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A SEISMIC ANALYSIS OF EROSION, SALT DISSOLUTION AND STRUCTURAL RELIEF AT THE PALEOZOIC SUBCROP IN THE SULLIVAN LAKE AREA, SOUTH-CENTRAL ALBERTA

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ABSTRACT

The Paleozoic subcrop, or sub-Cretaceous unconformity, in the Sullivan Lake area of south-central Alberta (T34-35, R12-14W4), is a surface of extreme relief, up to 100 m locally. In this paper, we present two seismic lines and supporting well-log data from the area in support of the thesis that structural relief at the Paleozoic subcrop in the Sullivan Lake area has been controlled mainly by two processes: erosion during the pre-Cretaceous hiatus and the partial dissolution of bedded rock salt within the Famennian-age Wabamun Group.

The first seismic line crosses a dissolution-controlled paleochannel that deeply incised the Devonian strata. On the seismic section, the paleochannel is characterized by: 1) the absence, due to erosion, of the Mississippian event; 2) a pronounced thinning within the Wabamun interval; and 3) Cretaceous and reworked Paleozoic clastics deposited within the channel that are seen to onlap its walls. As a result of the compaction of these channel deposits, the Lower Cretaceous strata are anomalously low across the paleochannel.

The second seismic line crosses an isolated remnant of Wabamun rock salt. The salt-bearing interval is imaged as a moderately high-amplitude peak-trough sequence. Relative to those areas where the rock salt has been effectively leached, the salt-bearing interval is characterized by: 1) an anomalously thick Wabamun interval; 2) up to 25 ms of relative relief at the Mississippian level; and 3) up to 8 ms of velocity pull-up along presalt events. These observations suggest that up to 40 m of residual salt is preserved locally.

The seismic and well-log data presented support the following interpretation. Along the Wabamun subcrop, the edge of which crosses the northeastern part of the Sullivan Lake area, erosion during the pre-Cretaceous was so extensive that the rock salt of the Wabamun Group was exposed to a near-surface environment. Leaching was initiated along a more-or-less continuous front, which roughly paralleled the Wabamun outcrop. This salt-dissolution front migrated in a westerly direction (basinward, or downdip) through the Sullivan Lake area during pre-Cretaceous time and thereafter. As a consequence, Wabamun rock salt is now preserved within the study area only as randomly distributed remnants of variable thickness and limited areal extent.

INTRODUCTION

Throughout the region of south-central Alberta referred to here as the Stettler region (roughly, T30-40, R11-21W4), the Paleozoic subcrop is an unconformable surface (Figure 1) of significant (up to 100 m) localized relief (Belyea, 1964). This subcrop is comprised of Mississippian rocks throughout most of the region (Figure 2), except in its northeastern portion where Devonian strata constitute the subcrop. Three main processes are believed to have contributed to the paleostructure of this subcrop throughout this region: 1) erosion during the pre-Cretaceous; 2) partial dissolution of the Wabamun Group salt; and 3) differential compaction of on-reef versus off-reef strata. The overall effects of these three processes are illustrated by the regional cross-sections of Figure 3 and have been documented by several authors (Oliver and Cowper, 1983; Meijer-Drees, 1986; Hopkins, 1987; Anderson et al., 1988, 1989a, b; Anderson, 1991; Anderson and Franseen, 1991; Anderson and Brown, 1991a, b, 1992).

With regard to erosion, the Paleozoic subcrop in the Stettler region is an erosional surface incised by several fluvial channels. The eastern erosional edge of the Mississippian, as suggested in Figure 3, frequently forms a rather abrupt escarpment. Regarding salt dissolution, the Paleozoic subcrop is typically structurally low at those locations where some or all of the approximately 40 m of originally deposited Wabamun salt has dissolved, relative to areas where the salt is preserved (Figure 4). The third process to have affected structure at the Paleozoic subcrop in the Stettler region, differential compaction between on-reef and off-reef sediment (Figure 3), has not been a factor in the Sullivan Lake area, where the thickness of the Leduc is relatively constant (Belyea, 1964).

