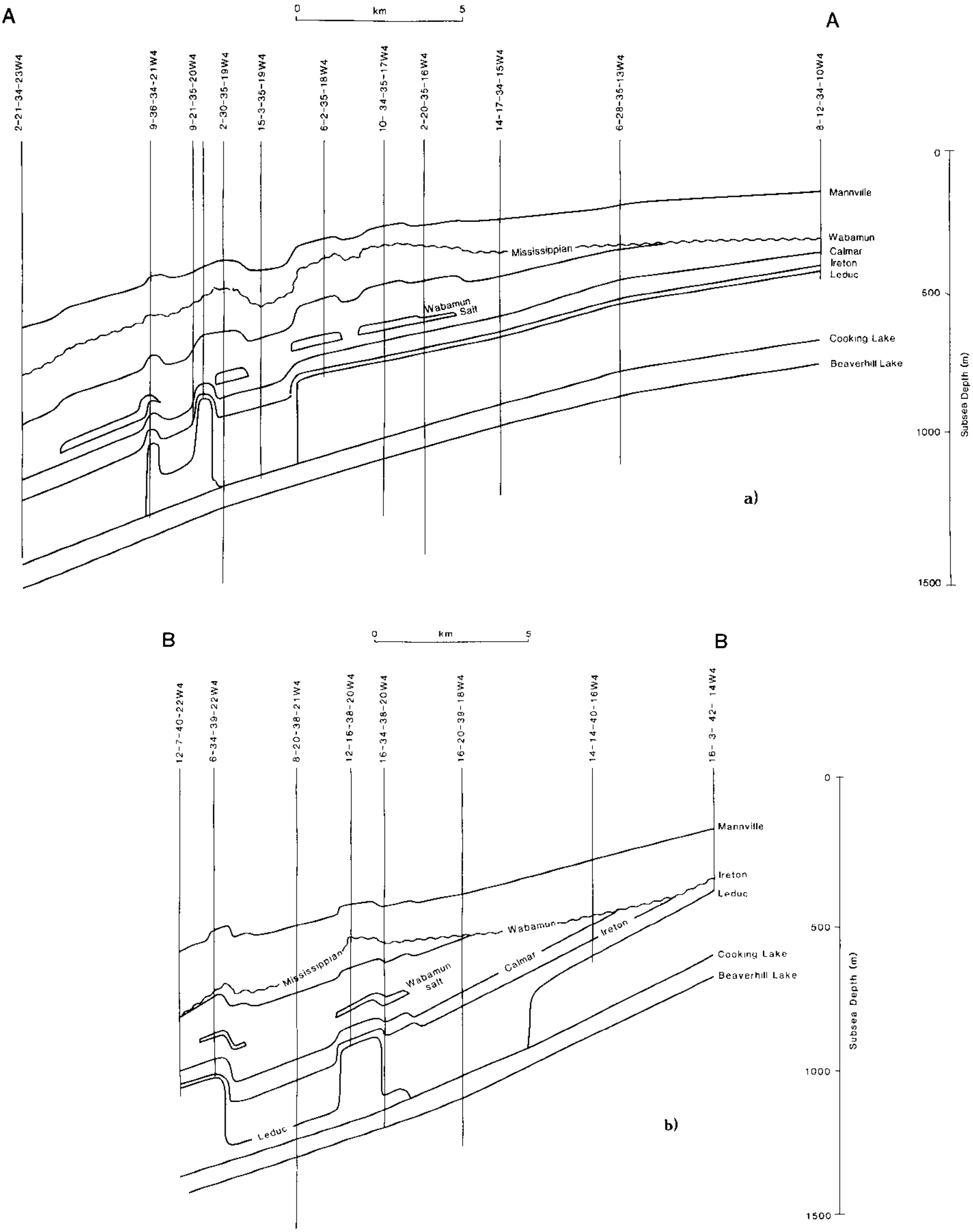


Fig. 5. Geologic cross-sections illustrating the discontinuous nature of the Wabamun salts in the study area and the overlying collapse pattern: (a) line AA; (b) line BB. See Figure 1 for Devonian stratigraphic nomenclature; the Mannville Group is in the Lower Cretaceous.

