THE EFFECTS OF CONTEMPORANEOUS EROSION AND SALT DISSOLUTION ON SUBSURFACE STRUCTURAL RELIEF; A SEISMIC ANALYSIS

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ABSTRACT

The sub-Cretaceous unconformity in the Sullivan Lake study area (T34-35, R11-14W4M) south-central Alberta, Canada, is a surface of extreme relief (up to 100 m locally). This relief is attributed to two processes: erosion, and the dissolution of bedded rock salt.

Erosion during the pre-Cretaceous hiatus denuded the paleo-surface in the Sullivan Lake area to the extent that Mississippian and Devonian strata constitute the sub-Cretaceous unconformity. Mississippian strata are preserved in the western part of the study area; to the east, the Devonian subcrops. These strata were deeply incissed by scouring fluvial channels that were ultimately infilled with Cretaceous clastics or reworked Paleozoic detritus. In places, erosion was so extensive that the rock salts of the Wabamun Group (Devonian) were exposed to a near-surface environment and dissolution initiated. These established salt-dissolution fronts appear to have migrated through the Sullivan Lake area during the pre-Cretaceous time and thereafter. As a consequence, Wabamun rock salt is now preserved only as isolated remnants of variable thickness.

In this paper, two seismic lines and supporting geologic data from the Sullivan Lake study area are presented in support of the thesis that structural relief at the Paleozoic level has been controlled by erosion and salt dissolution. The first seismic line crosses a deeply incissed paleo-channel. The second seismic line crosses an isolated remnant of Wabamun rock salt.

On seismic data, the paleo-channel is characterized by the absence of the Mississippian event and a pronounced thinning within the Wabamun interval. Cretaceous and re-worked Paleozoic clastics deposited within the paleo-channel are seen to onlap the Paleozoic valley walls. As a result of the compaction of these channel deposits, the Lower Cretaceous strata are anomomalously low across the paleo-channel. On the second line, the remnant rock salt is imaged as a relatively high amplitude trough/peak sequence. Relative to those areas where the rock salt has been effectively leached, the salt-bearing zone is characterized by an anomalously thick Prairie salt/Wabamun time interval, up to 8 ms of velocity pullup at the top Prairie event, and up to 25 ms of relative relief at

the Mississippian level. These observations are consistent with the thesis that up to 40 m of remnant salt is preserved locally.

INTRODUCTION

The Paleozoic subcrop in the Stettler area (T33-43, R10-24W4M; Figures 1, 2 and 3) is an unconformable surface of significant (up to 100 m) localized relief (Belyea, 1964). This structure is attributed to three primary processes: 1) erosion; 2) dissolution of the Wabamun salts; and 3) differential compaction of reef and off-reef strata (Anderson, 1992; Anderson and Brown, 1991, 1992, 1993; Anderson et al., 1988, 1989). The overall effect of these three processes is illustrated in cross-sections A-A' and B-B' (Figures 4 and 5, respectively).

Consider first the process of erosion. In the Stettler area, as a result of erosion during the pre-Cretaceous, the Paleozoic surface is the pre-Cretaceous subcrop (Figure 3, 4 and 5). In the western part of the Stettler area, the Mississippian constitutes the sub-Cretaceous unconformity; to the east, the Wabamun subcrops. The eastern erosional edge of the Mississippian, as suggested in Figures 4 and 5, frequently forms a rather abrupt escarpment. Throughout the Stettler area, relief at the Paleozoic subcrop level reflects pre-Cretaceous erosional patterns.

As evidenced by Figures 3 and 4, relief at the Paleozoic subcrop is also related to the present-day thickness of the remnant Wabamun salt (Oliver and Cowper, 1983). In a relative sense and on a local scale, relief at the Paleozoic surface is a direct function of the thickness of these remnant salts. This is not unexpected. Work we have done to-date suggests that: 1) about 40 of Wabamun Group (Devonian) salts were more-or-less uniformly deposited throughout most of the Stettler area; and 2) these salts were leached during the pre-Cretaceous and thereafter (Anderson, 1992; Anderson and Brown, 1991; Anderson and Brown, 1992, 1993; Anderson et al., 1988b; Cederwall and Anderson, 1991). As a consequence, the Paleozoic subcrop has subsided and is relatively low at those sites where dissolution has occurred.

The third process to have significantly affected structure at the Paleozoic subcrop, is the differential compaction of reef and offreef sediment. As illustrated in Figures 3 and 4, the Paleozoic surface, in a relative sense, is structurally higher onreef than offreef. The magnitude of this type of relief is principally a function of the relative compactibilities of the reef and offreef sediments, the extent to which these sediments were compacted prior to the onset of Cretaceous sedimentation, and the thickness of the Cretaceous section (Anderson and Brown, 1989b; Anderson and Franseen, 1991; Anderson et al., 1989c).

In summary, structural relief at the Paleozoic level in the Stettler area is principally the result of three processes: erosion, dissolution, and differential compaction. Throughout most of the Stettler study area, these processes were largely independent. Erosion occurred during the pre-Cretaceous hiatus. Salt dissolution (west of the Wabamun subcrop) occurred predominantly after the onset of Cretaceous sedimentation. Differential compaction occurred before and after the the pre-Cretaceous hiatus (Anderson and Brown, 1992; Anderson et al., 1988a, 1989b,c).

In places, however, the three processes were probably somewhat interdependent. For examples: 1) along the Wabamun subcrop, erosion during the pre-Cretaceous exposed the Wabamun rock salt to a near-surface environment and triggered dissolution; and 2) in the same area surface subsidence, in response to dissolution, probably affected drainage patterns.

In an effort to further elucidate the interrelationships between erosion and salt dissolution along the Wabamun subcrop, we examine herein two anomalous structural in the Sullivan Lake area (T34-35, R11-14W4M; Figure 6). The first structure is a paleo-channel of erosional origin; at the second site, the Mississippian is draped across an isolated remnant of Wabamun rock salt. Seismic data, is used in support of the ideas presented.

EROSIONAL FEATURE: PALEOZOIC CHANNEL

The geologic section C-C' extends across the eastern erosional edge of the Mississippian subcrop (Figure 7). Immediately to the east of this escarpment, Cretaceous strata lie unconformably on either the Wabamun or reworked Paleozoic detritus. Detritus is preserved in those areas where the Wabamun is anomalously structurally low. The original Wabamun salts are thought to have been effectively leached at all of the incorporated well sites.

Eight horizons have been interpretively correlated across the geologic section (Figure 7). The depths to six of these horizons (Wabamun, Mississsippian, Mississsippian detritus, Mannville, Viking, and Second Specks; Figure 1) are well site controlled. The other two horizons (near-top salt zone and reconstructed Wabamun) are based on regional and/or local trends. The near-top salt zone is an estimate of the depth to the top of the original salt-bearing zone. The reconstructed Wabamun horizon represents our estimate of structural relief at the top of the Wabamun in the absence of both erosion and salt dissolution.

With respect to the reconstructed Wabamun horizon, note that our previous work suggests that: 1) about 40 m of Wabamun salt was deposited in the Sullivan Lake area; and 2) most of this salt was effectively leached from the rock record. On the basis of these conclusions, we have previously reconstructed the top of the Wabamun in the Stettler area (Anderson and Brown, 1992; Anderson et al., 1988b). The reconstructed Wabamun horizon in Figure 5 is based on this earlier regional work, and represents our estimate of structural relief at the top of the Wabamun in the absence of both erosion and salt dissolution. A comparison of the present-day and reconstructed Wabamun horizons allows for the probable identification of remnant salt at those well sites where only the top of the Wabamun was penetrated.

On the basis of the geologic section as correlated, the relationships between erosion, salt dissolution, and relief along the sub-Cretaceous unconformity can be elucidated. Our non-unique scenario is as follows:

1. Erosion during the pre-Cretaceous scoured the Paleozoic surface in the vicinity of the 14-29 well site, and to the east of the 6-7 well site to the extent that the Wabamun salt was exposed to a near-surface environment. Rock salt was unstable in this environment and leaching was initiated

locally. (Immediately prior to the onset of Cretaceous sedimentation in the Stettler area, the zones of active leaching formed a more-or-less continuous salt-dissolution front along the Wabamun subcrop edge; Anderson and Brown, 1992).

2. Salt dissolution in the Stettler area, is thought to be somewhat self-perpetuating (Anderson and Brown, 1992; Anderson et al., 1988b). We envision a process whereby leaching causes subsidence, subsidence enhances porosity and permeability, and increased hydraulic conductivity allow for further dissolution. This self-perpetuating nature of salt dissolution accounts for the apparent westward migration of the salt-dissolution front that was established along the Wabamun subcrop during the pre-Cretaceous.

3. With respect to the timing of salt dissolution at those well sites included in the geologic section, we submitt that dissolution at the 14-29 and 6-7 wells occurred earliest, probably prior to the onset of Cretaceous sedimentation. As a consequence, these wells contain detrital Mississippian, and are relatively high at the Mannville level.

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 at these sites is elevated relative to wells 4-27, 7-2, and 12-28, while the Paleozoic subcrop is high relative to the 6-7 and 4-29 sites.

5. Dissolution at the 4-27, 12-28, and 7-2 wells appears to have been principally post-Mannville/pre-Second Specks in origin (Figure 1). Structure at the Second Specks level is consistent with the compaction of a thicker Cretaceous section off-structure. Our 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.

