Reconstruction of the Leduc (Cairn) and Wabamun salts, Youngstown area, southern Alberta

(Twps. 25-35, Rges. 5-20 W4M)

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ABSTRACT

The Late Devonian age (Wabamun Group and Leduc Formation) halite deposits in the Youngstown area, Alberta, Canada (T25-35, R5-20W4M) have been leached to the extent that they are now preserved only as isolated bodies of irregular shape and variable areal extent, having maximum net thicknesses on the order of 40 m and 45 m respectively.

In an effort to elucidate the dissolution of these salts, we have conducted a well-log based study of the Youngstown area. We have identified correlation patterns involving the thicknesses of the Wabamun and the Leduc intervals, structural relief at the Wabamun and Leduc levels, relief along post-Devonian horizons, and the thicknesses of the salt remnants. On the basis of these relationships, we have reconstructed the distribution of these salts at selected times from late Paleozoic to the present. We have concluded the following:

A) Up to 45 m of Leduc salt was deposited in each of two main sub-basins in the eastern part of the study area (on the shelfward side of the developing Leduc fringing reef complex).

B) About 40 m of Wabamun salt was uniformly deposited throughout the Youngstown study area.

C) Both the Wabamun and Leduc salts were extensively leached subsequent to deposition. The dissolution of these salts was initiated and/or enhanced by some or all of four principal processes: 1) the near-surface exposure of these salts, as a result of the erosion of the overlying Paleozoic sediment during the pre-Cretaceous hiatus; 2) the partial dissolution of underlying salts; 3) regional faulting/fracturing during the mid-Late Cretaceous; and 4)

glacial loading and unloading.

D) The leaching of both salts appears to have been self-perpetuating; a process whereby fractures, created by the collapse of overlying strata, provide conduits for water thereby facilitating further dissolution.

INTRODUCTION

The halite salts of the Wabamun Group (Figures 1, 2, 3 and 4) are preserved throughout much of southern Alberta as isolated to contiguous bodies of irregular shape, having maximum net thicknesses on the order of 40 m. The Leduc salts (Figures 1, 2, 3 and 5), in contrast, appear to be preserved only as a single, more-or-less contiguous body with a maximun net thickness on the order of 45 m. Both the Leduc and Wabamun salts are thought to have been more widely deposited than their present-day distribution might suggest, and both are believed to have been extensively leached (Anderson, 1991; Anderson and Brown, 1987, 1991a,b; Anderson et al., 1988, 1989; Hopkins et al., 1987; Meijer Drees, 1986 and Oliver and Cowper, 1983).

In an effort to elucidate the timing, magnitude, and mechanisms of salt dissolution in southern Alberta, Anderson and Brown (1991b) reconstructed the distribution of the Wabamun Group salts in the Stettler area (T30-45, R10-25W4M) at various times since their deposition. On the basis of their suite of paleo-distribution maps, these authors concluded that the dissolution of the Wabamun Group salts in the Stettler area occurred, in places, more-or-less continuously from the late Paleozoic to the present, and as a result of several principal processes. In support of their conclusions Anderson and Brown demonstrate that:

A) On a local scale, the thickness of the Wabamun interval varies by up to 40 m, and can be directly and linearly correlated to the thickness of the remnant Wabamun salt, suggesting that these salts were widely distributed, uniformly deposited, and extensively leached.

B) Spectacular collapse features are imaged on seismic data across the present-day edges of remnant Wabamun salt, evidence that leaching and collapse have occurred.

C) Post-salt strata drape across remnants of both Wabamun and Leduc salt, implying that some dissolution of these salts has occurred.

D) Wabamun salts are not generally encountered along the Wabamun subcrop edge, suggesting that the dissolution of the these salts initiated along the Wabamun outcrop during the pre-Cretaceous hiatus.

E) There is a pronounced orthogonal pattern to the dissolution of the Wabamun Group salts in the Stettler area of Alberta (T30-45, R10-25W4M). This pattern of leaching is consistent with regional faulting/fracturing during the mid-Late Cretaceous and with the thesis that dissolution is self-perpetuating: a process whereby the collapse of overlying strata enhances both their porosity and permeability, thereby providing a conduit for unsaturated water and facilitating further dissolution.

F) Present-day drainage patterns appear to correlate, in places, to areas where one or both salts are thin or absent suggesting that dissolution has occurred in the post-Pleistocene, possibly as a result of glacial loading and unloading.

We have followed up these previous studies of salt dissolution in southern Alberta, and we have analyzed the leaching of the Wabamun Group and Leduc Formation salts in the Youngstown study area of southern Alberta (T25-35, R5-20W4M). Following the methodology of Anderson and Brown (1991b), we have reconstructed the distribution of these Late Devonian salts at various times since their deposition (Figures 6-15). This suite of paleo-reconstructed maps is of significance in that it corroborates previous studies of salt dissolution in southern Alberta (Anderson and

Brown, 1991b; Cederwall and Anderson, 1991; Hopkins et al., 1987; and Oliver and Cowper, 1983), and further elucidates some of the large-scale mechanisms of salt dissolution.

ORIGINAL DISTRIBUTION: LEDUC AND WABAMUN SALTS

LEDUC SALTS

The lithology of the Upper Devonian age, Leduc Formation in the Youngstown area of Alberta varies significantly. Near the edge of the East Ireton Shale Basin (Figure 16), the Leduc is dolomitized and described as fringing reef. Shelfward (to the east in the study area) of this fringing reef complex, the Leduc becomes increasingly evaporitic and consists predominantly of interlayered dolomites, anhydrites and in places a basal halite unit. From a facies perspective, the Leduc Formation in the eastern part of the study area is equivalent to the evaporitic Duperow Formation of southwestern Saskatchewan.

In order to estimate the original (end of Leduc time) distribution of the Leduc salts in the Youngstown study area (Figure 6) and following the methodology described by Anderson and Brown (1991b), we constructed a suite of four maps: 1) net Leduc salt, based on sonic/density/caliper log control only; 2) Leduc-isopach; 3) present-day Leduc-structure (Figure 17); and 4) restored Leduc-structure (Figure 18).

Our analysis of this map suite indicates that there is a direct, linear correlation between the structure at the top of the Leduc and the thickness of the Leduc interval. We have also concluded that there is a direct correlation between these values and the thickness of Leduc salt that was dissolved in post-Leduc time.

Outside of the postulated Leduc salt sub-basins (Figure 6) for example, the top of the Leduc is consistent with the restored Leduc-structure map, suggesting that little, if any, Leduc salt was either deposited and/or dissolved in post-Leduc time. Within the sub-basins however, the present-day structure values are lower than the restored structure values, except at those well locations where thick remnant salt is preserved. Our conclusion is that these relative structural lows can provide a direct and reasonable estimate of the thickness of Leduc salt that was dissolved in post-Leduc time. It is on the basis of the apparent correlations between these data, that we have reconstructed the original distribution of the Leduc salt within the Youngstown study area.

More specifically at each control point, the difference between the present-day Leduc-structure and the restored Leduc-structure was interpreted to be equal to the thickness of salt dissolved in post-Leduc time. In those areas where the Leduc salts are now absent, these values are thought to represent the original salt-thickness. At those control points where remnant salts are preserved, our estimate of the original salt-thickness was determined by summing the thickness of the remnant and our estimate of post-Leduc dissolution. In those areas where deep well control is absent, the contouring of the present-day Leduc-structure map was constrained by apparent local trends and structural patterns along shallower horizons.

