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Salt dissolution and subsidence in response to regional deformation, southcentral Alberta

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ABSTRACT

Analyses of well-log and seismic data suggest that a net thickness of about 40 m of Famennian-age bedded rock salt was uniformly deposited within Wabamun Group in the Stettler South study area (T33-34, R18-21W4M) in south-central Alberta. Subsequent to deposition, this original rock salt was leached to the extent that it is now preserved as irregular shaped bodies of widely varying areal extent and thickness. In the immediate study area, dissolution appears to have been initiated by regional deformation during the mid-Late Cretaceous, and accentuated thereafter by various large-scale mechanisms including glacial loading and unloading.

Seismic data suggest that some of the salt-dissolution features in the Stettler South area retain a marked linear orientation (SSW-NNE). In short cross-section (on west-east oriented seismic lines), these structures are manifested as upward-expanding conical-shaped zones of observable subsidence. These zones of subsidence are characterized by increased structural relief at greater depth (due principally to the timing of the leaching, stoping and lateral strain within post-salt strata), and small-amplitude near-vertical offsets.

The character of these subsidence features is consistent with: 1) the onset of dissolution as a result of regional deformation during mid-Late Cretaceous time; 2) the plastic deformation (creep) of rock salt; 3) the plastic deformation (on a large scale) and relatively gradual subsidence of the post-salt strata; and 4) accelerated rates of leaching in response to glacial loading and unloading.

INTRODUCTION

The Upper Devonian Wabamun Group in south-central Alberta is subdivided into the Stettler and Big Valley formations (Figure 1). The Stettler consists predominantly of interlayered dolomites, anhydrites and residual halite-bearing bedded rock salt; the Big Valley is composed of green shales and fossiliferous limestones (Belyea, 1964).

The rock salt of the Wabamun Group was widely distributed and uniformly deposited throughout much of southeastern Alberta (Anderson, 1992; Anderson and Brown, 1991, 1992a,b; Anderson, Brown and Hinds, 1988; Oliver and Cowper, 1983; Meijer Drees, 1986). However, as a result of extensive post-depositional dissolution, this salt is preserved now only as isolated-to-contiguous bodies of irregular shape, having maximum net thicknesses on the order of 40 m (Figures 2, 3, and 4).

Previous geological based studies suggest that in the Stettler South area (T33-34, R18-21W4M; Figures 2 and 4), dissolution of the Wabamun rock salt was initiated by regional deformation during the mid-Late Cretaceous (Santonian time), and continued thereafter at significantly reduced rates (Anderson, 1992; Anderson and Brown, 1991, 1992a,b; Anderson, Brown and Hinds, 1988). These conclusions are based on the the following observations:

1) Post-salt/pre-Santonian strata in this area (except for the sub-Cretaceous unconformity, or Paleozoic subcrop), are more-or-less parallel and draped across the residual rock salt. Relative structural relief is a direct function of the thickness of the residual rock salt, and to a lesser extent, erosional topography at the sub-Cretaceous level.

2) On the reconstructed salt-distribution map for end-Santonian time (end Colorado Group deposition), dissolutional features, basinward of the Wabamun subcrop edge, exhibit a preferred NNE-SSW or WNW-ESE orientation.

3) This near-orthogonal dissolutional pattern for Santonian time has, on post-Santonian reconstructed salt-distribution maps, become increasingly masked by progressive dissolution.

In support of these geological (well-log based) interpretations, we present three parallel seismic lines. These lines cross a NNE-trending salt-dissolution lineament and associated subsidence feature. These geophysical data support the interpretation that dissolution of the Wabamun rock salt in the Stettler South area was initiated by regional deformation during the mid-Late Cretaceous and continued thereafter, although at a markedly reduced rate. The data further suggest that salt dissolution is largely a self-substaining process, whereby salt removal facilitates continued dissolution, and is influenced by processs including rock-salt creep and glaciation.