Our thesis regarding erosion and salt dissolution at the well sites shown in Figure 7, is supported by the seismic data displayed as Figures 8 and 9. This west-east oriented seismic line crosses the erosional paleo-channel intersected by the 14-29 well (Figure 7). 14-29 appears to tie the seismic line reasonably well at trace 136. The other wells are off-line. These normal-polarity, 24-fold, nonmigrated data were acquired using the following acquisition parameters:

1) single 0.5 kg dynamite charges at 18 m;
2) 50 m group interval;
3) 100 m shot interval;
4) 96 trace split spread (50 m - 2000 m); and
5) 2 ms sample rate.

As an aid to the interpretation of these seismic data, synthetic seismograms were generated for a suite of wells including 2-20-35-16W4M (Figure 10). 2-20 is the closest deep well (Elk Point penetration; 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 traverse of the seismic line. This interpretation is supported by the absence of reflections from the top and base of the Wabamun salt, and by an analysis of the Wabamun to top Prairie salt time interval. This interval is at least 5 ms thicker on the synthetic seismogram (where about 12 m of Wabamun salt is preserved) than anywhere along the example seismic line.

The seismic line (Figures 8 and 9) crosses a paleo-channel of pre-Cretaceous origin, and is presented herein in support of our interpretation of the geologic section of Figure 7. The paleo-channel, as interpreted on the seismic data, has deeply incissed the Paleozoic surface between traces 96 and 168. The edges of the paleo-channel are characterized by the relatively abrupt termination of the Mississippian reflector and the pronounced thinning of the Wabamun to top Prairie salt interval.

Within the paleo-channel, the Mississippian has been removed. The Wabamun surface appears to have been eroded (by up to 30 ms/80 m), and to be overlain by a relatively thick (up to 25 ms/40 m) veneer of detrital

Mississippian and basal Cretaceous sediment. Correlatable reflections from within these strata onlap the valley walls and appear to merge visually with the higher amplitude Mississippian event. These estimates and observations are consistent with the 14-29-34-13W4M well in Figure 7.

The Wabamun adjacent to the paleo-channel is overlain by relatively thick Mississippian strata (up to 25 ms/40 m). This situation is different than that presented on the geologic section of Figure 5, where the Mississippian is absent east of the paleo-channel. This apparent discrepency is attributed to the fact that the 4-27 well (Figure 7) is located about 1.5 km east of the seismic line.

Structure along the Mannville, Viking, Second Specks, and Colorado events in Figures 8 and 9, also appears to have been affected by the pre-Cretaceous channeling. All of these events are structurally lower (relative to the regional southwesterly dip) across the paleo-channel than elsewhere. The magnitude of this drape decreases with the decreasing depth to the reflectors, indicating that these structures are principally due to the compaction of the sediments that infilled the paleo-channel.

REMNANT WABAMUN ROCK SALT

In Figure 11, the east-west geologic section B-B' is shown. The geologic section crosses a 40 m thick remnant of Wabamun salt, and the edge of the Mississippian subcrop. Immediately to the east of this escarpment, the 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, Mississsippian, Mississsippian detritus, Mannville, Viking, and Second Specks; Figure 1) are controlled at the well sites. The other three horizons (remant Wabamun salt, near-top salt zone and reconstructed Wabamun) have been located on the basis of apparent regional and/or local trends.

With respect to the remnant Wabamun salt note that this interpretation is based primarily on the relationship between the Wabamun and reconstructed Wabamun horizons. At the 10-30 and 12-28 well sites the Wabamun salt has been leached and the Wabamun horizon is 40 m below the reconstructed Wabamun (Figures 7 and 11). 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 sites (Figure 11). This interpretation is consistent with; 1) the anomalous relief observed along the post-Wabamun horizons at the 6-20 and 1-19 well sites; 2) the maximun known thickness of remnant Wabamun salt in the Stettler area (Anderson et al., 1988b); and our regional reconstruction of the Wabamun horizon in the Stettler area (Anderson and Brown, 1992).

On the basis of the geologic section as correlated, the relationships between erosion, salt dissolution, and relief along the sub-Cretaceous unconformity can be elucidated. Our non-unique scenario is as follows:

1. Erosion during the pre-Cretaceous scoured the Paleozoic surface to the east of the 6-7 well site to the extent that the Wabamun salt was exposed to a near-surface environment and leaching was initiated. The established salt dissolution front migrated laterally across the Sullivan study area sometime thereafter.

2. With respect to the wells in the geologic section (Figure 11), dissolution at the 11-22 and 6-7 wells appears to have occurred earliest, probably before the onset of Cretaceous sedimentation. As a consequence, these wells contain detrital Mississippian 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 strat are thick and structural low at the 11-22 and 6-7 well sites (relative to the 1-19 and 6-20 wells). We interpret these features as being primarily of compactional origin, however it is possible that significant leaching occurred at these locations after the onset of Cretaceous sedimentation.

4. Dissolution at the 7-2 and 12-28 wells appears to have occurred principally after the deposition of the Viking and prior to the end of Second

Specks deposition. As a result the Mississippian, Mannville, and Viking are anomalously low at these well sites relative to 1-19 and 6-20, and the Second Specks/Viking interval is anomalously thick (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 sites.

Our thesis regarding erosion and salt dissolution at the well sites shown in Figure 11, is supported by the seismic data displayed as Figures 12 and 13. This west-east oriented seismic line crosses the salt remnant interpreted as present at the 1-19 and 6-20 well sites (Figure 11). 6-20 appears to tie the seismic line reasonably well at trace 80. The other wells are off-line. These reverse-polarity, 12-fold, nonmigrated data were acquired using the following acquisition parameters:

1) single 0.5 kg dynamite charges at 18 m;
2) 33.5 m group interval;
3) 134 m shot interval;
4) 96 trace split spread (33.5 m - 1608 m); and
5) 2 ms sample rate.

The seismic line (Figures 12 and 13) ties the 6-20 well, and is presented herein in support of our interpretation of the geologic section of Figure 11. The salt remnant, as interpreted on the seismic data, is situated between traces 32 and 96. The rock salt is thought to have been leached from the rock record elsewhere. The dissolution of the rock salt iimmediately to the west and east of the remnant salt is thought to have occurred near or shortly after the onset of Cretaceous sedimentation. This thesis is based on primarily on two observations: 1) the Mississippian appears to be continuous across the seismic line; and 2) the basal Createaceous events appear to onlap the Mississippian.

On the seismic data, the interpreted rock salt bearing zone is manifested as a relatively high amplitude trough/peak sequence, originating from the top and base of the salt-bearing interval respectively. The salt-bearing zone is characterized by an anomalously thick top Prairie salt/Wabamun interval, up to 8 ms of velocity pullup at the top Prairie event, and up to 25 ms of relative relief at the Mississippian level. These observations are consistent with the thesis that up to 40 m of remnant salt is preserved between traces 32 and 96. More specifically, the top Prairie salt/Wabamun interval is consistently 15-20 ms (30-40 m) thicker within the interpreted salt-bearing zone than elsewhere on either seismic line (Figures 9 and 10, and Figures 6 and 7). Similarly, the observed 8 ms of velocity pushdown beneath the zones where the rock salt has been effectively leached, is consistent with the replacement of 40 m of high velocity salt (4200 m/s) by 40 m of lower velocity Cretaceous clastics (2950 m/s). 40 m of structural relief at the Mississippian (in response to post-Mississippian salt dissolution) would likewise account for the observed 25 ms of time-structural relief along this event.

CONCLUDING SUMMARY

The sub-Cretaceous unconformity in the Sullivan Lake study area is a surface of extreme relief (up to 100 m locally). This relief is attributed to two processes: erosion, and the dissolution of underlying bedded rock salt.

Erosion at the sub-Cretaceous level in the Sullivan Lake area, occurred during the pre-Cretaceous hiatus. During this time, the sub-Cretaceous surface (top Paleozoic) was denuded in places to the extent that the Wabamun salt was exposed to a near-surface environment. Rock salt was unstable in this environment and leaching was initiated. Salt dissolution is thought to have been a somewhat self-perpetuating process within the study area. In a more-or-less continuous manner, leaching caused surface subsidence, subsidence enhanced porosity and permeability, increased hydraulic conductivity resulted in further dissolution. During the pre-Cretaceous and thereafter, and as a result of the self-perpetuating nature of salt dissolution, 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 variable thickness and areal extent.

On seismic data, the deeper paleo-channel are characterized by the absence of the Mississippian event and a pronounced thinning within the

Wabamun interval. Cretaceous and re-worked Paleozoic clastics deposited within the paleo-channel are seen to onlap the Paleozoic valley walls. As a result of the compaction of these channel deposits, the Lower Cretaceous strata are anomomalously low across the paleo-channel. The thick remnant rock salt, in contrast, is characterized by an anomalously thick Prairie salt/Wabamun time interval, up to 8 ms of velocity pullup at the top Prairie event, and up to 25 ms of relative relief at the Mississippian level. The seismic image of the remnant salt is manifested as a relatively high amplitude trough/peak sequence.

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FIGURE CAPTIONS

Figure 1A. Stratigraphic chart for the Mesozoic: southern plains of Alberta (modified after AGAT Laboratories, 1988).

Figure 1B. Stratigraphic chart for the Paleozoic: southern plains of Alberta (modified after AGAT Laboratories, 1988).

Figure 2. Facies distribution and paleogeography of the Stettler Formation and its equivalents, western Interior Plains. The halite facies is referred to as the Wabamun salts. (Modified after Meijer Drees, 1986).