WABAMUN SALTS

The Upper Devonian Wabamun Group in the Youngstown area is subdivided into the Stettler and Big Valley formations (southern plains area, Alberta; Figure 1). The Stettler consists predominantly of interlayered dolomites, anhydrites and isolated to contiguous remnants of halite; the Big Valley is composed of green shales and fossiliferous limestones.

The salts of the Wabamun Group (Stettler Formation) have been mapped in detail by Anderson et al. (1988) and Anderson and Brown (1991) over the Stettler area

(T30-45, R10-25W4M). These authors concluded that about 40 meters of these halites were deposited throughout much of southeastern Alberta and subsequently leached.

In order to estimate the original distribution of the Wabamun salt in the Youngstown study area, we constructed four maps: 1) net salt, based on sonic/density/caliper log control only; 2) Wabamun-isopach; 3) present-day Wabamun-structure; and 4) restored Wabamun-structure.

Our analysis of this map suite indicates that outside of the postulated Leduc sub-basins, there is a direct, linear correlation between the structure at the top of the Wabamun and the thickness of the Wabamun interval. We have also concluded that there is a direct correlation between these values and the thickness of Wabamun salt that was dissolved in post-Wabamun time.

More specifically, outside of the postulated Leduc salt sub-basins the top of the Wabamun is up to 40 m lower than the respective restored Wabamun-structure contour value. At control well sites, the difference between these two structure contour maps plus the thickness of any remnant Wabamun salt is consistently about 40 m. At control sites within the postulated Leduc salt sub-basins, the difference between these two structure contour maps, plus the thickness of any remnant Wabamun salt, less our estimate of the thickness of Leduc salt that was dissolved in post-Wabamun time, is consistently about 40 m. These relationship supports our thesis that about 40 m of Wabamun salt were uniformly deposited within the Youngstown study area.

PRESENT-DAY DISTRIBUTION OF THE LEDUC AND WABAMUN SALTS

LEDUC SALTS

In order to estimate the present-day distribution of the Leduc salts (Figure 14), we analyzed three maps: 1) original salt-thickness (Figure 6); 2) present-day Leduc-structure (Figure 17); and 3) restored Leduc-structure (Figure 18). At each well control point, our present-day salt-thickness estimate (A) is equal to the original (end Leduc time) salt-thickness (B) less the difference between the restored (C) and present-day (D) Leduc-structure values (Figures 21 and 22). Following Anderson and Brown (1991b), we use the formula:

$$A = B - (C - D).$$

In those areas where deep well control is absent, the contouring of the present-day Leduc-structure map was constrained by apparent local trends and structural patterns along shallower horizons. At all available deep well control points, our present-day salt-thickness estimate (A) and the actual thickness of the remnant salt (as per the well-log data) were effectively the same.

The original and present-day thicknesses of the Wabamun salts were estimated concurrently with our analysis of the Leduc salts. This was necessary in order to ensure that our paleo-distribution maps were compatible.

WABAMUN SALTS

In order to estimate the present-day distribution of the Wabamun salt (Figure 15), we analyzed three maps: 1) original salt-thickness (Figure 7); 2) present-day Wabamun-structure; and 3) restored Wabamun-structure. At each well control point our present-day salt-thickness estimate (A) is equal to the original salt-thickness (40 m) plus our estimate of the thickness of Leduc salt dissolved in post-Wabamun time (B) less the difference between the restored (C) and present-day (D) Wabamun-structure values. We use the formula:

$$A = 40 \text{ m} + B - (C - D).$$

At all available deep well control points, our present-day salt-thickness estimate (A) and the actual thickness of the remnant Wabamun salt (as per the well-log data) were effectively the same. In those areas where Wabamun control is sparse, the contouring of the present-day Wabamun-structure map was constrained by apparent local trends and structural patterns along shallower horizons).

PALEO-DISTRIBUTION OF THE LEDUC AND WABAMUN SALTS

METHODOLOGY

The paleo-distributions of the Leduc and Wabamun salts were estimated following the three steps outlined below:

Step 1) The subsea depths to the eight horizons listed below were determined at about 3500 well locations within the study area; (increasing depth and age, top to bottom):

A) top Lea Park
B) top Colorado
C) top Second Specks
D) top Viking
E) top Mannville
F) base Cretaceous
G) top Wabamun
H) top Leduc

Step 2) Both present-day and restored structure maps were drafted for each of these eight data sets. (Figures 17 and 18, and 19 and 20 are the present-day and restored maps for the Leduc and Viking, respectively. Ideally, the restored map for a particular horizon represents the pattern of structural relief that would exist if we replaced all of the Leduc (and Wabamun) salts that were dissolved after deposition of that respective horizon. Differences in structural relief between corresponding present-day and restored structure maps are therefore estimates of the thickness of all of the salt (both Leduc and Wabamun) removed after the deposition of the relevnt strata (Figures 21 and 22).

Step 3) The paleo-distribution of the Leduc and Wabamun salts were determined at the following times following the methodology outlined below:

A) end Leduc (Figure 6)
B) end Wabamun (Figure 7)
C) end Mannville
D) end Viking (Figure 8 and 9)
E) end Second Specks
F) end Colorado (Figure 10 and 11)
G) end Lea Park (Figure 12 and 13)
H) present-day (Figure 14 and 15)

The salt-thicknesses at these times were estimated on the basis of: 1) the original salt distribution map; 2) the present-day structure maps; and 3) the restored structure maps. For example, the total thickness of Leduc salt at the end of Viking time (E) was calculated to be equal to the present-day thickness of the Leduc salt (F) plus the difference between the restored (G) and present-day (H) Viking structure values less the thickness of Wabamun salt leached in post-Viking time (I). We use the equation:

$$E = F + (G - H) - I.$$

In an analogous manner, we concurrently estimated the thicknesses of the Leduc and Wabamun salts at the other selected times within the Cretaceous. At most of our control points this process was relatively straightforward (or at least constrained) for one of several reasons: 1) Leduc salts were not deposited (as per Figure 6) and hence only Wabamun salts were leached; 2) thick (on the order of 40 m) Leduc salts were preserved (Figure 14) suggesting that only Wabamun salts were leached; 3) the thicknesses of the remnant Wabamun and/or Leduc salts were known from well control; and 4) both salts had been totally leached from the section (Figures 14 and 15). The agreement between our present-day salt-thickness estimates (A) and the actual thicknesses of the remnant salts, and the compatibility of the suite of reconstructed salt distribution maps suggests to us that the paleo-reconstructed salt-thickness estimates are reliable to within ± 10 m or less.

PALEO-RECONSTRUCTIONS

The past and present-day distribution of the Leduc and Wabamun salts is depicted in Figures 6-15 (decreasing age). On the basis of these maps we have concluded.

1) The Leduc salts in the study area are thought to have been deposited in two, possibly interconnected, fault/fracture controlled, restricted basins on the shelfward side of the developing Leduc fringing-reef complex (Figures 6 and 16). The maximum thickness of the Leduc salt in the study area was probably on the order of 45 m.