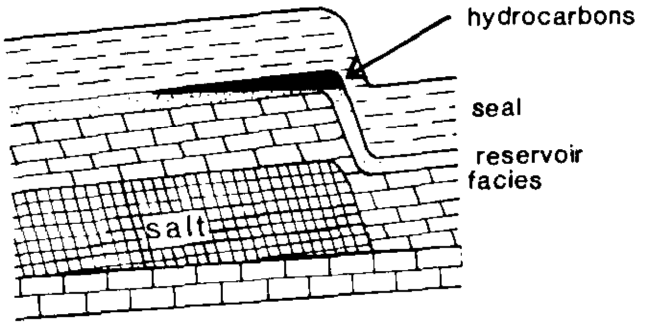


Fig. 6. Schematic diagram showing how a reservoir facies can be structurally closed across the edge of a salt remnant due to salt dissolution.

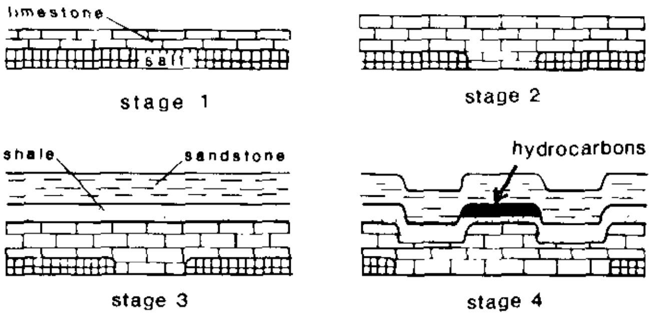


Fig. 7. Schematic diagram showing in four stages how a reservoir facies can be structurally closed over a salt remnant as a result of the progressive leaching of salt.

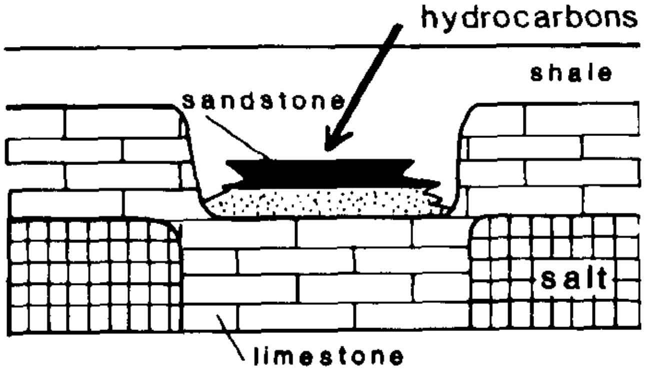


Fig. 8. Sketch showing how a reservoir facies can be preferentially deposited within a salt-dissolution low.

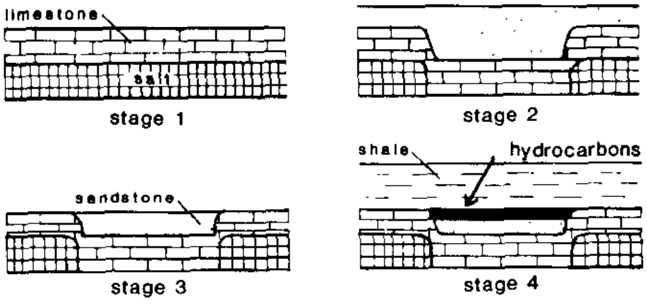


Fig. 9. Sketch showing how a reservoir facies can be preferentially preserved in a salt-dissolution low.

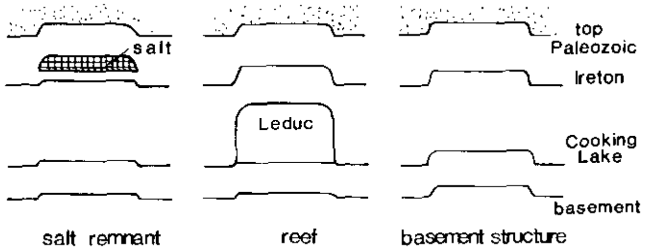


Fig. 10. Sketch showing how, on seismic data, a remnant of salt can be misinterpreted as either reef or basement structure. The top of the Paleozoic is time-structurally draped across the salt remnant, the reef and the basement structure; the basement event is also locally high beneath these features as a result of pullup and/or reef structural relief.

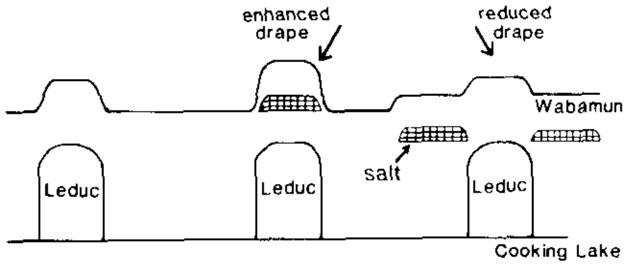


Fig. 11. Sketch showing how drape at the Wabamun level, due to differential compaction of reef and offreef strata, can be either enhanced or subdued as a result of the dissolution of Wabamun salts.