Figure 3. Plan view map of the general Stettler area. The Sullivan Lake study area (Figure 6), and locations of the wells incorporated into geologic sections A-A' and B-B' are highlighted (Figures 4 and 5, respectively).

Figure 4. Geologic section A-A'.

Figure 5. Geologic section B-B'.

Figure 6. Plan view map of the Sullivan Lake study area. The locations of the wells incorporated into geologic sections C-C' and D-D" are highlighted (Figures 7 and 8, respectively).

Figure 7. Geologic section C-C'.

Figure 8. Normal-polarity, nonmigrated seismic line C-C'. The seismic line crosses the Paleozoic channel displayed in Figure 7.

Figure 9. Enlargement of a portion of seismic line C-C' illustrating the edge of the Paleozoic channel.

Figure 10. Synthetic seismogram for the 2-20-35-16W4M well. 2-20 is the closest deep well (Elk Point penetration; Figure 1) for which a sonic log is available. This well encountered about 12 m of Wabamun salt.

Figure 11. Geologic section D-D'.

Figure 12. Reverse-polarity, nonmigrated seismic line D-D'. The seismic line crosses the isolated remnant of Wabamun salt displayed in Figure 11.

Figure 13. Enlargement of a portion of seismic line C-C' illustrating the edge of the isolated remnant of Wabamun salt displayed in Figure 11.

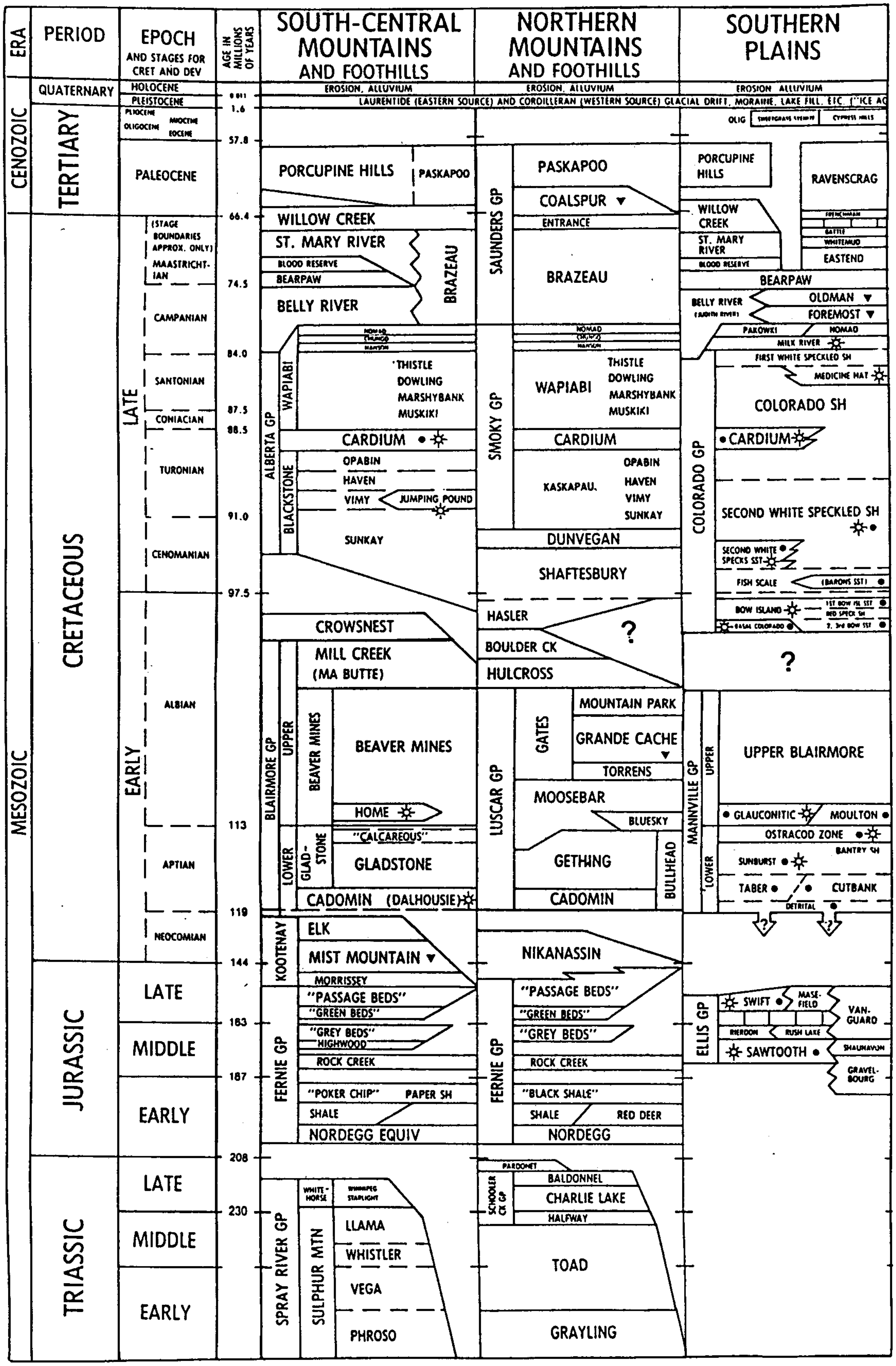

Figure 1A. Stratigraphic chart for the Mesozoic: southern plains of Alberta (modified after AGAT Laboratories, 1988).

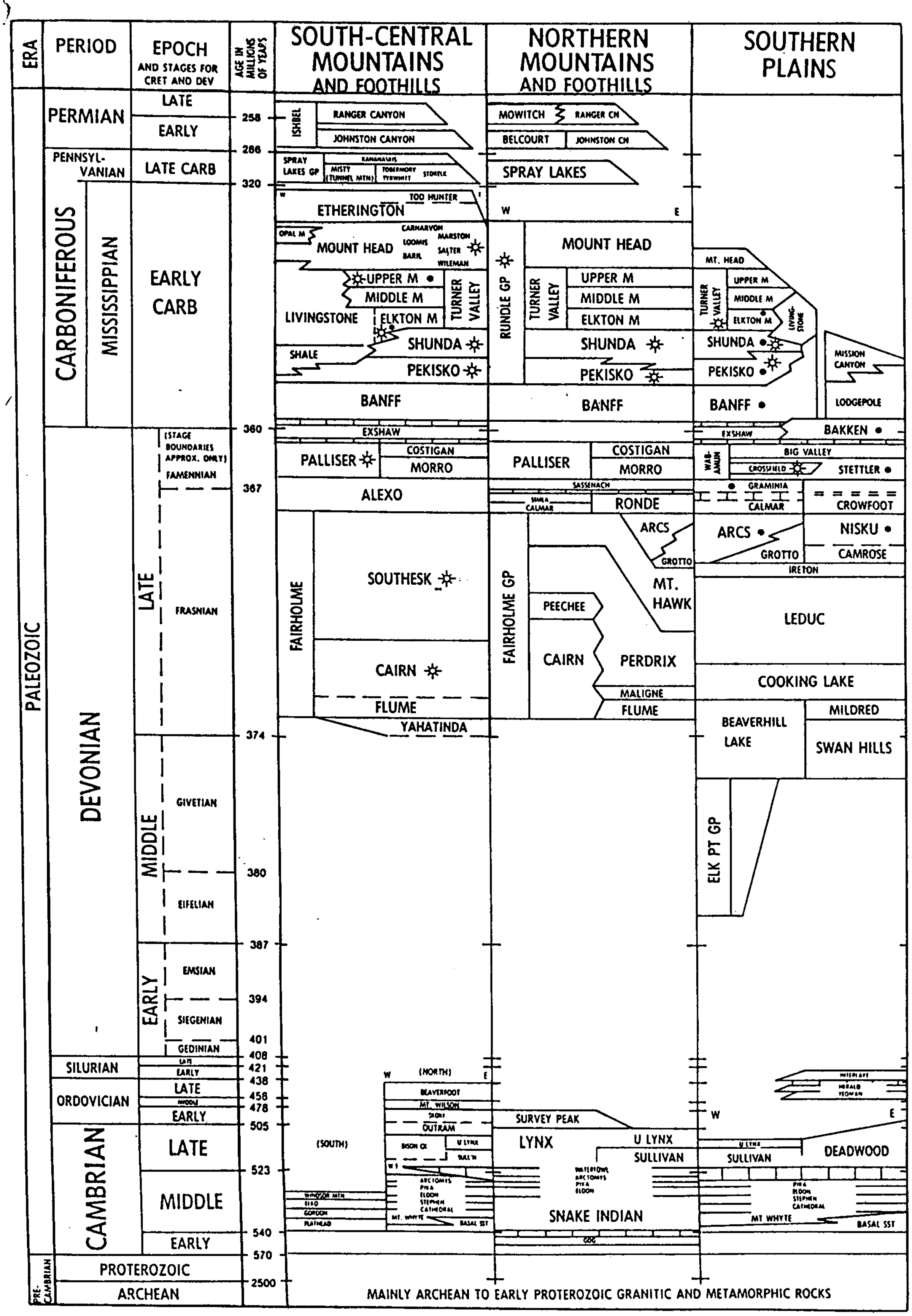

Figure 1B. Stratigraphic chart for the Paleozoic: southern plains of Alberta (modified after AGAT Laboratories, 1988).