SALT DISSOLUTION FEATURE

The geologic section A-A' originates in the Ireton shale basin and extends eastward onto the Leduc fringing reef complex (Figure 5). Seven stratigraphic horizons have been interpretively correlated across this section. Six of these horizons (Leduc, Ireton, Wabamun, Mississsippian, Mannville, and Second Specks; Figure 1) are well-site controlled. The seventh plotted horizon, the reconstructed Wabamun, is our estimate of where the Wabamun would be structurally situated if all of the dissolved Wabamun salts were restored. We base this estimate on the hypothesis that 40 m of Wabamun rock salt were uniformly deposited in the Stettler South area, and that dissolution occurred in mid-Late Cretaceous time (subsequent the deposition of the Second Specks) or thereafter (Anderson and Brown, 1992a,b).

As indicated in Figure 5, Wabamun rock salt is preserved at the 7-14 and 6-4 well sites and absent at the 10-5 and 3-30 locations. On the basis of structural control at the Wabamun level or shallower horizons, residual rock salt is interpreted as being preserved at the 10-13, 16-27, and 8-31 locations. (Note that the net rock salt thicknesses are presented. The gross thickness of the rock salt-bearing zone is typically two to three times the net salt thickness.)

Figures 6, 7, and 8, are three interpreted seismic lines. These lines are west-east oriented and parallel, although slightly offset. Line M-1 is about 1 km north of 3-30 (Figure 3), Line M-2 is 0.2 km north (3-30 effectively ties Line M-2 at trace 81), Line M-3 is about 0.8 km south. These 12-fold dynamite data were acquired using DFS-V recording equipment, and a split spread with near and far offsets of 25 m and 1500 m, respectively.

As an aid to the interpretation of these seismic data, a suite of synthetic seismograms were generated. The synthetic seismogram from one of the deeper, rock salt bearing wells in the general area (2-20-35-16W4M) is displayed as Figure 9. The more significant synthetic seismic events have been identified. On the reverse-polarity display, the Prairie salt event is manifested as a high amplitude peak, the top and base of the 15 m thick residual Wabamun rock salt zone generates a high amplitude peak-trough sequence, the Wabamun, Mississippian, Mannville, Viking, and Lea Park horizons correspond to prominent troughs, the Colorado is manifested as a peak. These reflectors, as well as several other marker events, have been correlated on the example seismic lines (Figures 6, 7 and 8).

The most prominent structure on these seismic data is the NNE trending subsidence feature centered on line M-1 at shotpoint 87, on line M-2 at 89, and on Line M-3 at 15 (Figures 6, 7 and 8). This subsidence feature is attributed to the dissolution of Wabamun rock salt. Leaching is thought to have initiated along a regional NNE trending shear zones during the mid-Late Cretaceous, and to have continued thereafter, albeit at a significantly reduced rate. In support of these interpretations we note:

1) The Wabamun salt interval and the encompassing Wabamun/Ireton interval are thinner immediately below the collapse feature than elsewhere on the seismic lines, indicating that salt dissolution is the most plausible cause of subsidence.

   The Wabamun salt and Wabamun/Ireton intervals thin by about 20 ms (40 m) within the zone of subsidence on Line M-2 (Figure 7) indicating that there is little, if any, residual salt near the center of the feature, and that up to 40 m of rock salt are preserved elsewhere. Significantly less thinning (about 10 ms) is observed on Lines M-1 and M-3, suggesting that up to 20 m of rock salt is preserved within the zone of maximum subsidence on these lines (Figures 6 and 8).

2) The Wabamun, Mississippian, Mannville, and Second Specks events are more-or-less time-structurally parallel across the subsidence feature (Figures 6, 7 and 8). Significantly less subsidence is observed at and above the Colorado event. These observations support the thesis that dissolution initiated in mid-Late Cretaceous and continued thereafter at a reduced rate.

3) The subsidence feature is oriented NNE, supporting the thesis that dissolution initiated along a NNE shear zone. The three west-east oriented seismic lines are oriented more-or-less orthogonal to the lineament.

4) The Wabamun event on line M-2 is about 55 ms lower at shotpoint 89 than at shotpoint 201 (Figure 7). This time-structural relief is attributed to the dissolution of about 40 m of Wabamun rock salt (up to 20 ms), up to 25 m of erosional relief at the Mississippian level (up to 10 ms), and a possible decrease in the average velocity of the Colorado/Wabamun interval in the vicinity of trace 89 (as a result of stoping and/or subsidence-related

fracturing). Relative to Line M-2, the Wabamun within the zone of subsidence is time-structurally higher on Lines M-1 and M-3, supporting the interpretation that residual salt is preserved within the subsidence feature on these lines (Figures 6 and 8).