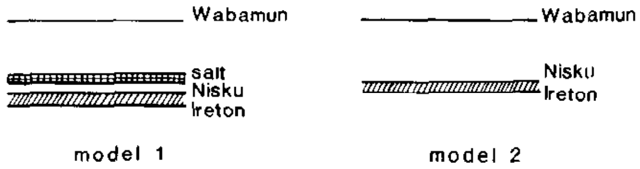


Fig. 12. Schematic diagram showing how, on seismic data, the relatively low-velocity Wabamun salts (~4200 m/s) can be misinterpreted as porosity within the Nisku Formation.

reversed polarity for four different values of wavelet "breadth" (Ricker, 1977, p. 93), or central period (20, 25, 30 and 35 ms).

In the Wabamun interval of the 16-24 well, the top and the base of the salt (not shown in Figures 13 and 14) come about one-third and two-thirds of the way through the Wabamun interval. On the normal-polarity synthetics of Figures 13 and 14, the top and base of the Wabamun salt interval in the 16-24 well are manifested as a trough and a peak, respectively. The peak at the base of the salt is seen quite clearly at about 0.1 s for all four wavelets used. However, the resolution of the salt top, at about 0.08 s, degrades with increasing wavelet breadth (decreasing frequency). At 20 ms the salt top trough is very sharp while at 35 ms it has totally merged with the negative lobe of the Wabamun reflection peak.