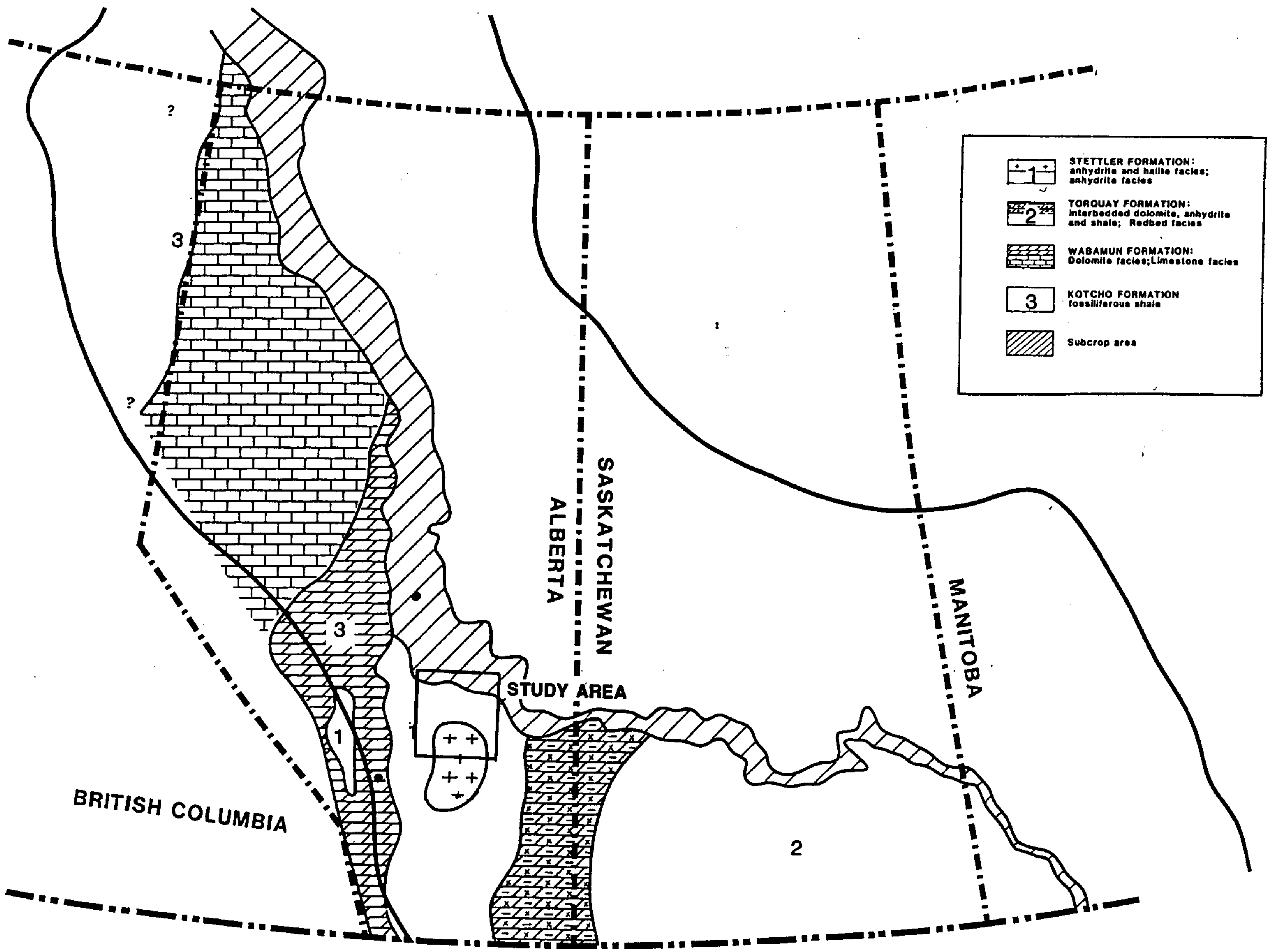

Figure 2. Facies distribution and paleogeography of the Stettler Formation and its equivalents, western Interior Plains. The halite facies is referred to as the Wabamun salts. (Modified after Meijer Drees, 1986).

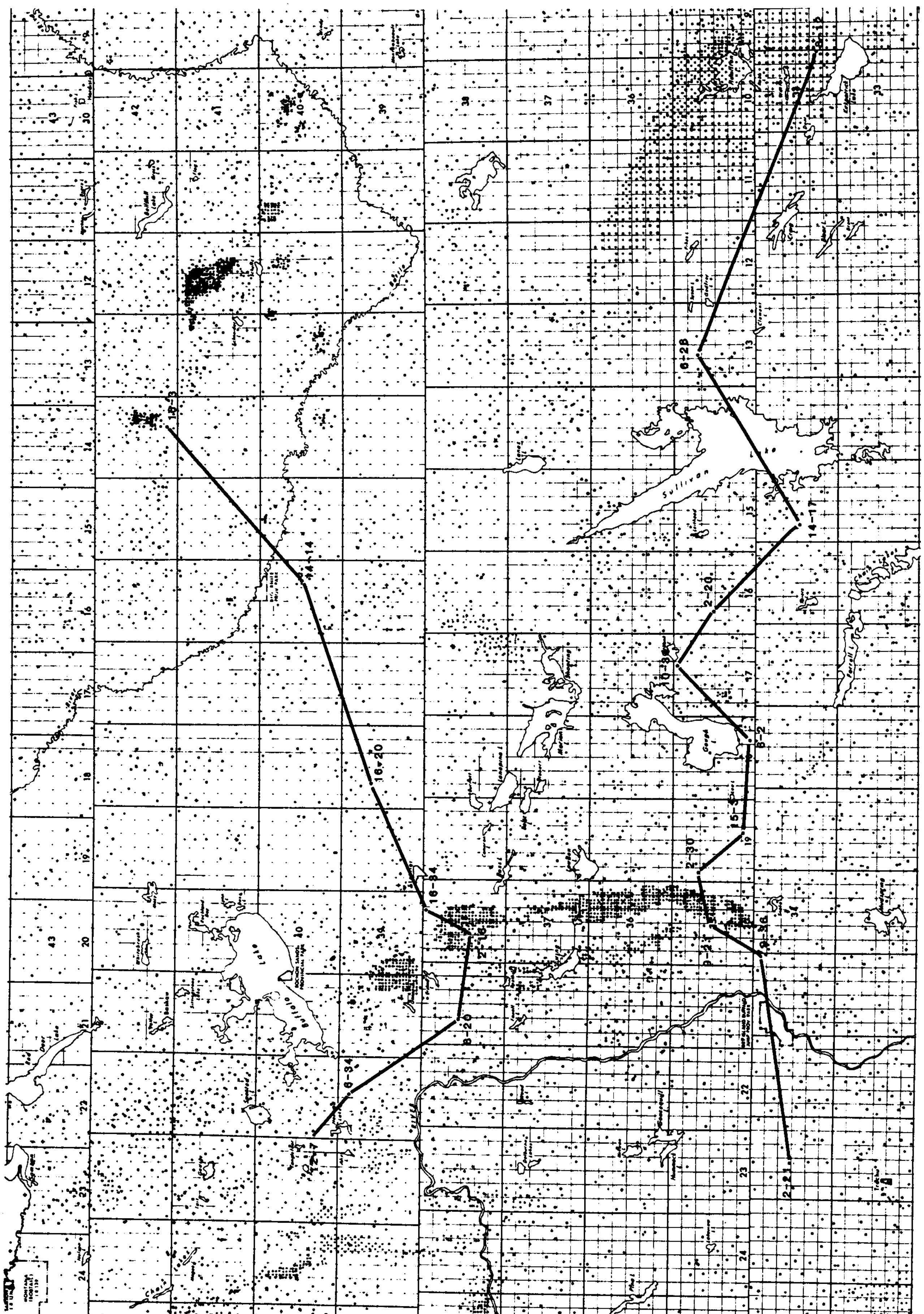

Figure 3. Plan view map of the general Stettler area. The Sullivan Lake study area (Figure 6), and locations of the wells incorporated into geologic sections A-A' and B-B' are highlighted (Figures 4 and 5, respectively).