5) Pre-Wabamun events on Line M-2 are about 25 ms time-structurally lower beneath shotpoint 89 than shotpoint 201 (Figure 7). This pattern is consistent with the interpretation that 40 m of rock salt has been leached at shotpoint 89, 25 m of erosional relief at the Mississippian level, and a possible decrease in the average velocity of the Colorado/Wabamun interval. Less velocity "push-down" is observed beneath the subsidence feature on Lines M-1 and M-3 (Figures 6 and 8).

6) The Wabamun/Ireton and top/base salt intervals thicken gradually away from the center of the subsidence feature (Figures 6, 7 and 8). Time-structural relief along the post-salt horizons similarly increases gradually away from the center of the subsidence feature. These observations suggest that the edge of the residual rock salt is gradational rather than abrupt, and support the theses that: a) the residual rock salt tends to creep toward sites of active leaching; and b) the uppermost soluble layers were most rapidly leached.

7) On Line M-2, subsidence is seismically visible at the Wabamun between shotpoints 37 and 157; at the Mannville between shotpoints 27 and 161; at the Colorado between shotpoints 105 and 167; and at the shallow marker between shotpoints 101 and 178 (Figure 7). Similar patterns are observed on Lines M-1 and M-3 (Figures 6 and 8). In general terms, the subsidence feature, in short cross-section, can be described as an upward-expanding conical-shaped zone of seismically measurable subsidence, a feature characteristic of gradual rather than catastrophic collapse (Anderson and

Brown, 1993; Anderson *et al.*, 1993a,b). This geometry suggests that the post-salt strata have undergone horizontal as well as vertical strain.

8) On Line M-2, the shallow marker beds are up to 10 ms higher above the center of the subsidence feature (shotpoint 89) than nearer the edge of the zone of seismically measurable subsidence (west of shotpoint 101 and east of 33; Figure 7). These beds also appear to be vertically offset at trace 177. Similar patterns are observed on Lines M-1 and M-3 (Figures 6 and 8), suggesting that the zone of seismically measurable subsidence is slowly expanding as a result of continuing dissolution and the long term creep of rock salt toward the shear lineament (Anderson and Brown, 1993). We speculate that these shallow subsidence features may be partially the result of a most recent phase of relatively rapid dissolution related to glacial loading and unloading.

DISCUSSION

On the basis of the incorporated seismic data and previous geologic studies of the Wabamun salt, we have reconstructed the history of salt dissolution and subsidence in the Stettler South area. Our proposed scenario is as follows:

1) During the Fammennian Stage of the Late Devonian, about 40 m of bedded Wabamun Group rock salt were uniformly deposited within the Stettler South area.

2) During the pre-Cretaceous hiatus the paleo-surface was intensely scoured. In the Stettler South area, the Mississippian is the Paleozoic subcrop. Further to the east, along the Wabamun subcrop, rock salt was exposed to a near-surface environment during the pre-Cretaceous and dissolution was

initiated as a more-or-less continuous front that effectively paralled the Wabamun outcrop edge.

3) The bedded rock salt in the Stettler South area remained relatively undisturbed until mid-Late Cretaceous (Santonian time), at which time regional deformation (possibly associated with the onset of the Cordilleran Orogeny) occurred. These shear zones provided conduits between the evaporitic beds (at a depth of about 750 m) and adjacent aquifers; leaching and subsidence were thereby initiated.

4) Initially, thick sections of rock salt were in direct contact with vertical conduits and rate of dissolution was relatively high. In a general sense, the rock salt in proximity to the shear zone was leached from the top down (ie., at any location, the most rapid dissolution occurred along the uppermost remaining soluble bedded layer). As a result of both this top-down pattern of leaching and the progressive creep of rock salt towards the shear zone, the residual rock salt thickens gradually (in a step-wise manner) away from the shear zone.