In Figure 14, the effect of density has also been included

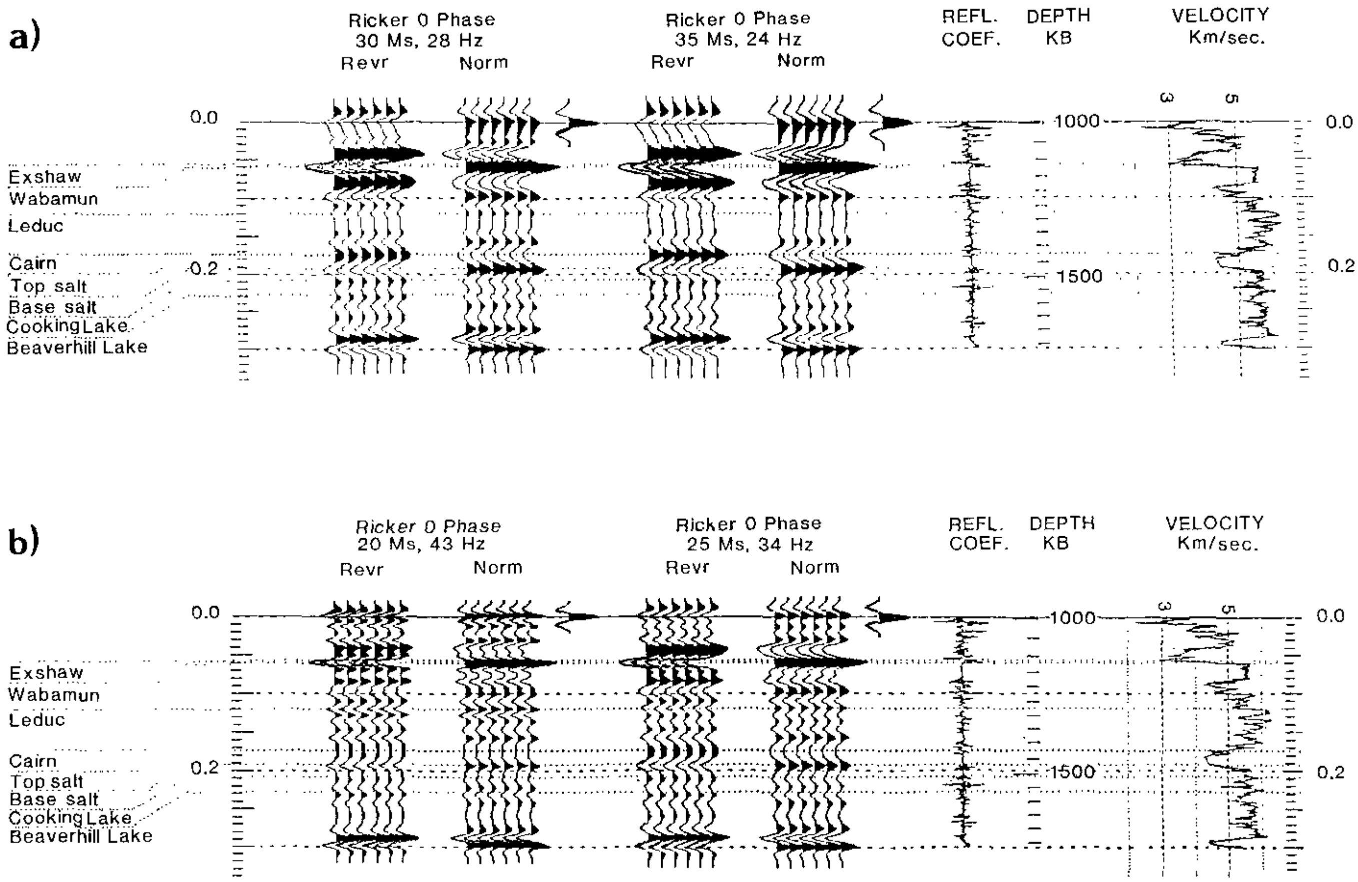


Fig. 13. 1-D synthetic seismogram for the 16-24-25-13W4 well based on velocity only: **(a)** for 35-ms and 30-ms Ricker wavelets; **(b)** for 25-ms and 20-ms Ricker wavelets. This well penetrated about 30 m of Wabamun salt and about 35 m of Cairn salt. Two-way traveltime in seconds is given at the left and right extremities.

in the synthetic traces. For the Wabamun salt, this has increased resolution only slightly. However, for the Cairn salt lower in the section, for which the density-log anomaly is much more pronounced, the modelled reflections stand out significantly more clearly on Figure 14 (with density) than on Figure 13. Thus, in general, when modelling salt-bearing intervals, the effect of density should not arbitrarily be neglected. In Figure 15, a 1-D seismogram for the 7-11 well is shown. This well encountered no Wabamun Group salt. Although there are differences between Figures 13 and 15 for the Wabamun interval for all four wavelets, these differences are clearer and easier to resolve for a narrower wavelet than for a broader one, generally speaking.

Two-dimensional (2-D) modelling

The synthetic seismic signatures of wells containing salt are often significantly different from those without salt. In order to illustrate these differences, a 2-D sonic-log model and corresponding synthetic seismic section (Figure 16) were generated, the latter using a 25-ms Ricker wavelet. This synthetic seismic section illustrates two interesting features:

(1) that zones of relatively thick salt can very likely be visually differentiated from neighbouring zones where salt dissolution has occurred, but where the stratigraphy is otherwise much the same; and

(2) that seismic events associated with older units will probably not be significantly pushed down or pulled up beneath salt remnants relative to the off-salt section; this is under the assumption that dissolution has occurred mainly during Mesozoic and Cenozoic time so that, although the salt is of low velocity relative to the overlying units which have collapsed to the salt-base level, the ultimate compensation sediments are, for example, Cretaceous clastics (or even younger sediments) which are of relatively low velocity.

We intend to test these modelling indications on some real examples in our future research.

GRAVITY MODELLING

In order to determine whether or not one would have a chance of seeing the effects of partial salt removal in gravity data, we consider relative values of g, the acceleration of gravity, over a full salt-bearing section, taken here to be 25 m thick, and over an adjacent section with no salt. For simplicity we shall consider just two cases: one in which dissolution has occurred in a very short space of time, i.e., before the end of the Devonian, and one in which dissolution has taken place totally during post-Devonian time.