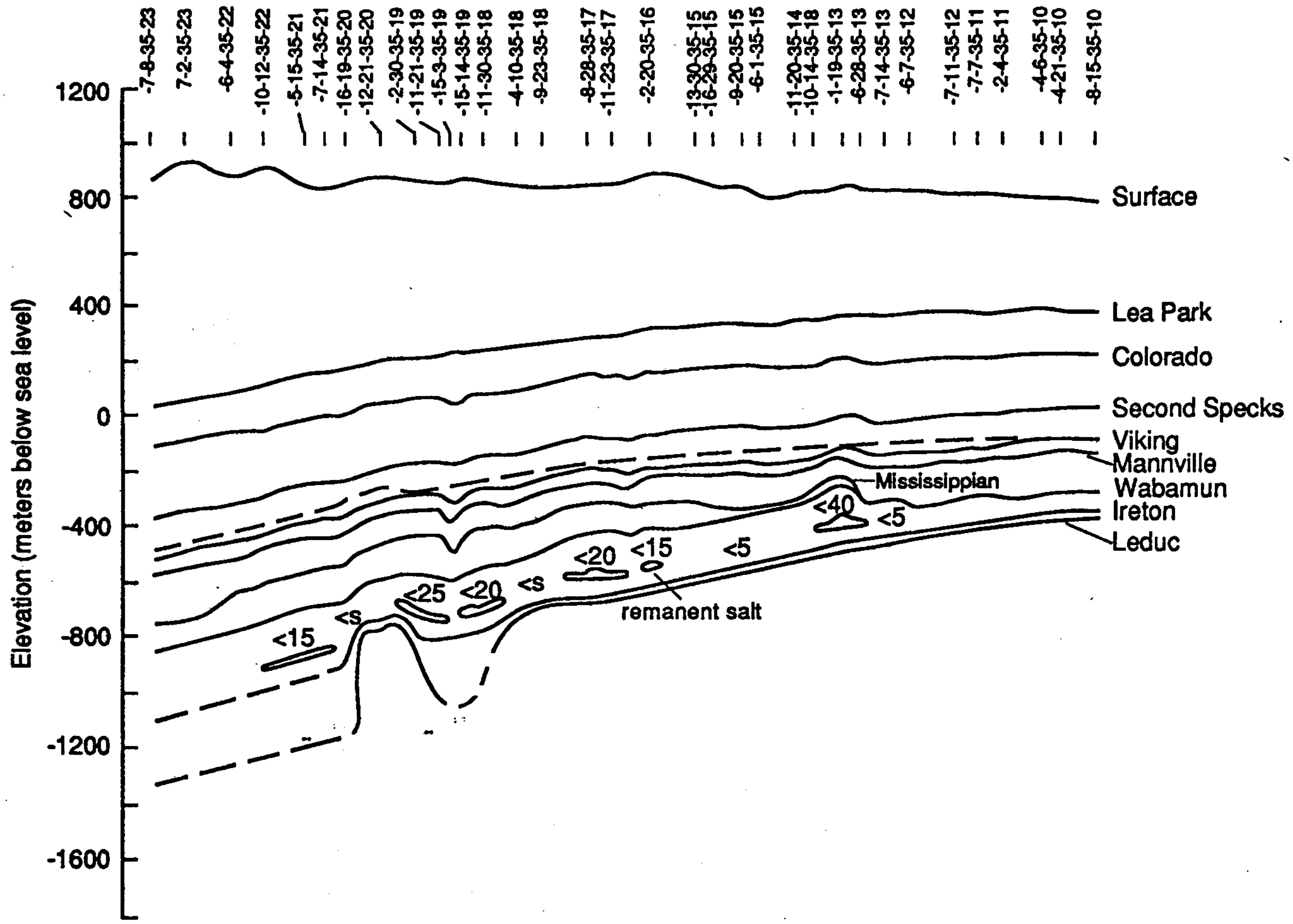

Figure 4. Geologic section A-A'.

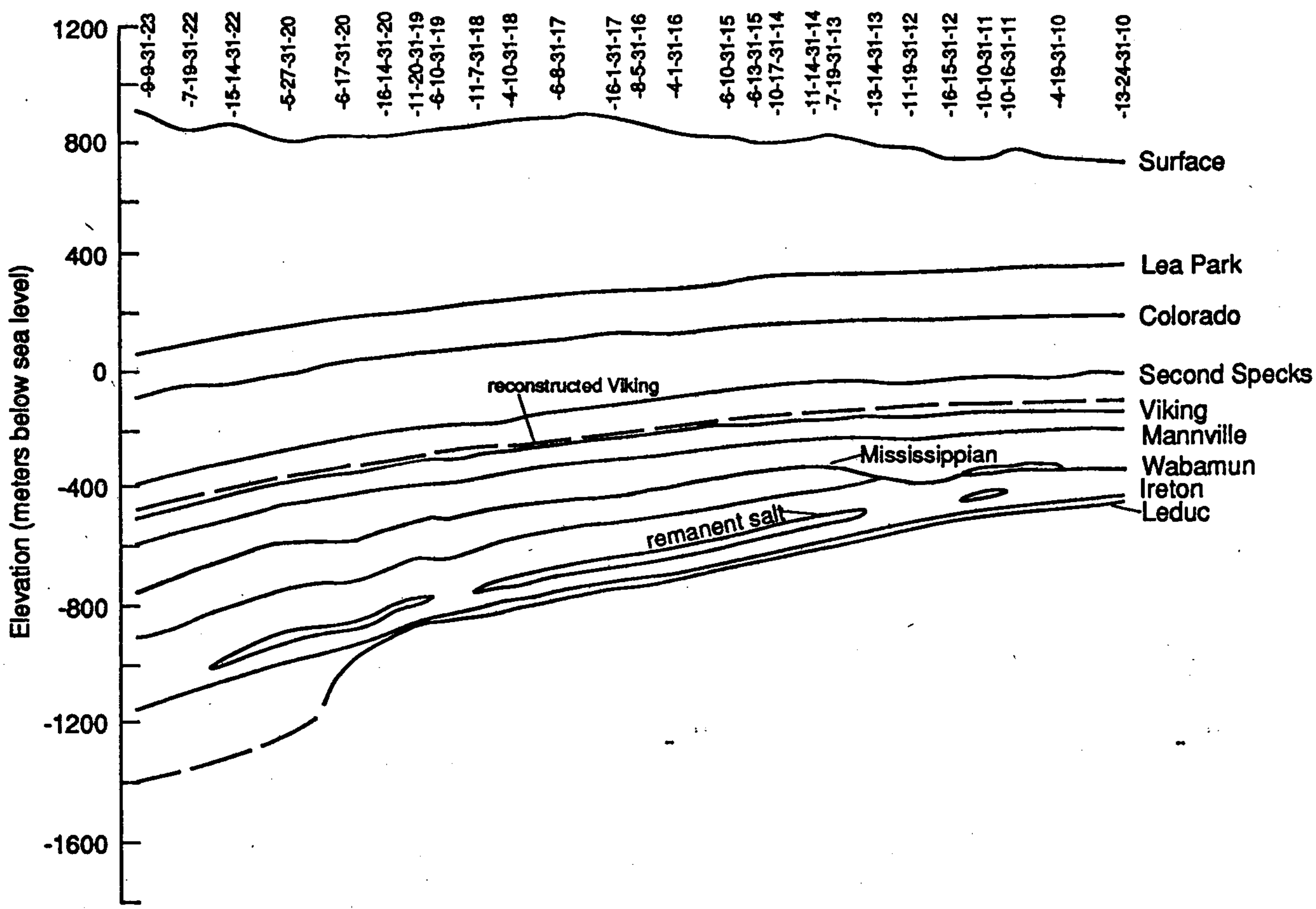

Figure 5. Geologic section B-B'.

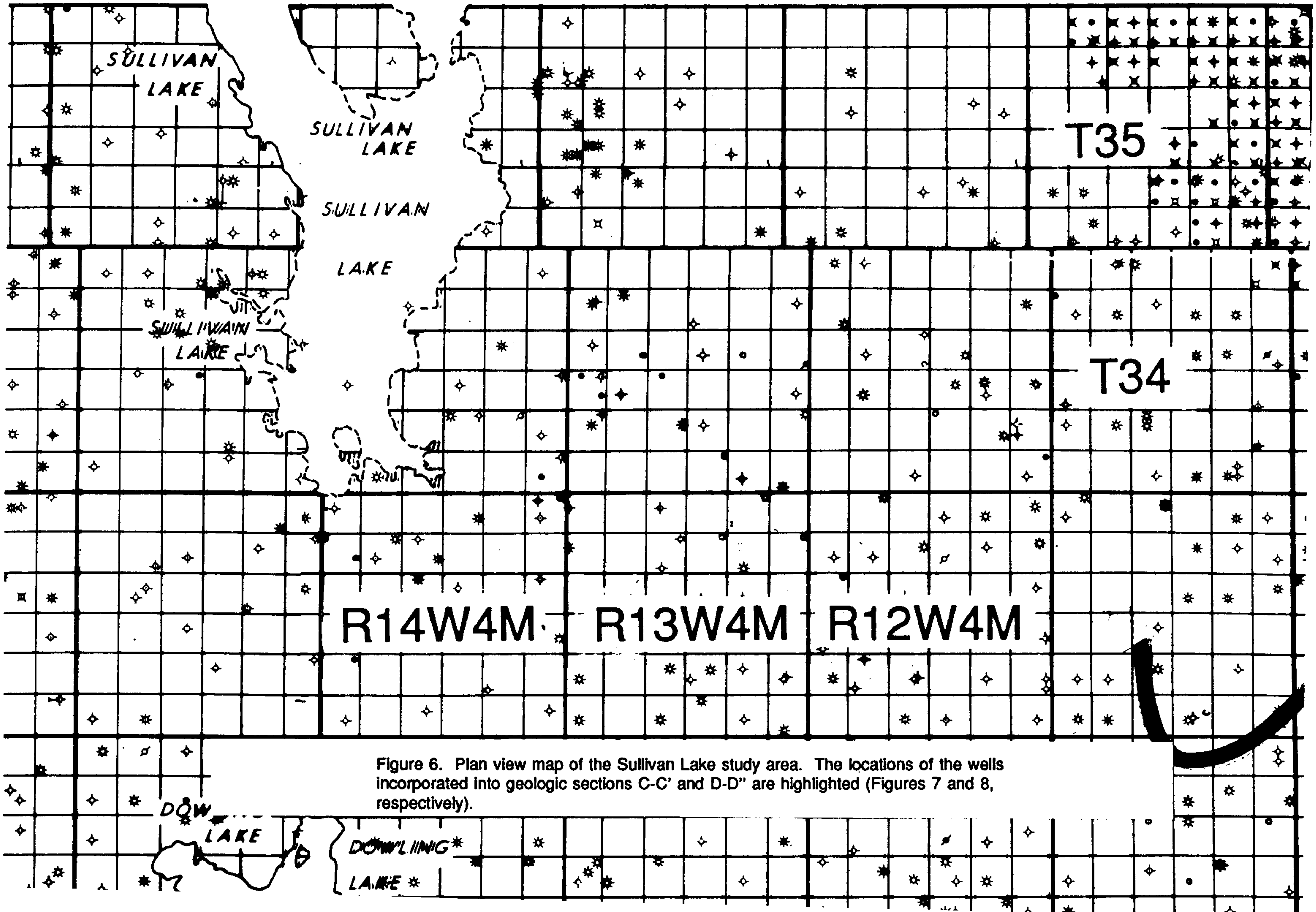

Figure 6. Plan view map of the Sullivan Lake study area. The locations of the wells incorporated into geologic sections C-C' and D-D'' are highlighted (Figures 7 and 8, respectively).