There are several reasons for sugesting that the Leduc salt-basins were fault/fracture-controlled: 1) prominent diffraction patterns and vertical offsets are clearly visible along near-basement events (pre-Leduc) on seismic data from the Leduc salt-basin areas (unfortunately we do not have access to enough data to conclusively establish the orientation of these lineaments); the original, postulated salt-basins are oriented more-or-less parallel to the edge of the fringing-reef complex, suggesting that both features could have been influenced by the reactivation of pre-existing planes of weakness (a near-orthogonal pattern of faulting/fracturing can satisfactorily explain any observed non-linearities in the shape of the basin); 3) the western depositional edges of the Leduc salt are interpreted as being abrupt rather than gradational, a feature more characteristic of a fault-controlled basin than of a gradual environmental change; 4) the dissolution of both the Wabamun and Leduc salts appears to have initiated along an orthogonal set of lineaments, that possibly represent pre-existing faults and/or fractures; and 5) with respect to the western salt-basin, dissolution of the Leduc salts has been most extensive near the basin margins, perhaps as a result of the reactivation of the fractures/faults that influenced the development of the basin originally.

2) About 40 m of Wabamun salt were uniformly deposited throughout the Youngstown study area (Figure 7). This conclusion is based on our observation that there is a direct, linear correlation between the structure at the top of the Wabamun, the thickness of the Wabamun interval, and the thickness of Wabamun salt that was dissolved in post-Wabamun time. All three values vary, in a relative sense, by 40 m or less.

3) The dissolution of the Leduc and Wabamun salts was initiated and/or enhanced by some or all of four principal processes: 1) near-surface exposure,

as a result of the erosion during the pre-Cretaceous hiatus; 2) regional faulting/fracturing during the mid-Late Cretaceous; 3) glacial loading and unloading; 4) the partial dissolution of the underlying salts.

4) With respect to erosion during the pre-Cretaceous, the earliest phases of Wabamun salt dissolution appear to have occurred along the projected Wabamun outcrop edge during the pre-Cretaceous (Figures 7, 9, 11, 13 and 15). As indicated on the suite of reconstructed maps, the dissolution front, that was established along the subcrop edge, appears to have migrated over time to the southwest, suggesting that leaching is a self-perpetuating process. As noted on Figure 7, minor dissolution of the Leduc salt along the margins of the postulated sub-basins could have occurred during the post-Leduc/pre-Viking interval. This apparent phase of leaching could have been initiated during the pre-Cretaceous hiatus, and in response to an influx of unsaturated water along the Leduc outcrop to the northeast of the study area.

5) The orthogonal pattern displayed on the suite of Wabamun and Leduc salt paleo-distribution maps strongly suggest that dissolution fronts developed along a suite of more-or-less orthogonally-oriented (NNE-WNW) regional fault/fracture planes (Figure 28) during the mid-Late Cretaceous (Figures 6-15). The apparent expansion of these areas of dissolution over time, implies that the dissolution fronts migrated laterally. It is interesting to note that the edge of the fringing reef complex, as well as edges of the postulated Leduc sub-basins, are consistent with the hypothesized fault/fracture planes. Perhaps these lineaments are reactivated planes of weakness.

6) Several lakes to the west of the postulated Leduc sub-basins (Gough, Sullivan and Dowling; Figure 15) are situated in areas where the Wabamun salts are thin or absent; all of the larger lakes in the Leduc sub-basin area (Plover, Antelope, Goose, Gopher, Contracosta, Coleman, Oakland, and the Berry Reservoir) are situated in areas where the Leduc salts have been extensively leached. These relationships suggest that a significant salt leaching occurred in post-glacial times, possibly in response to glacial loading and unloading and an influx of unsaturated glacial melt water. It is very possible that leaching is still occurring.

7) Elk Point (Cold Lake and Prairie Evaporite) salts are present within the study area. Although we have found no evidence that these salts have been leached in the study area, it is possible that the dissolution of these underlying halites could have triggered the leaching of the Wabamun and/or Leduc salt. Within the confines of the postulated Leduc sub-basins, the dissolution of the Wabamun salt could have been triggered by the leaching of the underlying Leduc salt. Such leaching could have occurred at any time after the deposition of the Wabamun salt.

8) The dissolution of the Leduc and Wabamun salts has occurred at various times during the geologic past, supporting the thesis that dissolution, in places, has been more-or-less continuous since deposition. Several trigger mechanisms have been identified and it has been suggested that leaching is self-perpetuating. With respect to this self-perpetuating process, we note that the established dissolution fronts do not advance at a uniform rate. These observations suggest that a number of secondary factors influence salt dissolution. Consideration should be given to effects of features and/or processes such as regional tectonism, periods of emergence, underlying reefs, the differential compaction of pre-salt sediment, uneven loading and

unloading, gypsum to anhydrite conversion (and vice-versa), facies changes within both the salt and encompassing strata, the local hydrological and geochemical environment and changes therein, and the effects of oil and gas wells.

9) The timing of salt dissolution is of significance to the explorationist for several reasons: 1) stratigraphic traps can form where reservoir facies were either preferentially deposited or preserved in salt-dissolution lows; 2) reservoir facies can develop in high energy environments such as topographic highs that are controlled by salt edges or remnants; 3) structural traps can form where reservoir facies are draped across salt remnants or collapse features; and 4) salt remnants can be misinterpreted as reefs, faults or other structural features.

10) The methodology developed by Anderson and Brown (1991b), and employed in this study, is based on the premise that the dissolution of subsurface salt causes the contemporaneous collapse of the overlying strata. The thickness of leached salt and the magnitude of collapse are assumed to be equal. Although the methodology appears to be relatively robust, as evidenced by the suite of compatible, consistent, restored structure maps, it might not, in places, adequately account for processes such as: 1) non-uniform primary deposition; 2) erosion; 3) differential compaction; 4) horizontal strain associated with collapse; 5) differential compaction of infill (compensation) sediments; 6) salt flow; 7) dissolution of underlying salts; and 8) faulting.

SUMMARY

About 40 m of Wabamun Group salt are thought to have been uniformly deposited throughout the Youngstown area; the Leduc salts (up to 45 m thick), in contrast, are thought to have been deposited only within two principal, fault/fracture-controlled, restricted sub-basins on the shelfward side of the developing Leduc fringing-reef complex. Both salts appear to have been extensively dissolved more-or-less continuously since deposition and by a variety of processes.

Our investigations suggest that the dissolution of the Wabamun and Leduc salts was initiated and/or enhanced by some or all of four principal processes: 1) the near-surface exposure of these salts, as a result of the erosion of the overlying Paleozoic sediment during the pre-Cretaceous hiatus; 2) the partial dissolution of underlying salts; 3) regional faulting/fracturing during the late Cretaceous; and 4) glacial unloading.

Herein, we have presented a suite of reconstructed salt distribution maps in order to substantiate the theses of continuous leaching and diverse mechanisms. We have, as well, discussed our reconstruction methodology and concluded that it is relatively robust. We are hopeful that this technique can be applied to other areas where the effects of leaching are not effectively masked by processes like erosion, compaction and salt flow.