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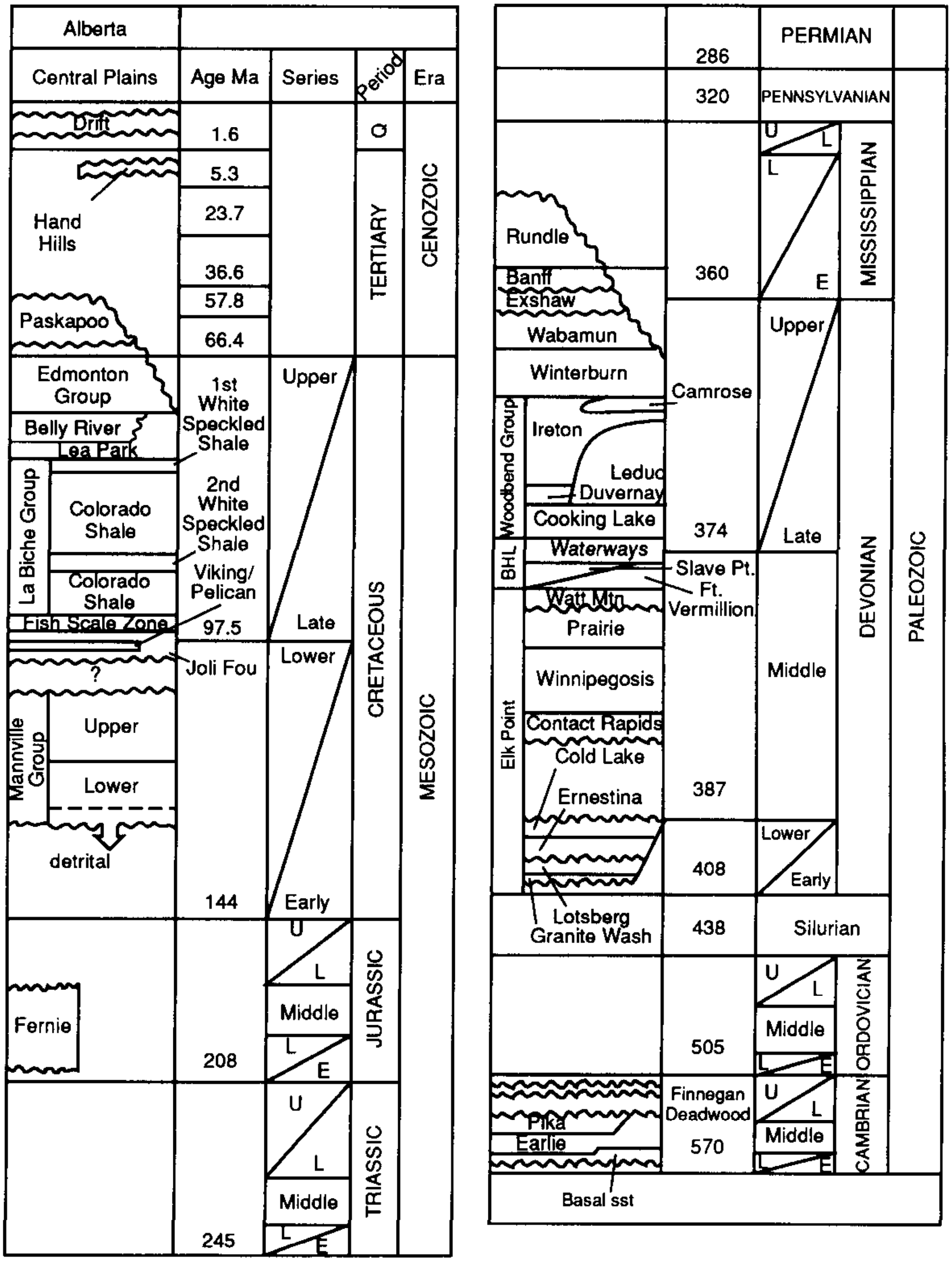

Fig. 1. Stratigraphic chart for south-central Alberta (modified after AGAT Laboratories, 1988).

Thus, relief at the Paleozoic subcrop in the Sullivan Lake area (T34-35, R12-14W4; Figure 2) is principally the result of the two processes: erosion and salt dissolution. In an effort to further elucidate the interrelationships among erosion, salt dissolution and this relief in the Sullivan Lake area, we examine below two anomalous structures. The first is a paleochannel of erosional origin. The second is an isolated remnant of Wabamun rock salt across which the Mississippian is draped. Seismic and well-log data are used in developing the interpretation.

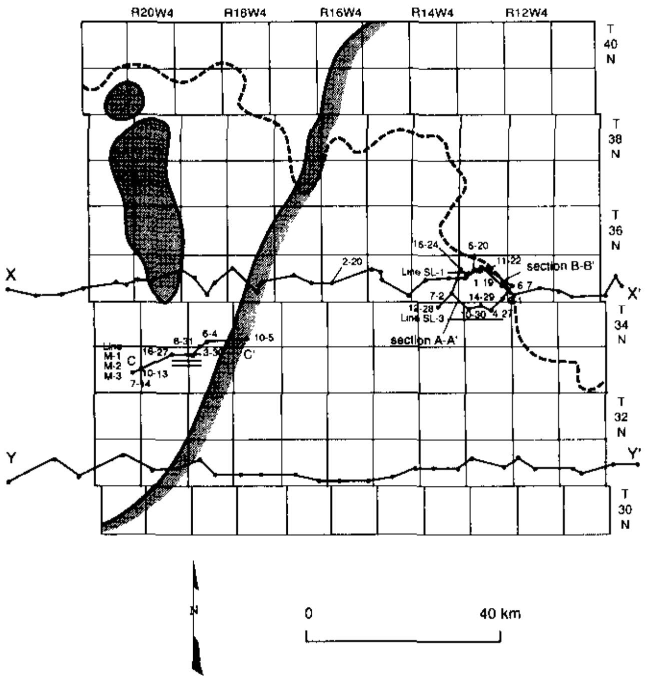

Fig. 2. Map of the Stettler region showing the margins of the Leduc reef complexes (solid lines) and the Wabamun subcrop edge (dashed line). The Sullivan Lake area (T34-35, R12-14W4), the approximate locations of the example seismic lines, and locations of the wells incorporated into Figures 5, 8 and 9, are also shown.

Erosional Feature: Paleozoic Channel

Geologic section A-A' (Figure 5) extends across the eastern erosional edge of the subcropping Mississippian (Rundle Gp, Banff Fm, Exshaw Fm; see Figure 1). Immediately to the east of this escarpment, Cretaceous strata lie unconformably on either the Wabamun or on reworked Paleozoic (essentially Mississippian) detritus. The thicker detritus is preserved in those areas where the Wabamun was most extensively eroded. The original Wabamun salt is thought to have been effectively leached at all of the incorporated well locations.

Eight horizons have been interpretively correlated across the geologic section (Figure 5). We have well control for the depths to six of these horizons [tops of the Wabamun, Mississippian, Mississippian detritus, Mannville, Viking and the Second White Speckled Shale (henceforth referred to as the Second Specks); Figure 1]. The other two horizons (near-top of salt and reconstructed Wabamun top) are based on regional and/or local trends. The near-top-of-salt horizon is an estimate of the depth to the top of the original salt-bearing interval. The reconstructed Wabamun horizon represents our estimate of where the top of the Wabamun would lie if neither erosion of the Wabamun surface nor salt dissolution had occurred in the Sullivan Lake area. The reconstructed Wabamun horizon is based on the previously published maps of Anderson and Brown (1991b).