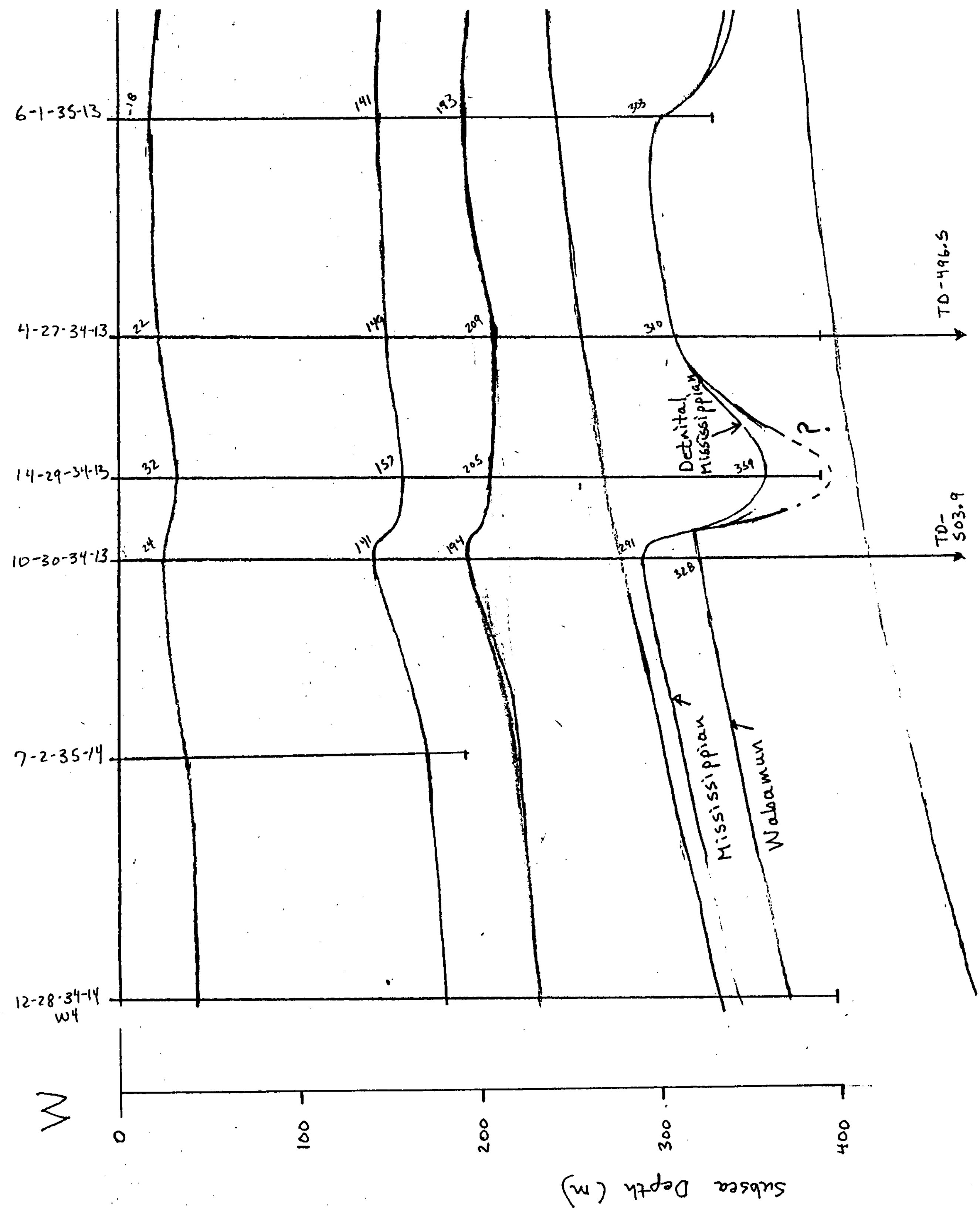

Figure 7. Geologic section C-C'.

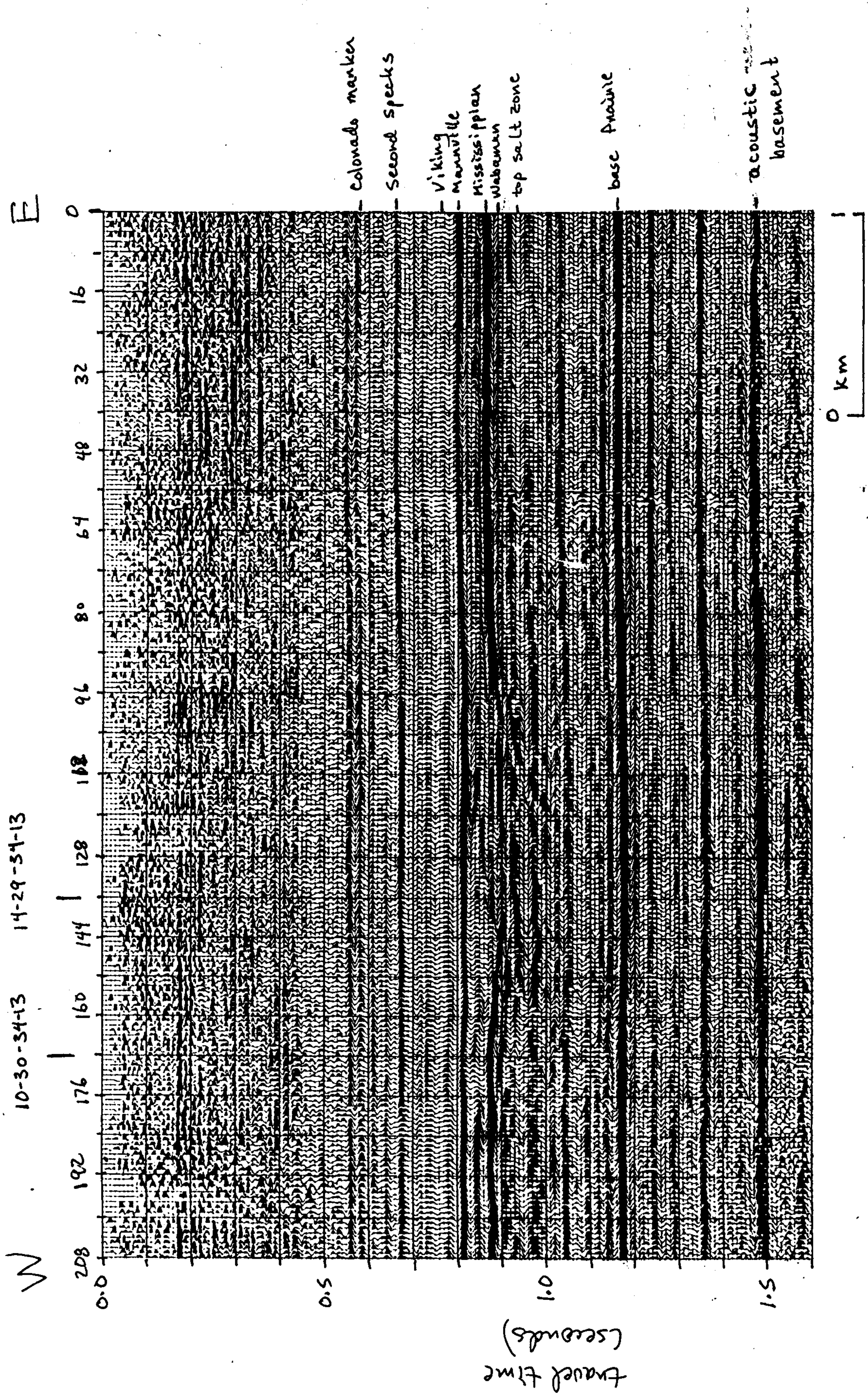

Figure 8. Normal-polarity, nonmigrated seismic line C-C'. The seismic line crosses the Paleozoic channel displayed in Figure 7.