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Figure 1. Stratigraphic chart for the Paleozoic of southern and central Alberta (modified after AGAT Laboratories, 1988): a) central plains; b) south-central mountains and foothills; c) southern plains. In the Youngstown study area (southern Alberta), Devonian halites occur within several stratigraphic intervals: Elk Point Group (both Cold Lake and Prairie formations), Beaverhill Lake Group, Leduc Formation and Wabamun Group (Stettler Formation). The authors have found conclusive evidence that the Leduc and Wabamun salts have been extensively dissolved within the confines of the study area, but no conclusive evidence that the older halites have been leached.

Figure 2. Stratigraphic chart for the Mesozoic of southern and central Alberta (modified after AGAT Laboratories, 1988): a) central plains; b) south-central mountains and foothills; c) southern plains.

Figure 3. Gamma-ray and sonic logs for the Wabamun to Cooking Lake intervals in the 17-11 and 16-24 wells. (Note: 1) this cross-section has been flattened at the top of the Cooking Lake; and 2) in the report, the Cairn salt and the Cairn/Cooking Lake intervals are referred to as the Leduc salt and lower Leduc intervals respectively.) The remnant Leduc and Wabamun salts are 36 m and 20 m thick in the 16-24-25-13W4M well; these salts have been leached from the 7-11-24-15W4M well.

Figure 4. 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 (fossiliferous shale). In addition 5 = the Wabamun (and equivalents) subcrop area

and 6 = the study area. Also shown are the locations of the two wells of Figure 3 (7-11 and 16-24).

Figure 5. Distribution of the Leduc Formation and its equivalents within the western Canadian interior plains (modified after Belyea, 1964; Meijer Drees, 1986). The approximate areal extent of the Leduc (Cairn) halite has been highlighted.

Figure 6. Contour map (in meters) depicting our interpretation of the original distribution of the Leduc Formation salts in the Youngstown study area. These salts are thought to have been deposited in two principal, possibly fault-controlled, restricted basins (east and west basins) on the shelfward side of the developing Leduc fringing reef complex. The solid line represents the Wabamun subcrop edge; the dashed lines denote the edges of Leduc reef complexes. The bold dots highlight those sections for which there is well-log control at the top of the Leduc.

Figure 7. Contour map (in meters) depicting our interpretation of the original distribution of the Wabamun Group salts in the Youngstown study area. About 40 m of Wabamun salt is thought to have been uniformly deposited throughout the study area. This map is consistent with the entire suite of Wabamun-structure and isopach maps. The wells incorporated into the cross-section of Figure 27 are highlighted. The solid lines represent the Wabamun subcrop edge; the dashed lines denote the edges of Leduc reef complexes.

Figure 8. Contour map (in meters) showing our interpretation of the distribution of the Leduc salts at the end of Viking time. This map suggests that during the end Leduc to end Viking interval, some (albeit minimal) dissolution of the Leduc salts occurred along the western margin of the west salt-basin. If extensive leaching occurred elsewhere, it cannot be confidently mapped on the basis of available well-log control.

Figure 9. Contour map (in meters) showing our interpretation of the distribution of the Wabamun salts at the end of Viking time. Extensive dissolution has occurred along and basinward of the Wabamun subcrop edge; additional leaching could have occurred along the margins of the Leduc salt-basin in response to the hypothesized on-going dissolution of the underlying Leduc salts.

Figure 10. Contour map (in meters) showing our interpretation of the distribution of the Leduc salts at the end of Colorado time. A comparison of this map with Figure 8, suggests that an extensive phase of salt dissolution was initiated by regional faulting/fracturing during Colorado time.

Figure 11. Contour map (in meters) showing our interpretation of the distribution of the Wabamun salts at the end of Colorado time. A comparison of this map with Figure 9, suggests that an extensive phase of salt dissolution was initiated by regional faulting/fracturing during Colorado time.

Figure 12. Contour map (in meters) showing our interpretation of the distribution of the Leduc salts at the end of Lea Park time. The dissolution fronts that were established by the end of Colorado time appear to have migrated laterally, supporting our thesis that salt leaching is a self-perpetuating process.

Figure 13. Contour map (in meters) showing our interpretation of the distribution of the Wabamun salts at the end of Lea Park time.
The dissolution fronts that were established by the end of Colorado time appear to have migrated laterally, supporting our thesis that salt leaching is a self-perpetuating process.

Figure 14. Contour map (in meters) depicting our interpretation of the present-day distribution of the Leduc salts. The lakes in the vicinity of the remnant salt are all situated in areas of extensive dissolution, suggesting that significant leaching has occurred in the post-Pleistocene. This latest phase of dissolution could have been triggered by glacial loading and unloading.

Figure 15. Contour map (in meters) depicting our interpretation of the present-day distribution of the Wabamun salts. Many of the lakes in the region are situated in areas of extensive dissolution, suggesting that significant leaching has occurred in the post-Pleistocene. This latest phase of dissolution could have been triggered by glacial loading and unloading.

Figure 16. Contour map (in meters) of the subsea depth to the top of the Leduc. The bold dots highlight those sections for which there is well-log control at the top of the Leduc. In those areas where deep well control is absent, the contouring of the present-day Leduc structure map was constrained by apparent local trends and structural patterns along shallower horizons.

Figure 17. Restored Leduc structure contour map (in meters). Ideally, the contours represent the pattern of structural relief, that would be observed if all of the original Leduc salt (dissolved in post-Leduc time) were replaced.

Figure 18. Contour map (in meters) of the subsea depth to the top of the Viking.

Figure 19. Restored Viking structure contour map (in meters). Ideally, the contours represent the pattern of structural relief, that would be observed if all of the original Leduc and Wabamun salts (dissolved in post-Viking time) were replaced.

Figure 20. Schematic diagram illustrating the technique used to calculate the present-day thickness of the Leduc salt. At each well control point, our present-day salt-thickness estimate PST (A) is equal to the original salt-thickness OST (B) less the difference between the restored RLS (C) and present-day PDL (D) Leduc structure values. We use the formula: A = B + (C - D).

Figure 21. Schematic diagram illustrating the technique used to calculate the thickness of leached Leduc salt (post-Leduc dissolution). On the map the top of the Leduc at each control point has been noted and the restored Leduc structure has been contoured; on the section both the restored and present-day Leduc tops have been correlated. At each well control point, the thickness of salt dissolved in post-Leduc time is equal to the difference between the restored and present-day Leduc structure values. For example at wells A and B, 0 m (-444 m - (-444 m)) and 20 m (-428 m - (-448 m)) of salt have been dissolved respectively.

Figure 22. West-to-east geologic cross-section from the Youngstown study area illustrating the discontinuous nature of the Wabamun and Leduc salts. Both present-day and reconstructed profiles are displayed on the cross-section. The wells incorporated into the cross-section are highlighted on Figure 7.