On the basis of the geologic section as correlated (Figure 5), we have developed the following interpretation of this dissolution-controlled fluvial channel:

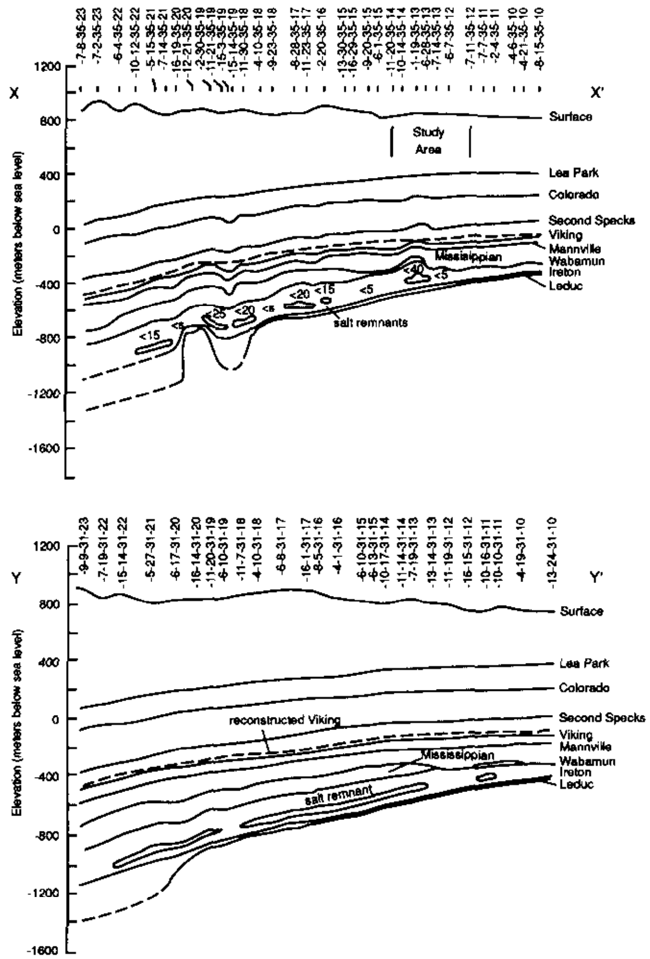

Fig. 3. West-east geologic profiles through the Stettler region illustrating the discontinuous nature of the Wabamun Group salts. The maximum known net thickness of rock salt in the Stettler area is approximately 40 m (Anderson and Brown, 1991b, 1992).

1. Erosion during the pre-Cretaceous scoured the Paleozoic surface in the vicinity of the 14-29 and 6-7 well locations (see also Figure 2) to the extent that the Wabamun salt was exposed to a near-surface environment. Rock salt was unstable in this environment and leaching initiated as a more-or-less continuous salt-dissolution front paralleling the Wabamun outcrop edge (Anderson and Brown, 1991b).
2. Salt dissolution is believed to be a somewhat self-sustaining process (Anderson et al., 1988; Anderson and Brown, 1991b), whereby leaching causes subsidence; subsidence influences drainage patterns on the surface and enhances porosity and permeability in the subsurface and this increased hydraulic conductivity allows for further dissolution (Anderson and Knapp, 1993). Once initiated during the pre-Cretaceous hiatus at the near-surface eastern limit of the Wabamun salt, dissolution continued with the westward migration (basinward, or downdip) of the salt-dissolution front.

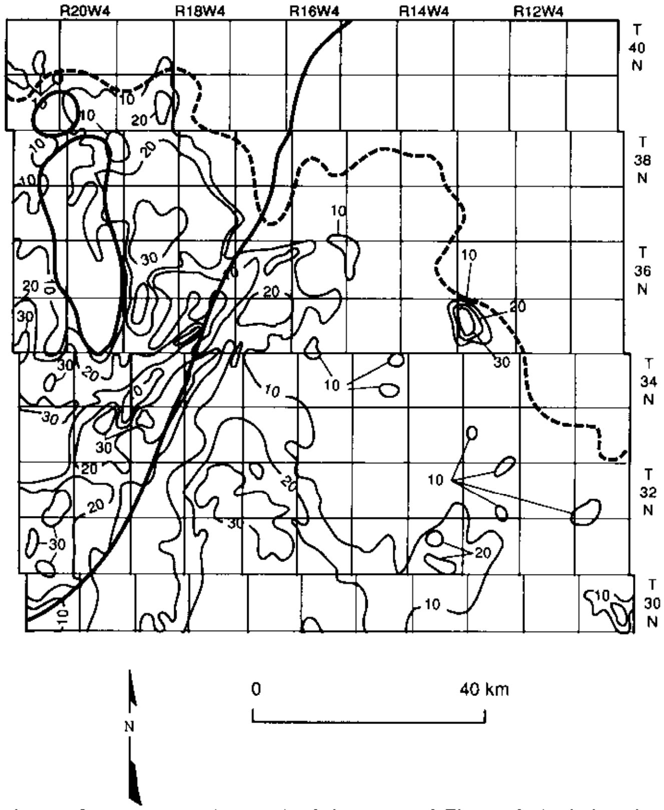

Fig. 4. Contour map (metres) of the area of Figure 2 depicting the interpreted present-day net thickness of the Wabamun rock salt in the Stettler region (modified after Anderson and Brown, 1991b). The salt remnant in T35, R13W4 is crossed by section B-B' and line SL-1 (Figure 2).