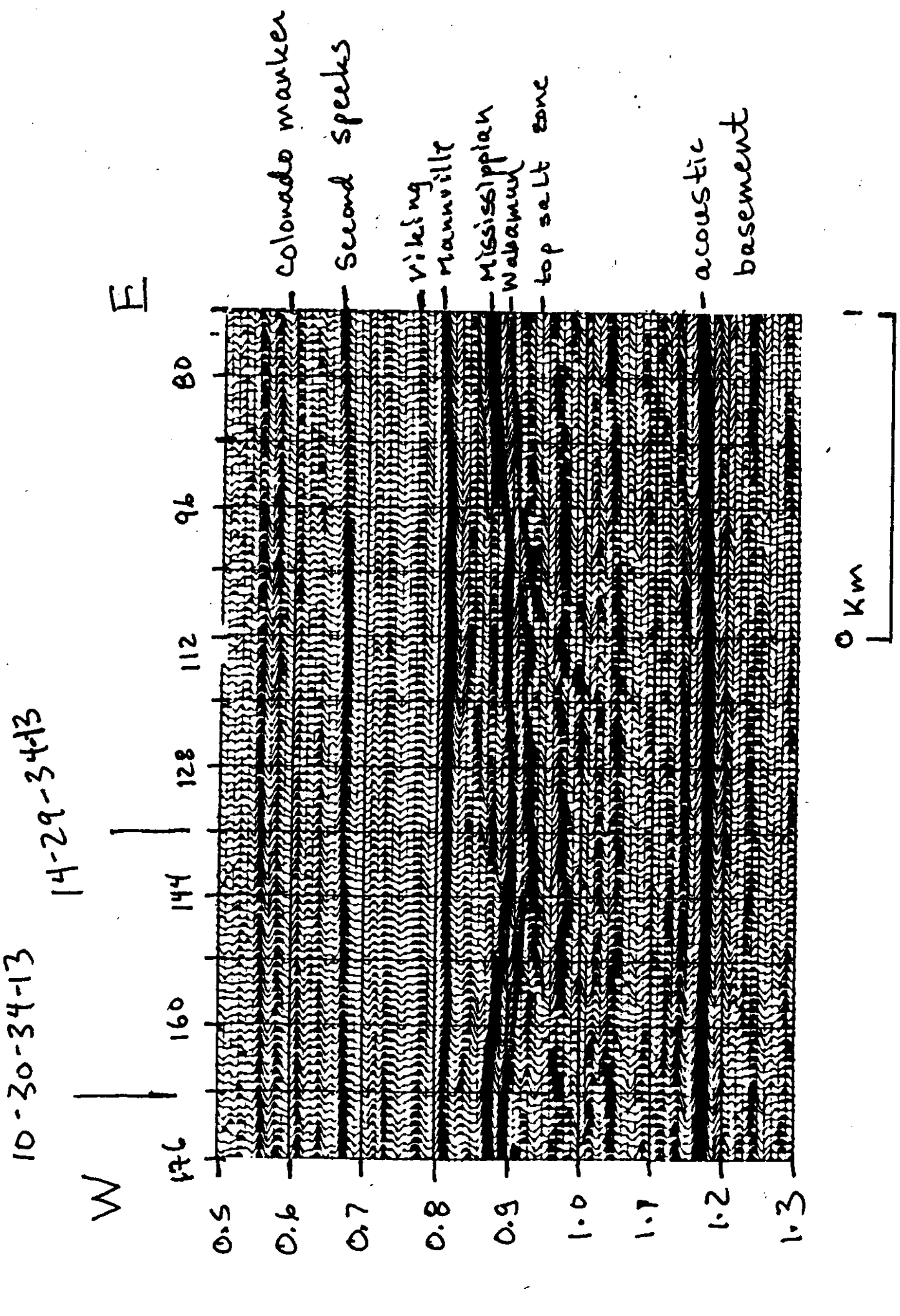

Figure 9. Enlargement of a portion of seismic line C-C' illustrating the edge of the Paleozoic channel.

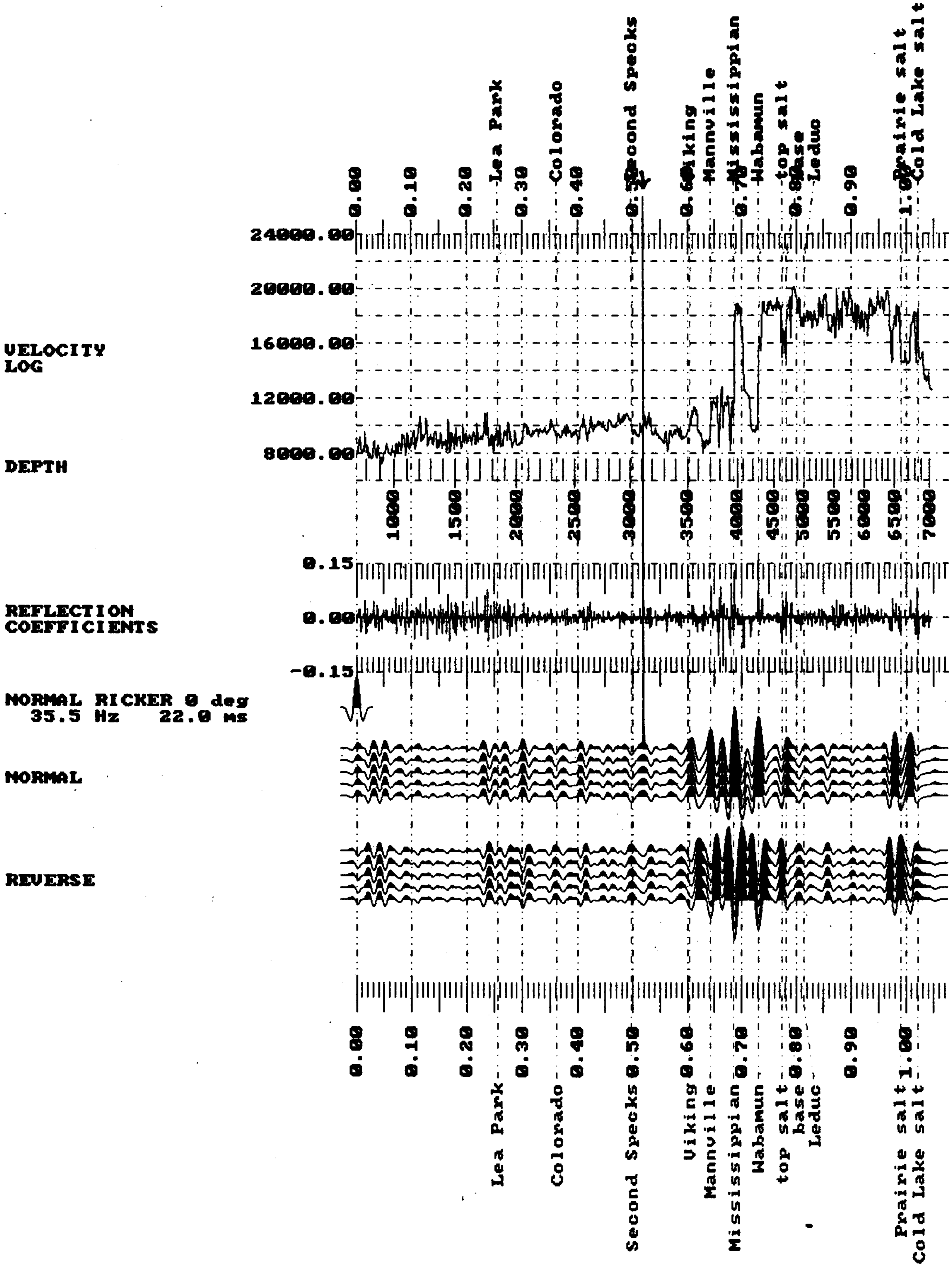

Figure 10. Synthetic seismogram for the 2-20-35-16W4M well. 2-20 is the closest deep well (Elk Point penetration; Figure 1) for which a sonic log is available. This well encountered about 12 m of Wabamun salt.