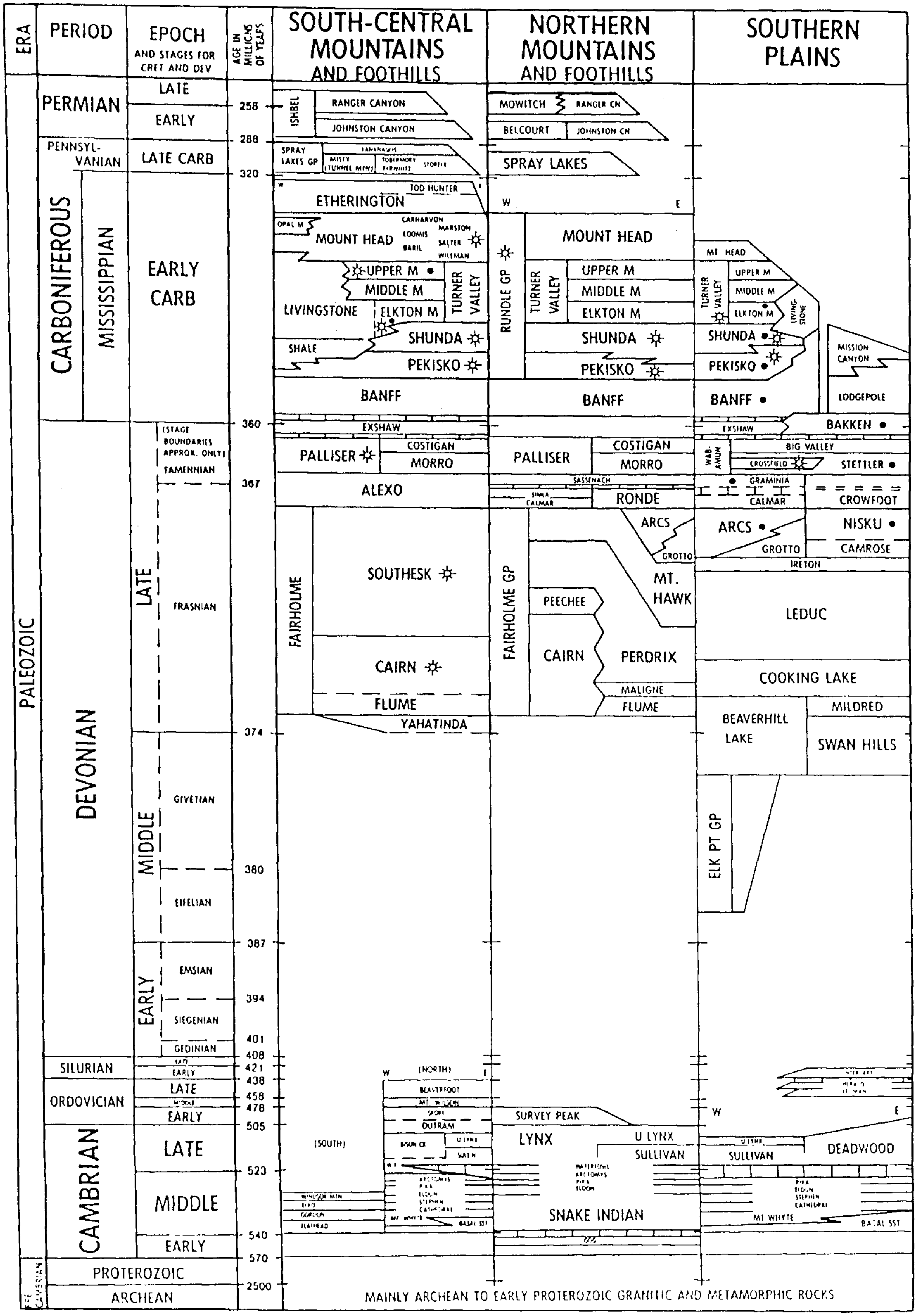

Figure 1. Stratigraphic chart for the Paleozoic of southern and central Alberta (modified after AGA Laboratories, 1988): a) central plains; b) south-central mountains and foothills; c) southern plains. I the Youngstown area (southern Alberta), Devonian halites occur within several stratigraphic interval Elk Point Group (Cold Lake and Prairie formations), Beaverhill Lake Group, Leduc Formation an Wabamun Group (Stettler Formation). The authors have found conclusive evidence that the Leduc an Wabamun salts have been extensively dissolved within the confines of the study area, and no direc evidence that the older halites have been leached.

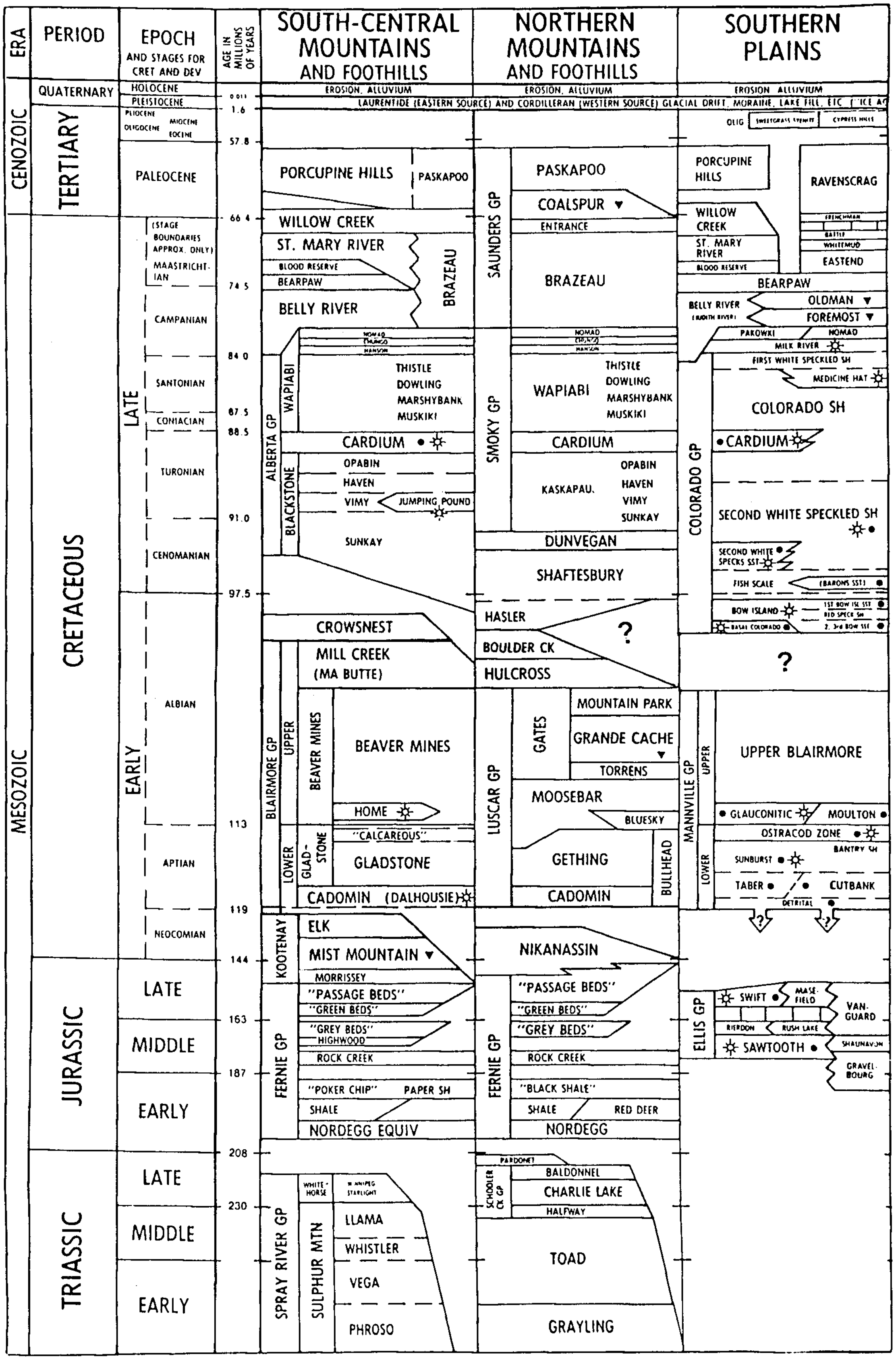

Figure 2. Stratigraphic chart for the Mesozoic of southern and central Alberta (modified after AGAT Laboratories, 1988): a) central plains; b) south-central mountains and foothills; c) southern plains.