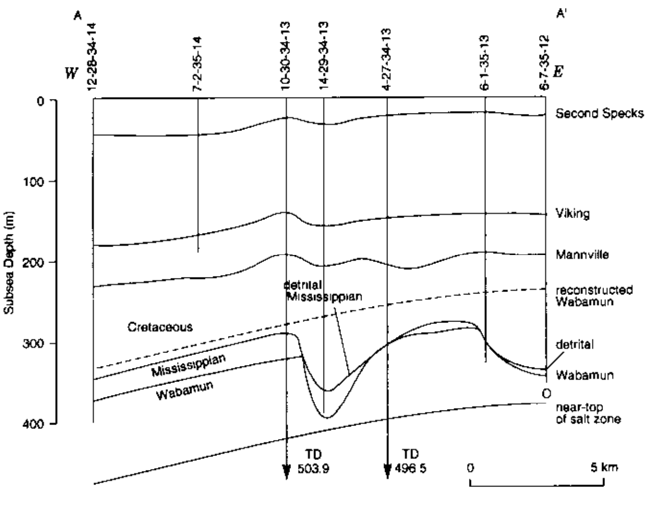

Fig. 5. Geologic section A-A'. Well locations are highlighted on Figure 2.

3. With respect to the timing of salt dissolution (deduced from interval thickening) at those wells included in the geologic section, dissolution at the 14-29 and 6-7 wells appears to have occurred earliest, probably prior to the onset of Cretaceous sedimentation. As a consequence, these wells contain detrital Mississippian and are structurally high at the Mannville level relative to the 12-28, 7-2 and 4-27 locations.
4. Dissolution at the 10-30 and 6-1 wells appears to have occurred later, probably during the deposition of the Lower Cretaceous Mannville Group. As a consequence, the Mannville surface at these well locations is elevated relative to wells 12-28, 7-2 and 4-27, while the Paleozoic subcrop is high relative to the 6-7 and 14-29 locations.
5. Dissolution at the 12-28, 7-2 and 4-27 wells appears to have been principally post-Mannville and pre-Second Specks in origin. Structure at the Second Specks level is consistent with the compaction of a thicker Cretaceous section off-structure. Our preferred interpretation is that, by the end of Second Specks time, the Wabamun salts had been effectively leached from all of the wells incorporated into the geologic section. However, it is possible that post-Second Specks dissolution has occurred at one or more of the well locations.

This scenario regarding erosion and salt dissolution at the well locations shown in Figure 5 is supported by the seismic line SL-3 displayed as Figures 6 and 7. This normal-polarity west-to-east seismic line crosses the erosional paleochannel intersected by the 14-29 well (Figure 5), which appears to tie the seismic line reasonably well at trace 248.

As an aid to the interpretation of these seismic data, synthetic seismograms were generated for a suite of wells including 2-20-35-16W4 (Figure 8). The 2-20 well, located on Figure 2, is the closest deep well (i.e., with penetration to the Elk Point; Figure 1) for which a sonic log is available. These synthetics allowed for the confident identification and correlation of several prominent seismic reflectors: Prairie salt, Wabamun, Mississippian, Mannville, Viking and Second Specks. Note that Wabamun salt is preserved within the 2-20 well but not along the length of the seismic line. This interpretation is supported by the absence of reflections from a salt-bearing interval and by the Wabamun/Prairie time interval, which is at least 5 ms thicker on the synthetic seismogram [where about 12 m (net) of Wabamun salt is preserved] than anywhere along the example seismic line. (Note that the gross salt-bearing interval is typically two to three times the net salt thickness.)

Seismic line SL-3 (Figures 6 and 7) crosses a paleochannel of pre-Cretaceous origin. This channel, as illustrated on the seismic data, has incised the Paleozoic surface between traces 208 and 264. Moving onto the channel from either side, there is a relatively abrupt termination of the Mississippian reflector and a significant thinning of the Wabamun-to-Prairie time interval. Within the channel, the Mississippian has been removed. The Wabamun surface has been eroded (by up to 30 ms, or 80 m) and is overlain by a relatively thick veneer (up to 25 ms, or 40 m) of detrital Paleozoic (Mississippian) and Lower Cretaceous sediment. Correlatable reflections from within these strata onlap the valley walls and appear to merge visually with the higher-amplitude Mississippian event. These seismic observations and estimates within the channel are consistent with data from the 14-29 well in Figure 5.