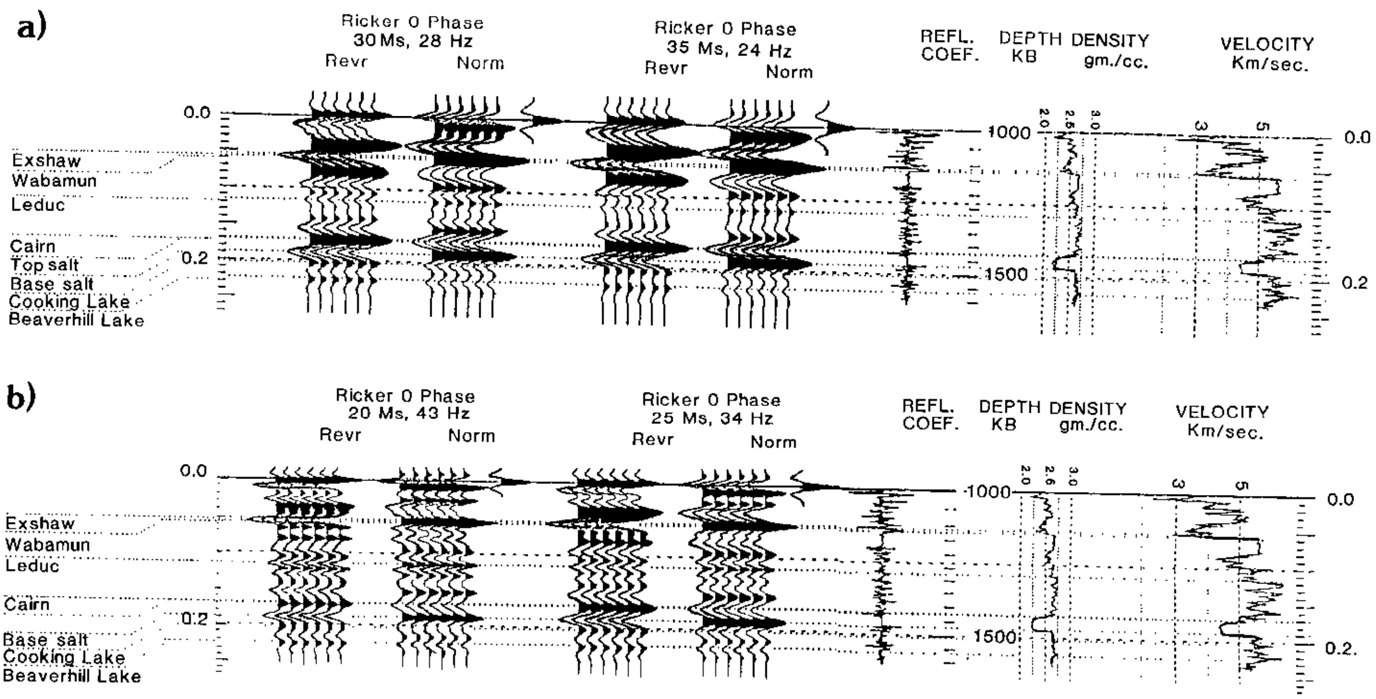


Fig. 14. Same as Figure 13 but with synthetics based on both velocity and density.