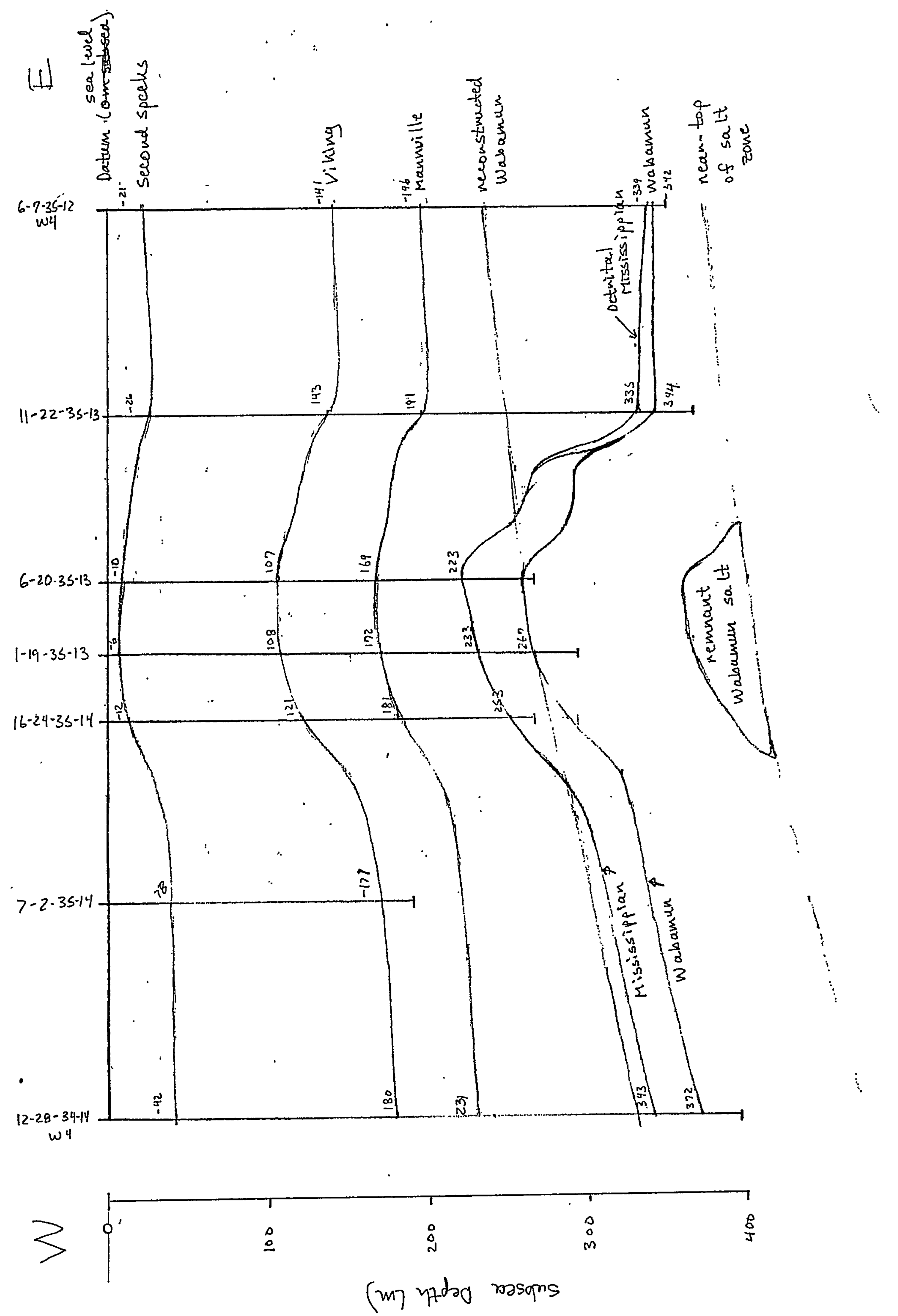

Figure 11. Geologic section D-D'

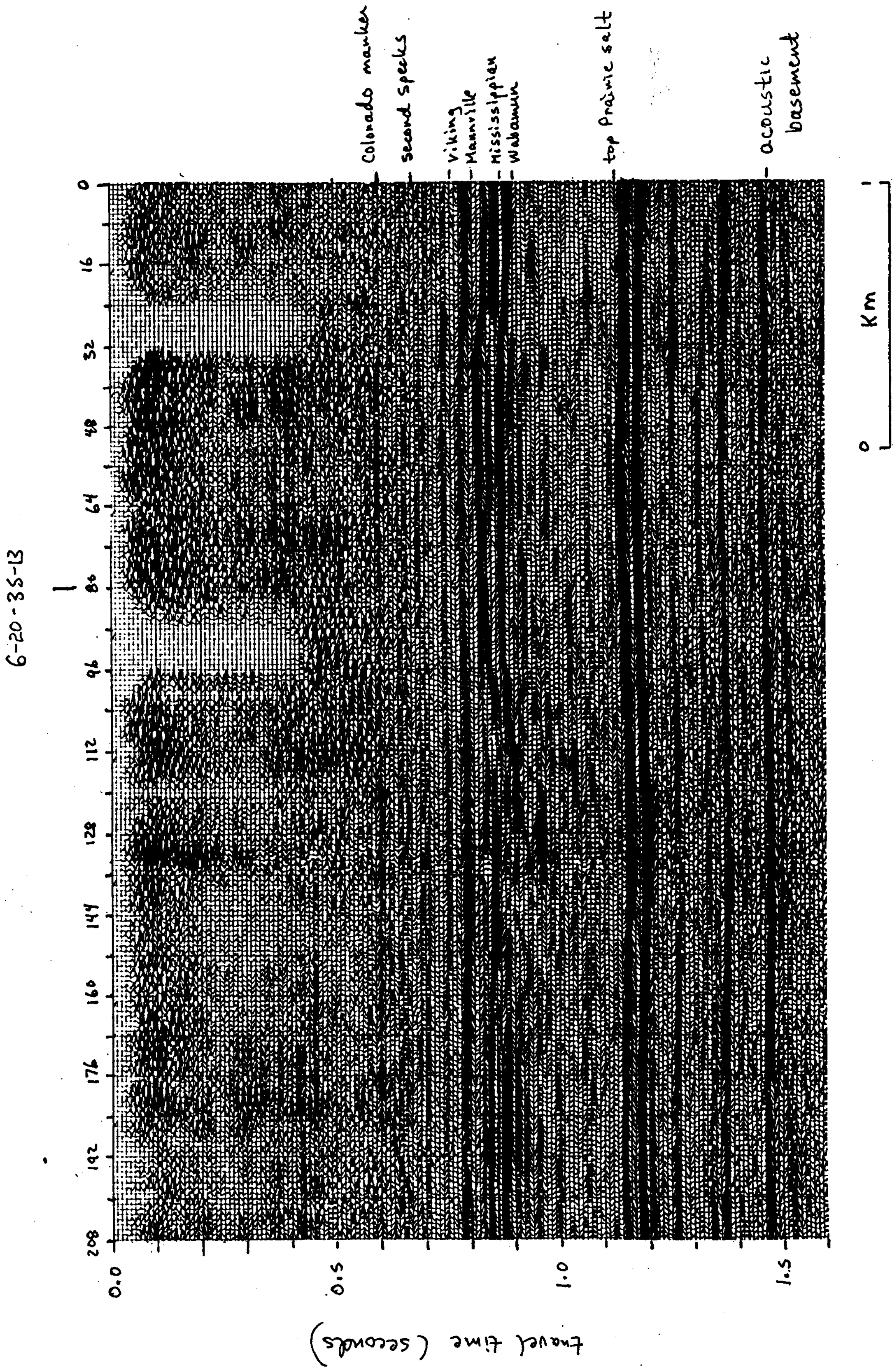

Figure 12. Reverse-polarity, nonmigrated seismic line D-D'. The seismic line crosses the isolated remnant of Wabamun salt displayed in Figure 11.

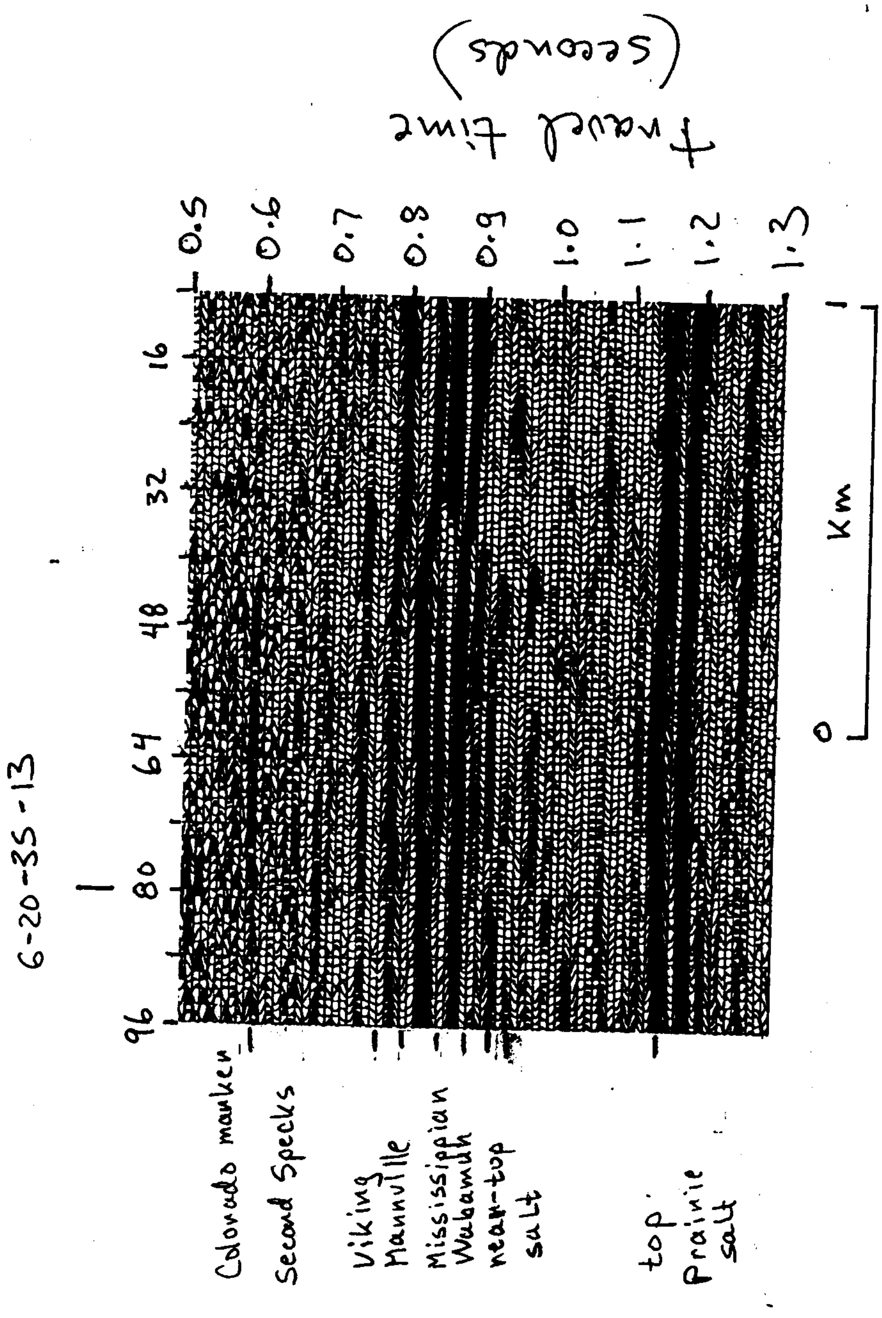

Figure 13. Enlargement of a portion of seismic line C-C' illustrating the edge of the isolated remnant of Wabamun salt displayed in Figure 11.