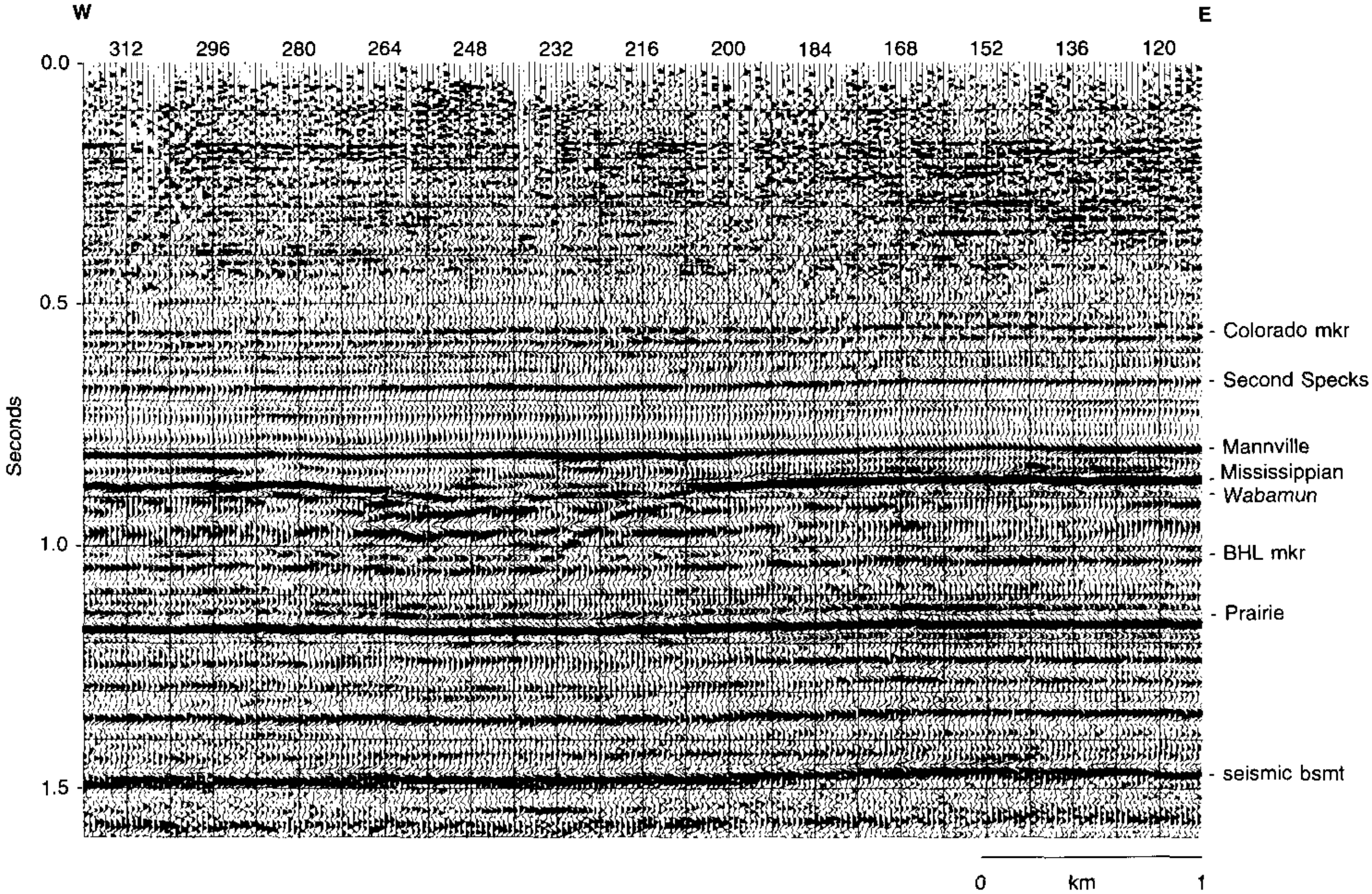

Fig. 6. Seismic line SL-3 (see Figure 2) crossing the Paleozoic channel displayed in Figure 5. Well 14-29 ties this seismic line at trace 248. These normal-polarity 24-fold unmigrated data were acquired with the following parameters: single 0.5-kg dynamite charges at 18 m; a 50-m group interval; a 100-m shot interval; 96-trace split spreads (50 m – 2400 m) and a 2-ms sample rate.

Structure along the Mannville, Viking and Second Specks horizons (Figures 6 and 7) also appears to have been affected by the pre-Cretaceous channelling. All of these are structurally lower (relative to the regional westerly dip) across the channel than elsewhere. There is a subtle indication of this effect on the Colorado event as well (Figure 7). The magnitude of this relief decreases with the decreasing depth of the reflectors, indicating that these structures are principally due to the compaction of the sediments that infilled this paleochannel.

Dissolution Feature: Wabamun Rock-salt Remnant

In Figure 9, the west-east geologic section B-B' is shown. The geologic section is interpreted to cross a remnant of Wabamun rock salt 40 m thick (shown on Figure 4 in T35, R13W4) and the eastern edge of the Mississippian subcrop. Immediately to the east of this structural relief and escarpment, the Lower Cretaceous strata lie unconformably on either Mississippian detritus or Wabamun (Devonian) strata. Nine horizons have been correlated across the geologic section. The depths to six of these horizons (Wabamun, Mississippian, Mississippian detritus, Mannville, Viking and Second Specks; Figure 1) are controlled at the wells. The other three horizons (residual Wabamun salt, near-top salt zone and reconstructed Wabamun) have been located on the basis of apparent regional and/or local trends.

Seismic line SL-1 (located in Figure 2) roughly parallels a portion of the geologic section of Figure 9 and intersects it in three places. It is important to note that this seismic section (Figures 10 and 11) has reversed polarity, whereas that of the previous example has normal polarity.

With respect to the residual Wabamun salt, note that this interpretation is based primarily on the relationship between the Wabamun and reconstructed Wabamun horizons. At the 12-28 and 7-2 wells, the Wabamun salt has been removed and the Wabamun horizon is 40 m below the reconstructed Wabamun (Figure 9). At the 6-20 and 1-19 locations, the Wabamun and reconstructed Wabamun are coincident, suggesting that about 40 m of Wabamun rock salt is preserved at these locations. This interpretation is consistent with: 1) the anomalous relief observed along the post-Wabamun horizons