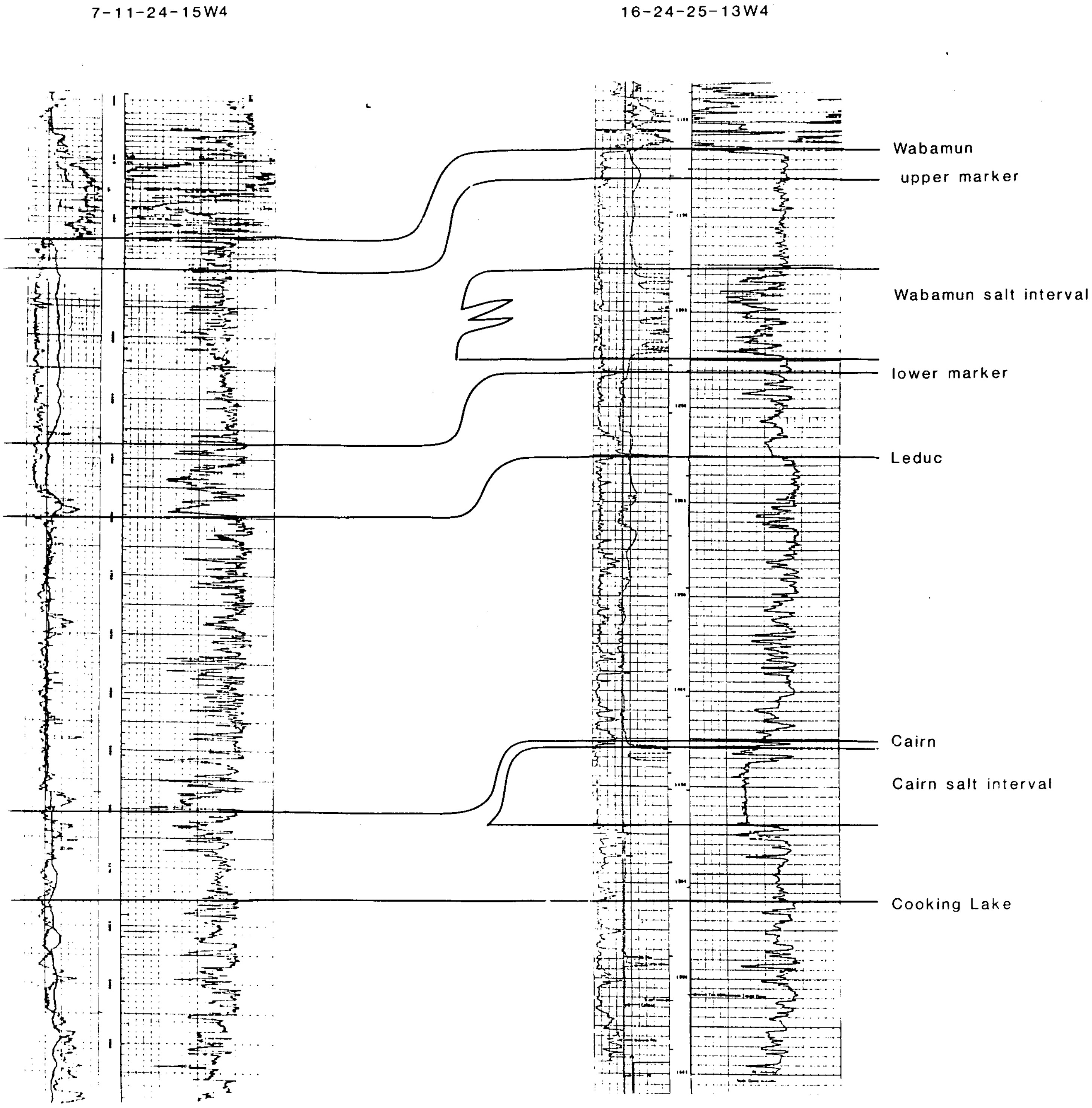

Figure 3. Gamma-ray and sonic logs for the Wabamun to Cooking Lake intervals in the 17-11 and 16-24 wells. (Note: 1) this cross-section has been flattened at the top of the Cooking Lake; and 2) in the report, the Cairn salt and the Cairn/Cooking Lake intervals are referred to as the Leduc salt and lower Leduc intervals respectively.) The remnant Leduc and Wabamun salts are 36 m and 20 m thick in the 16-24-25-13W4M well; these salts have been leached from the 7-11-24-15W4M well.