5) The collapse of post-salt strata was gradual as opposed to catastrophic. Plastic strain occurred both vertically and horizontally. In short cross-section (orthogonal to the shear zone), the collapse features developed as an upward expanding zones of measurable subsidence. These observations indicate that the shear strength of the post-salt strata and the rate of salt dissolution were relatively low, and that the rate of rock salt creep was relatively high (Anderson et al., 1994a,b). Creep was caused primarily by compressional stresses related to the leaching of rock salt, and accentuated by the presence of water (Urai et al., 1986).

6) As the thick salt in the immediate proximity of the vertical conduits was

progressively dissolved, the rate of leaching decreased markedly. Dissolution was controlled, at least partially by both the rate at which the residual rock salt crept toward the vertically permeable zones, and fluid flow within fractured post-salt strata.

7) In places, progressive dissolution (and associated creep) caused the near-zero edge of the residual salt to migrate laterally away from the shear zone. The rate of leaching and hence the rate of migration was affected by changes in the hydrologic environment, regional tectonism, and glaciation (Anderson and Knapp, 1993).

SUMMARY

The incorporated seismic data support the thesis that the dissolution of the Wabamun rock salt in the Stettler South area was initiated by regional deformation in mid-Late Cretaceous time. The shear zones provided vertical conduits between the rock salt and adjacent aquifers; leaching and subsidence were thereby initiated.

In short cross-section, the collapse feature in the Stettler South area forms an upward-expanding zone of measurable subsidence. Strata within this zone have not been intensely faulted, indicating that subsidence was gradual as opposed to catastrophic, and supporting the thesis that rock salt in the vicinity of the shear zones was dissolved in a top-down manner and deformed plastically (ie. crept toward the zone of dissolution even as the main edge of the rock salt migrated away). Dissolution appears to have been self-perpetuating; a process whereby fractures, created within the immediate post-salt strata as a result of subsidence, provided a conduit for unsaturated waters, thereby facilitating further dissolution. As the main edge of the rock salt (edge of the zone of measurable subsidence) migrated away from the shear zone conduits, the rates of dissolution and subsidence slowed in general. Periods of accelerated dissolution thereafter could have been triggered by regional changes in the hydrological environment or regional tectonism.

The most recent, seismically defined episode of accelerated dissolution and subsidence was possibly triggered by glacial activity. It is conceivable that this latest phase was caused by: 1) glacial loading and an associated increase in subsurface temperatures and stress differentials (Anderson and Knapp, 1993); 2) glacial unloading and an associated influx of fresh-water; and 3) a reversal in regional hydrologic environment from centrifugal-flow to centripetal flow as a consequence of sediment rebound in response to glacial retreat (Anderson and Brown, 1993; Anderson and Knapp, 1993).

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FIGURE CAPTIONS

Figure 1. Stratigraphic chart for south-central Alberta.

Figure 2. Plan view map of the general Stettler area. The Stettler South study area (T33-34, R18-21W4M), the approximate locations of the example seismic lines (Figures 6-8), and locations of the wells incorporated into geologic section A-A' (Figure 5) are highlighted.

Figure 3. West-east geologic cross-sections from the Stettler study area illustrating the discontinuous nature of the Wabamun Group salts. (The maximun net thickness of these salts in the Stettler area, as indicated on the cross-sections, is on the order of 40 m.) Both present-day and reconstructed profiles for the Viking horizon are displayed on the cross-sections.

Figure 4. Isopach map (in meters) depicting the interpreted present-day distribution and net thickness of the Wabamun rock salt in the Stettler area (modified after Anderson and Brown, 1992b). The dashed line represents the Wabamun subcrop edge; the heavy solid lines denote the edges of Leduc reef buildups.