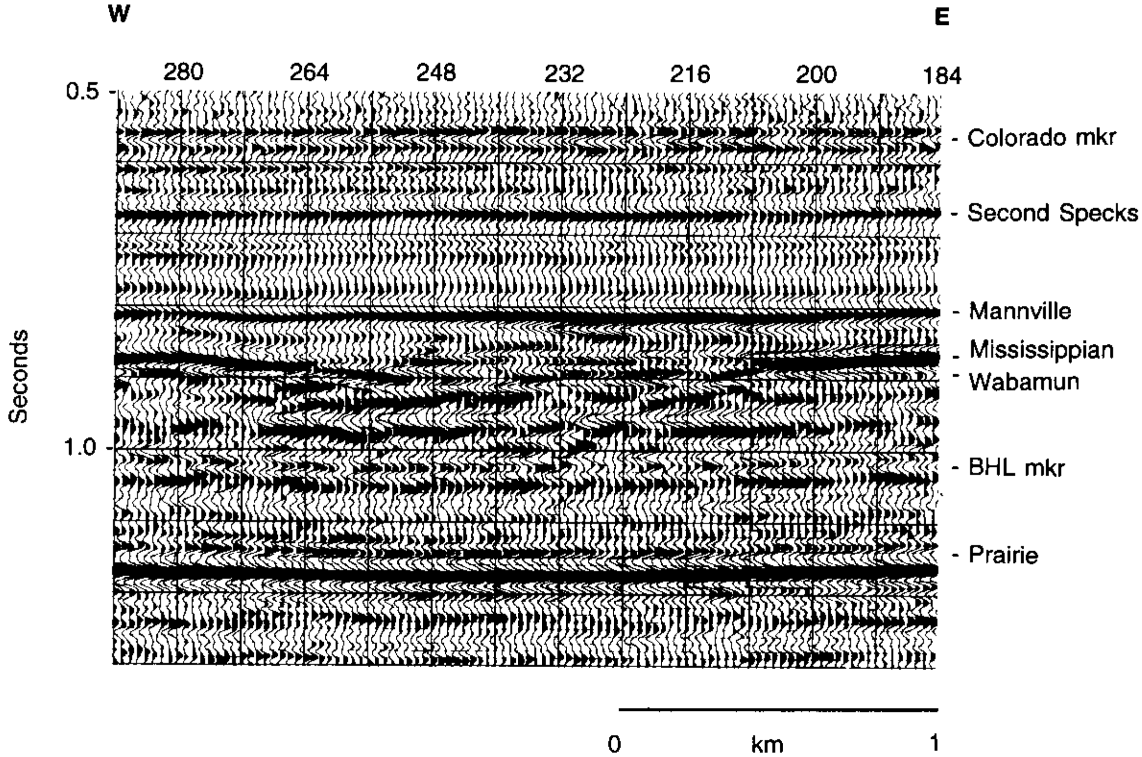

Fig. 7. Enlargement of a portion of seismic line SL-3 (Figure 6).

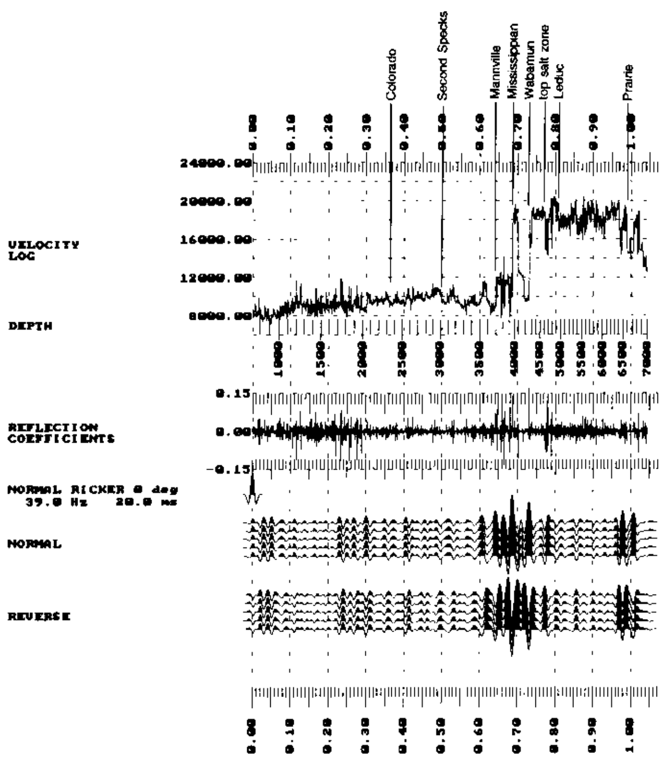

Fig. 8. Synthetic seismogram for the 2-20-35-16W4 well (Figure 2). This well encountered about 12 m (net) of Wabamun rock salt.

at the 6-20 and 1-19 wells; 2) the maximum known thickness of residual Wabamun salt in the Stettler region (Anderson et al., 1988); and 3) our regional reconstruction of the Wabamun horizon in this region (Anderson and Brown, 1991b).

On the basis of this correlated geologic section (Figure 9), our interpretation is as follows:

1. Erosion during the pre-Cretaceous scoured the Paleozoic surface to the east of the 6-7 well to the extent that the Wabamun rock salt was exposed to a near-surface environment and leaching was initiated. The established salt dissolution front migrated laterally across the Sullivan Lake area sometime thereafter.
2. With respect to the wells in the geologic section (Figure 9), dissolution at the 6-7 and 11-22 wells appears to have occurred earliest, probably before the onset of Cretaceous sedimentation. As a consequence, these wells contain detrital Mississippian sediment and, compared to the 7-2 and 12-28 wells, are relatively high at the Mannville, Viking and Second Specks levels. We note that the Cretaceous strata are thick and structurally low at the 6-7 and 11-22 wells, relative to the 1-19 and 6-20 wells. We interpret these features as primarily of compactional origin. However, it is possible that some leaching occurred at these locations (6-7 and 11-22) after the onset of Cretaceous sedimentation.
3. Dissolution at the 7-2 and 12-28 wells appears to have occurred principally after the end of Viking time and before the end of Second Specks time. As a result, the Mississippian, Mannville and Viking are anomalously low at these well locations relative to 1-19 and 6-20 and the Second Specks-to-Viking interval is anomalously thick

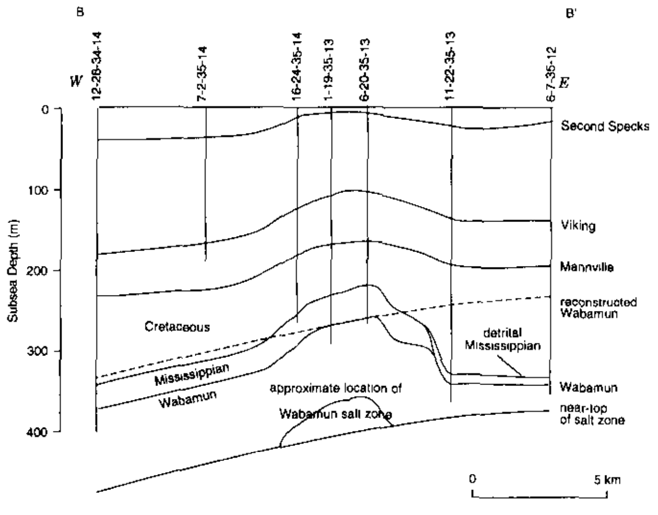

Fig. 9. Geologic section B-B'. Well locations are highlighted on Figure 2.