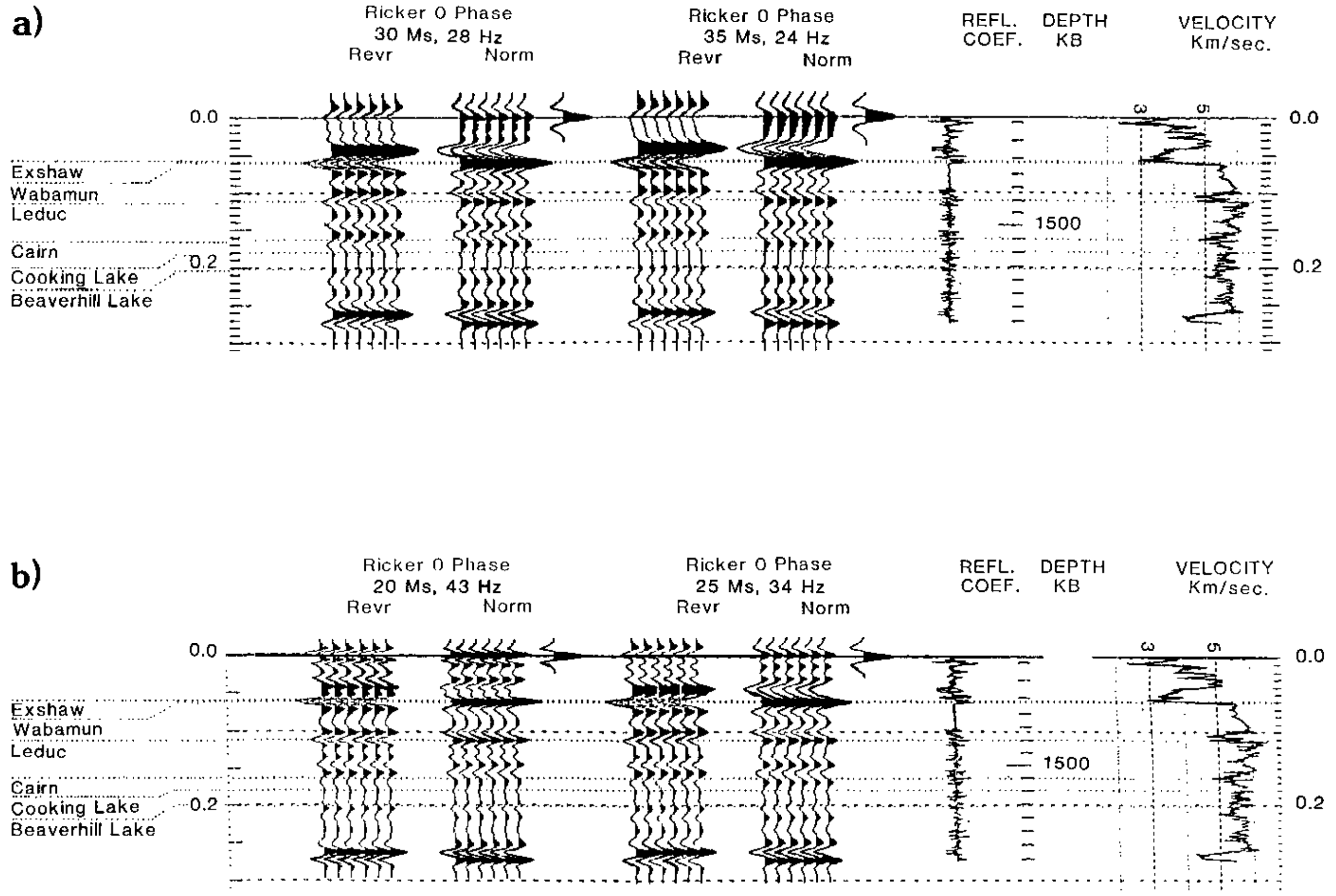


Fig. 15. Same as Figure 13 for the 7-11-24-15W4 well (velocity only). This well encountered neither Wabamun nor Cairn salts.

The first case is represented by the simple model of Figure 17a. The difference between the two asymptotic values, Δg, for this case will just be the difference in g for two infinite slabs, that is

$$\Delta g = 2\pi G h \Delta\rho \qquad (1)$$

where G is the gravitational constant (= 6.672×10^{-11} SI units), h is the thickness of salt dissolved, and $\Delta\rho$ is the difference between typical Devonian carbonate density and Wabamun salt density.

For the second case (Figure 17b), equation (1) still applies; however, $\Delta\rho$ is then the difference between the density of the replacement sediments (e.g., Mississippian carbonates, Cretaceous clastics) and that of Wabamun salt.

Representative values for the three densities mentioned are indicated in the density log of Figure 14. We have chosen a somewhat lower salt density than indicated there (which we suspect does not represent a full response to the salt) because salt densities can easily be as low as or lower than the value of 2250 kg/m^3 which we use (see, e.g., the Cairn salt density, also in Figure 14). For the two cases considered the gravity anomalies are 4.2 g.u. (0.42 mGal) and 2.1 g.u. (0.21 mGal), respectively. These are well above the limits of resolution of most modern gravimeters, which are typically in the range from 0.1 to 1 g.u. (0.01 to 0.1 mGal).

The gravity models considered here are intended only as order-of-magnitude analogues. The numerical values used are all intended to be representative averages but the models are oversimplified. Nevertheless, these simple model considerations indicate that gravity surveying might very well be an effective tool in delineating salt edges. We are currently working towards the acquisition of gravity data which will test this proposition.

CONCLUDING DISCUSSION

The present distribution of the Wabamun Group salts reflects both primary depositional patterns and secondary dissolutional trends. Such secondary dissolution frequently creates traps — both stratigraphic and structural. In order to explore for such traps, it is necessary to determine the timing and extent of the leaching and to reconstruct the distribution of the salts during the period of deposition of prospective reservoir facies. From this preliminary study, it is apparent that significant dissolution has occurred in the