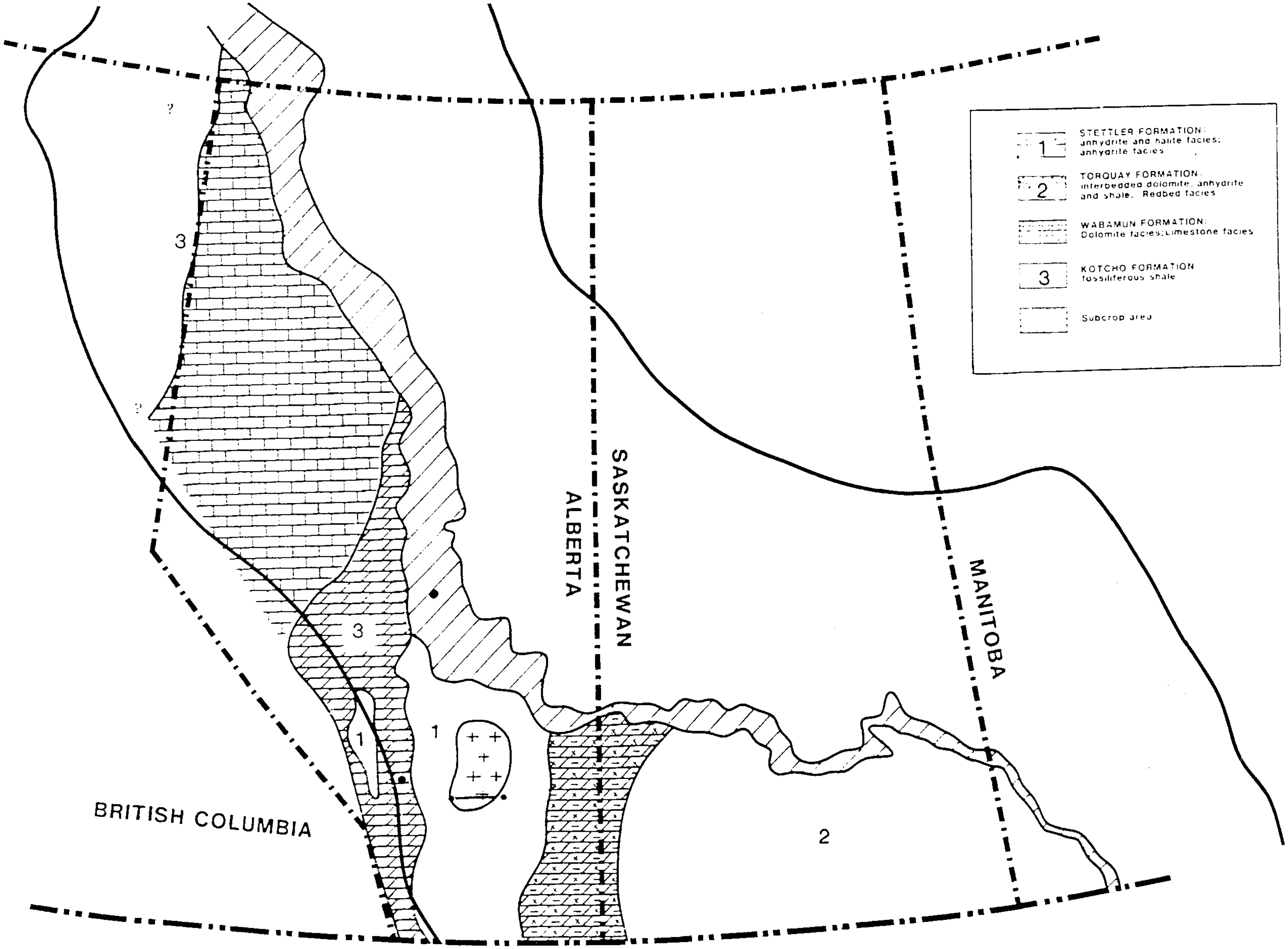

Figure 4. Distribution of the Stettler Formation (basal Wabamun Group) and its equivalents within the western Canadian interior plains (modified after Belyea, 1964; Meijer Drees, 1986). The approximate time equivalents are: 1 = Stettler Formation (white: anhydrite: crosses: halite and anhydrite; 2 =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

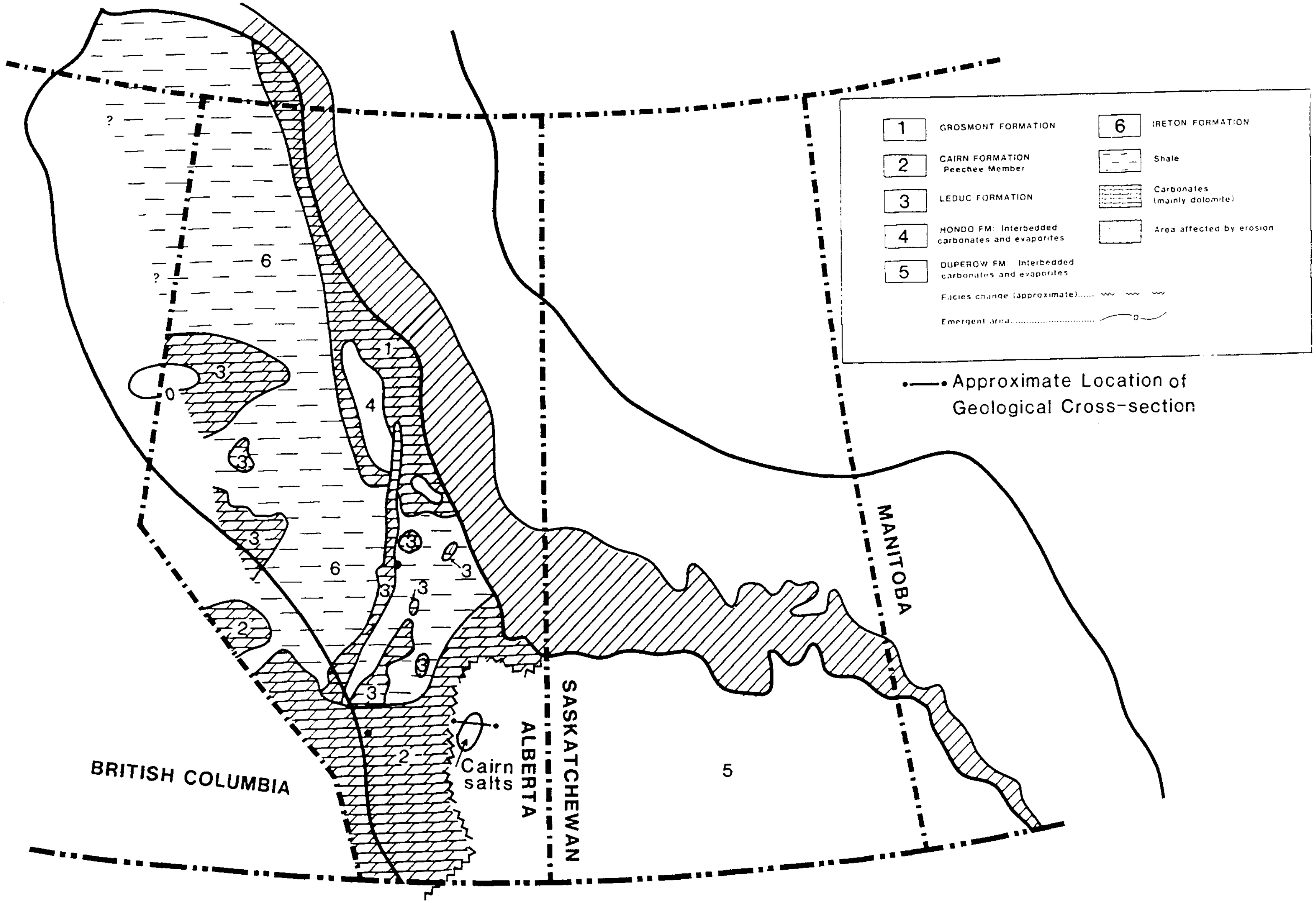

Figure 5. Distribution of the Leduc Formation and its equivalents within the western Canadian interior plains (modified after Belyea, 1964; Meijer Drees, 1986). The approximate areal extent of the Leduc (Cairn) halite has been highlighted.

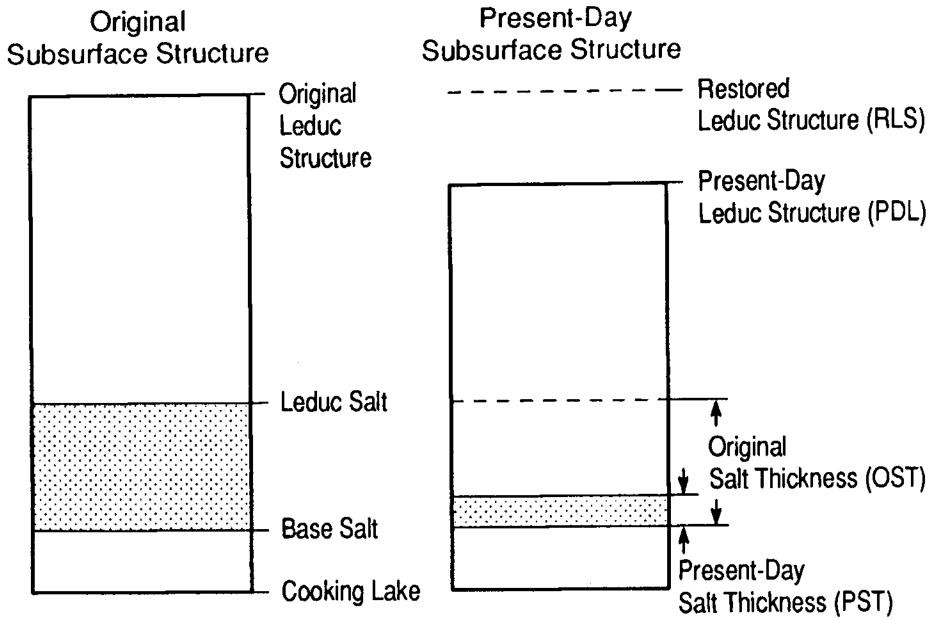

Figure 20. Schematic diagram illustrating the technique used to calculate the present-day thickness of the Leduc salt. At each well control point, **our present-day salt thickness estimate PST (A)** is equal to **the original salt thickness OST (B)** less **the difference between the restored RLS (C) and present-day PDL (D) Leduc structure values**. We use the formula: **(A = B + (C - D))**.