(about 30 m). Relief along the Second Specks across the geologic section is thought to be principally of compactional origin. However, it is possible that post-Second Specks dissolution has occurred at one or more of the well locations.

Our interpretation is supported by the seismic data of line SL-1 (Figures 10 and 11). This reverse-polarity west-to-east line crosses the rock-salt remnant interpreted as being present at the 1-19 and 6-20 wells (Figure 9) and appears to tie the 6-20 well reasonably well at trace 104.

Residual rock salt, as interpreted on the seismic section, is situated between traces 64 and 126 and to the west of trace 192. The rock salt is thought to have been leached from the geologic record over the rest of the section. The dissolution of the rock salt immediately to the west and east of the salt remnant centred around trace 96 (or well 6-20) is believed to have occurred around or shortly after the onset of Cretaceous sedimentation. This conclusion is based primarily on two observations: 1) the Mississippian appears to be continuous across the seismic section; and 2) the basal Cretaceous events appear to onlap the Mississippian.

On this section (Figures 10 and 11), the interpreted salt-bearing interval is manifested as a moderately high-amplitude peak-trough sequence originating from the top and base, respectively, of the salt. This portion of the line crossing the salt remnant (approximately from trace 56 to trace 144) also shows an anomalously thick Wabamun-to-Prairie interval, up to 25 ms of relative relief at the Mississippian level and up to 8 ms of velocity pull-up at the Prairie event. This pull-up phenomenon can be attributed to the contrast of the high-velocity Wabamun salt with the lower velocity Cretaceous clastics because there is no effective change in the thickness of the carbonate section, only a structural effect due to differential salt removal. The 8 ms of pull-up observed is indeed consistent with the replacement of 40 m of salt (*P*-velocity: ~ 4200 m/s) by 40 m of Cretaceous clastics (*P*-velocity: ~ 2950 m/s) west of trace 144 and east of trace 56. As further support we observe that the Wabamun-to-Prairie interval is consistently 15 to 20 ms (30-40 m) thicker within the interpreted salt-remnant portion of the line than elsewhere on either seismic line SL-1 (Figures 10 and 11) or SL-3 (Figures 6 and 7).

Summary

Relief on the Paleozoic subcrop in the Sullivan Lake area is attributed to two principal processes: erosion and the dissolution of bedded Wabamun rock salt. During the pre-Cretaceous hiatus, the Paleozoic surface was in places eroded to such an extent that the Wabamun salt was exposed to a near-surface environment and dissolution was initiated at this eastern salt limit. Once begun, such leaching causes subsidence, which enhances porosity and permeability leading to increased hydraulic conductivity and further dissolution. During the pre-Cretaceous and thereafter, the established salt-dissolution front appears to have migrated basinward (westwards) through the Sullivan Lake area. As a result, Wabamun rock salt is now preserved only as isolated remnants of essentially random distribution and shape and variable thickness.

On the seismic examples presented, the deeper paleochannel is characterized by the absence of the Mississippian event and a pronounced thinning within the Wabamun interval. Cretaceous and reworked Paleozoic clastics deposited within the channel are seen to onlap the Paleozoic valley walls. As a result of the compaction of these channel deposits, the Lower Cretaceous strata are anomalously low across the channel. The thick residual rock salt, in contrast, is characterized by an anomalously thick Wabamun/Prairie time interval, up to 8 ms of velocity pull-up along the Prairie event and up to 25 ms of relative relief at the Mississippian level. The seismic image of the salt remnant is manifested as a relatively high-amplitude peak-trough sequence. Familiarity with these characteristic features will be of use to the explorationist interpreting seismic data in similar areas. An example of the role of dissolutional control in an oil-bearing channel-sandstone reservoir is given by Hopkins (1987) for the Berry Mannville C pool. The second example of this paper is an actual case of trapping of Cretaceous gas across a salt-remnant structure, namely the Sullivan Lake Upper Mannville B pool.