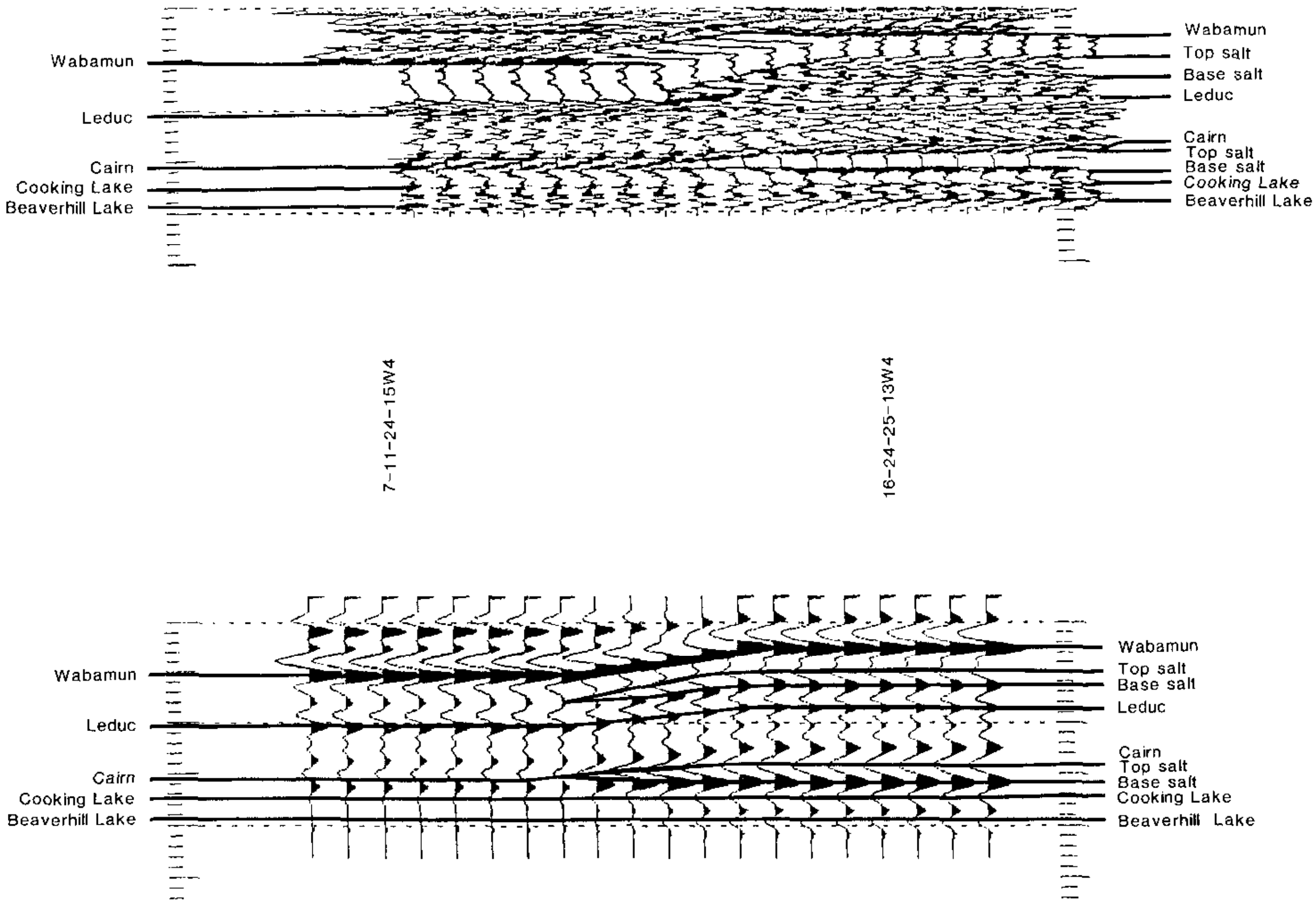


Fig. 16. A sonic-log model (above) and a corresponding 2-D synthetic seismic section (below). The seismic section illustrates the synthetic response to the thinning of the Wabamun and Cairn salts from 30 m and 35 m, respectively. A 25-ms, 0-phase Ricker wavelet was used; vertical axes give two-way traveltime in 10-ms graduations.

study area since the Paleozoic. This is consistent with the finding of Oliver and Cowper (1983) of Late Cretaceous salt removal in the Rumsey area (Twp. 33, Rge. 19W4) which is just on the southern edge of our study area (Figure 3).

The reconstruction of the original distribution of the Wabamun salts studied here is beyond the scope of this paper; however, a methodology for effecting this reconstruction is presented in another paper (Anderson et al., 1989b). Here, an initial step has been taken in that the present-day salt distribution within a relatively small study area has been determined and areas of extensive dissolution therein have been differentiated from areas of nondissolution.