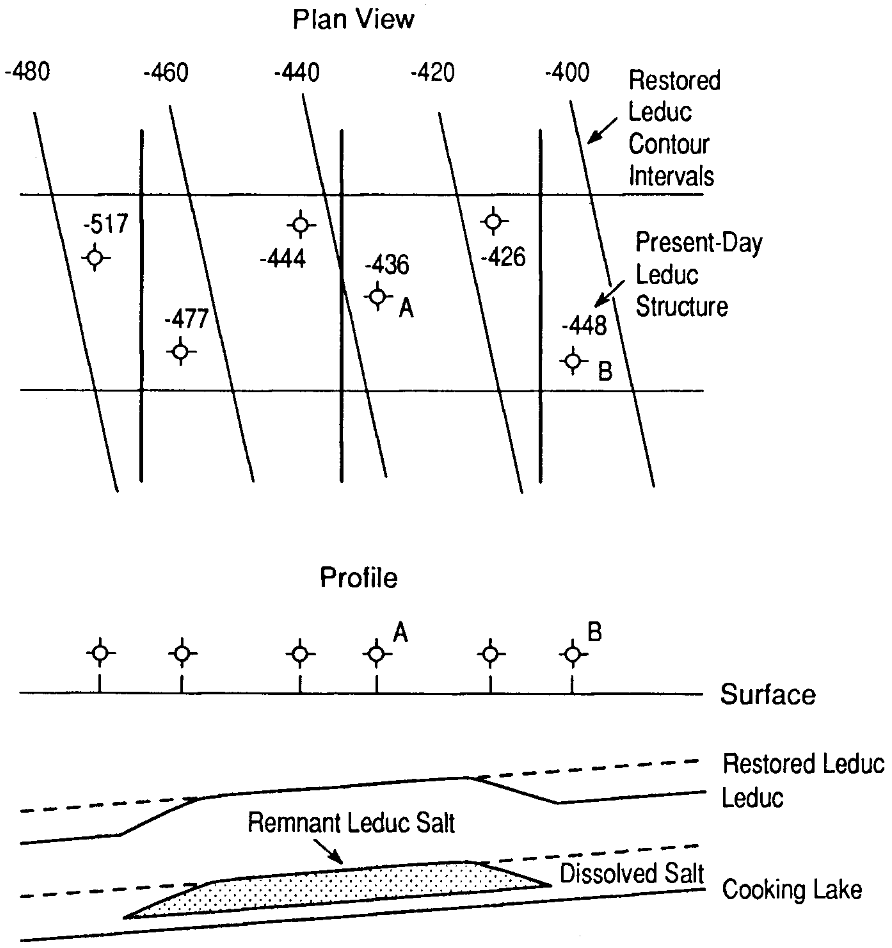

Figure 21. Schematic diagram illustrating the technique used to calculate the thickness of leached Leduc salt (post-Leduc dissolution). On the plan view map the **top of the Leduc** at each control point has been noted and the **restored Leduc structure** has been contoured; on the profile section both the **restored** and **present-day** Leduc tops have been correlated. At each well control point, the **thickness of salt dissolved in post-Leduc time** is equal to **the difference between the restored and present-day Leduc structure values**. For example at wells A and B, 0 m (-444 m - (-444 m)) and 20 m (-428 m - (-448 m)) of salt have been dissolved respectively.

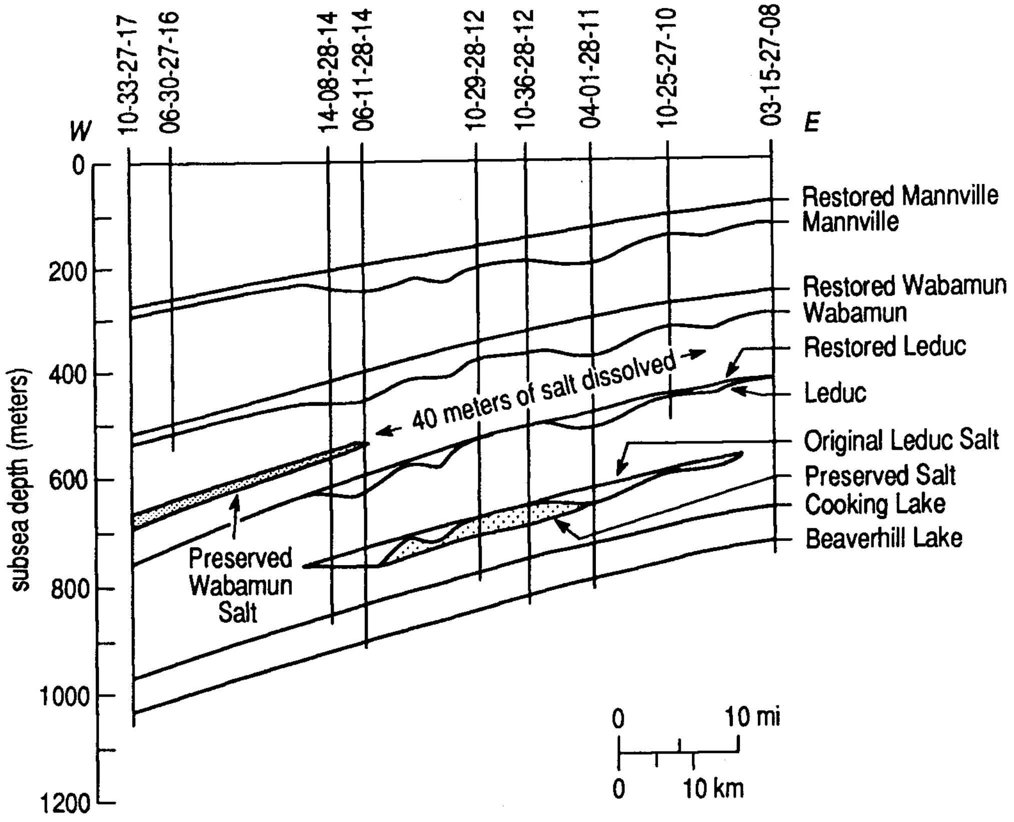

Figure 22. West to east geologic cross-section from the Youngstown study area illustrating the discontinuous nature of the Wabamun and Leduc salts. Both present-day and reconstructed profiles are displayed on the cross-section. The wells incorporated into the cross-section are highlighted on Figure 7.