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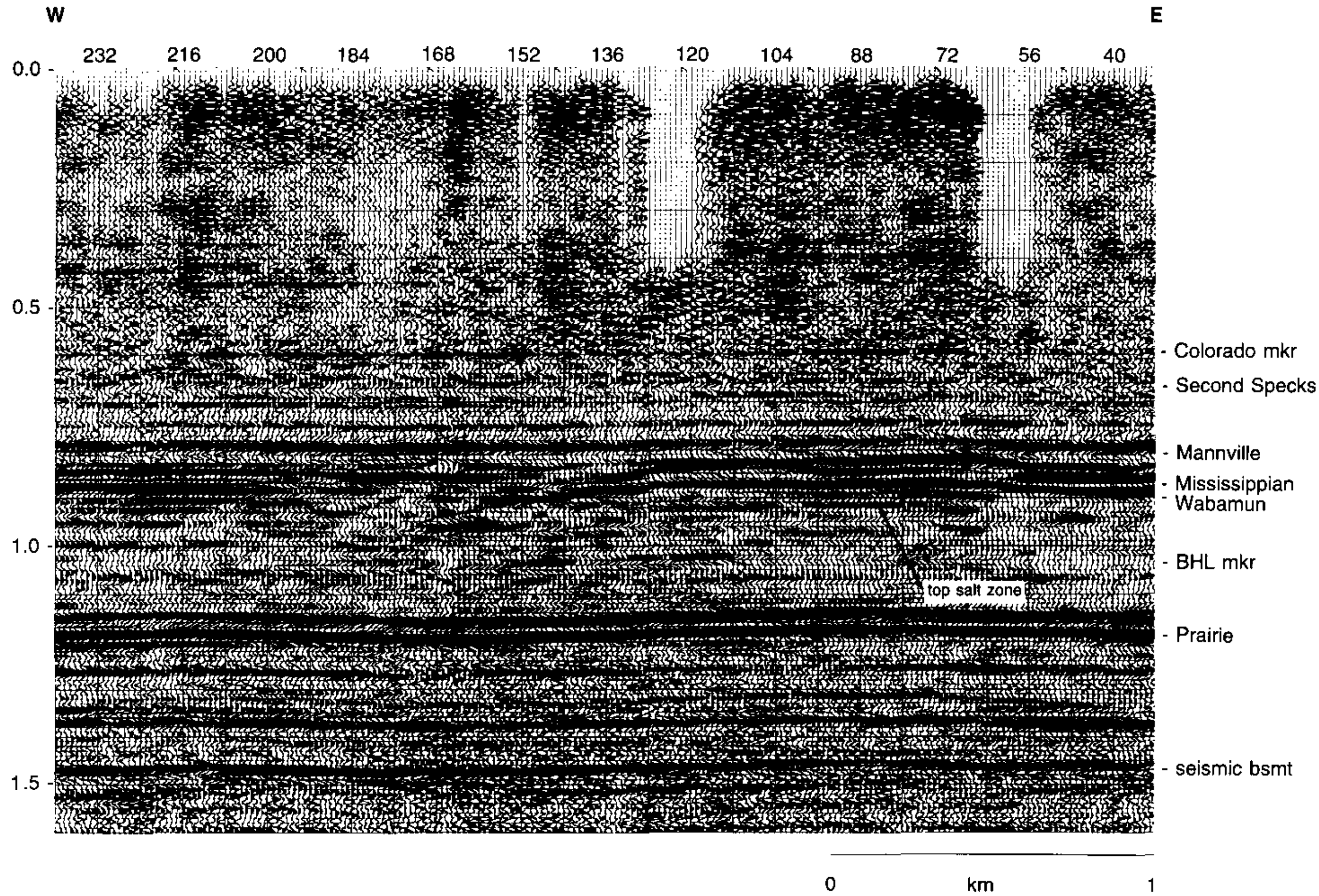

Fig. 10. Seismic line SL-1 (see Figure 2) crossing the isolated remnant of Wabamun salt displayed in Figures 4 and 9. The 6-20 well ties the seismic line at trace 104. These reverse-polarity 12-fold unmigrated data were acquired with the following parameters: single 0.5-kg dynamite charges at 18 m; a 33.5-m group interval; a 134-m shot interval; 96-trace split spreads (33.5 m – 1608 m) and a 2-ms sample rate.

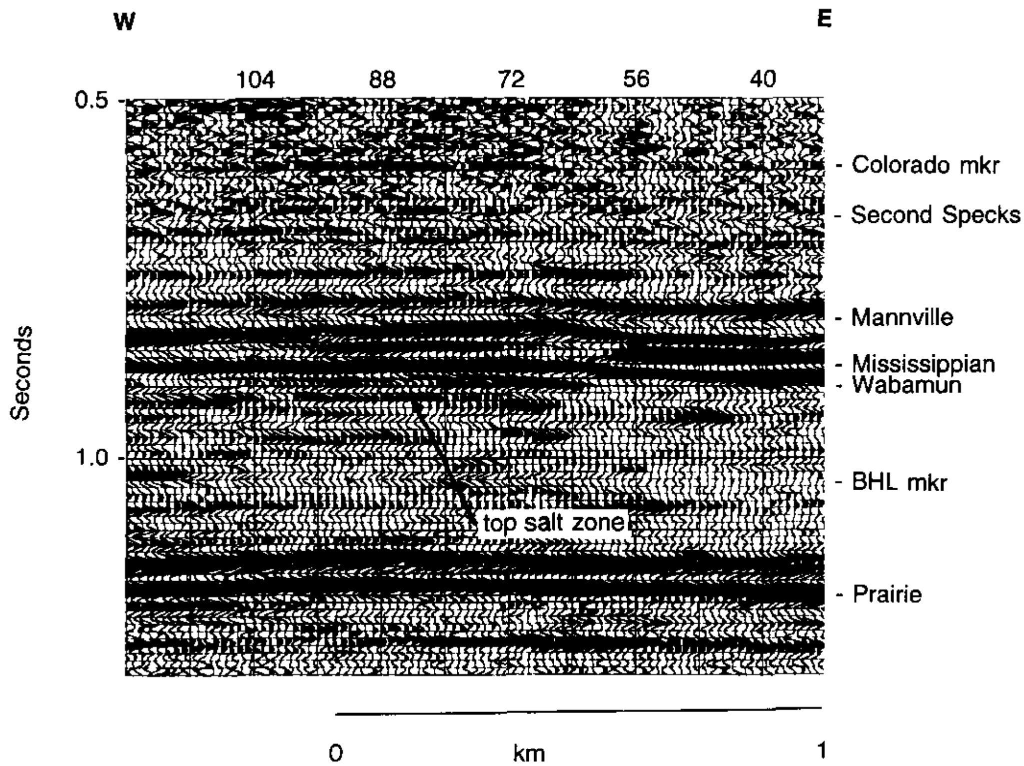

Fig. 11. Enlargement of a portion of seismic line SL-1 (Figure 10).

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