It is important that the geophysicist working in southern Alberta be aware of the distribution of these and other salts

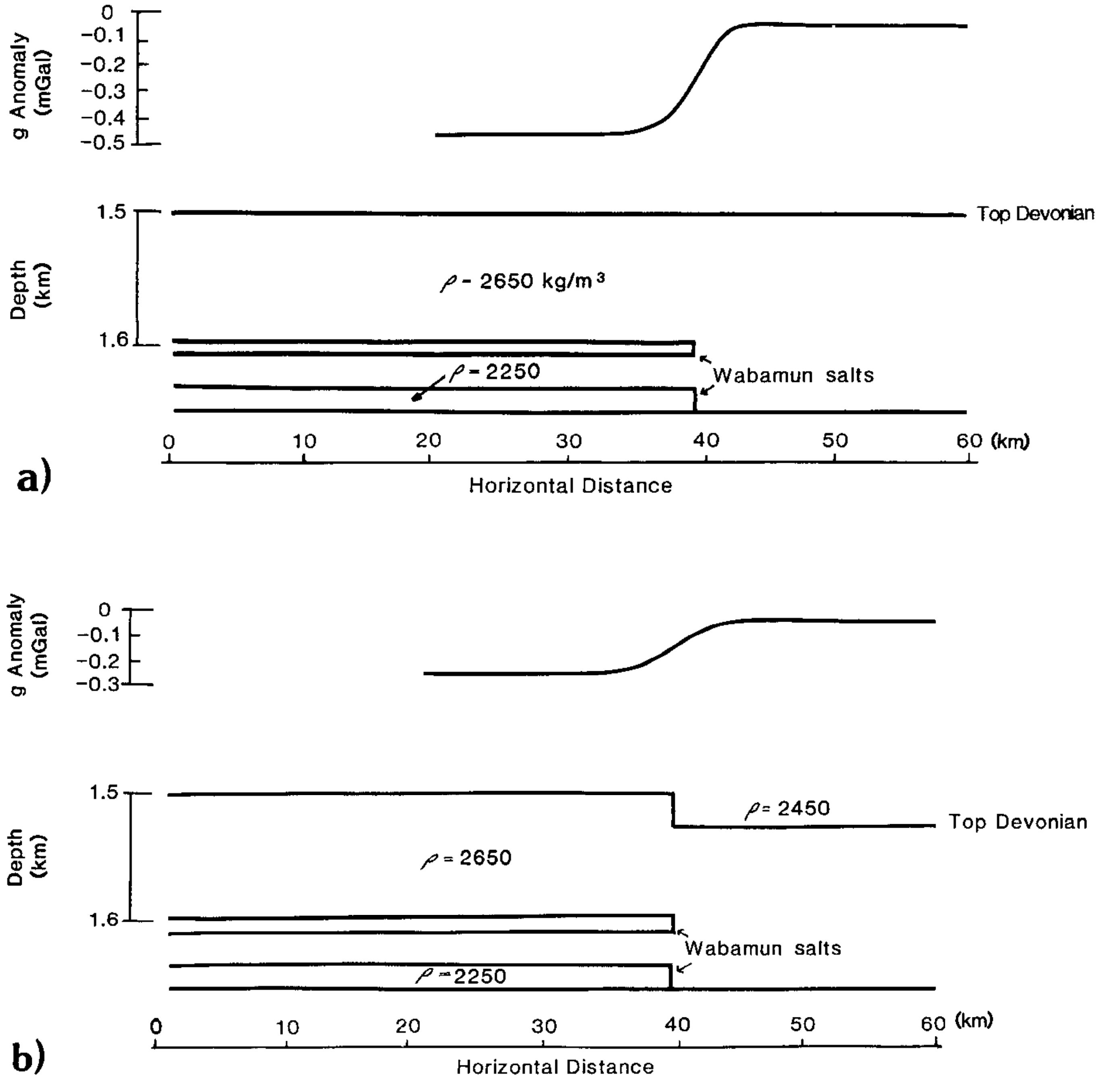


Fig. 17. Model gravity profiles (courtesy of Wild Rose Exploration Services Ltd.) across the edges of two Wabamun salt remnants: (a) assuming dissolution occurred during the Devonian; (b) assuming dissolution occurred entirely after the Devonian. The model of (b) is based on actual logs (slightly modified) from the two wells: 12-31-34-20W4 (salt-bearing) and 15-27-34-20W4 (no salt), both of which are within the study area.

(Anderson et al., 1989a) and their expected seismic and gravity signatures. The authors are aware of several instances where drape across salt remnants has been erroneously interpreted as closure across an underlying Leduc Formation reef and other instances where the salts themselves have been misinterpreted as porosity within the Nisku Formation.

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