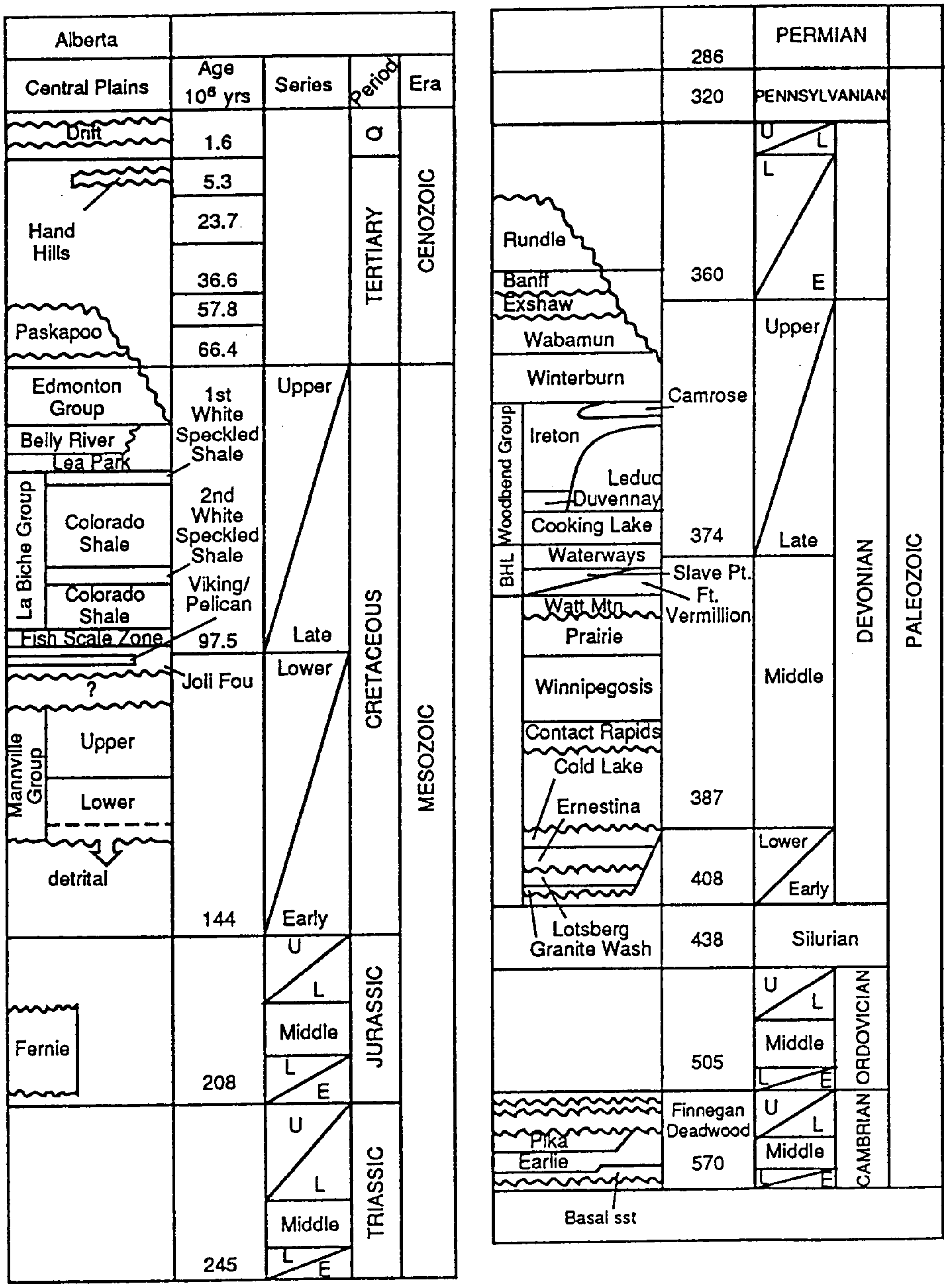
Figure 5. Geologic section A-A'. Well locations are highlighted on Figure 2.

Figure 6. Normal-polarity, nonmigrated seismic line M-1 (Figure 2), crossing the subsidence feature displayed in Figure 5.

Figure 7. Normal-polarity, nonmigrated seismic line M-2 (Figure 2), crossing the subsidence feature displayed in Figure 5.

Figure 8. Normal-polarity, nonmigrated seismic line M-3 (Figure 2), crossing the subsidence feature displayed in Figure 5.

Figure 9. Synthetic seismogram for the 2-20-35-16W4M well. Well 2-20 is the closest deep (Elk Point; Figure 1) penetration for which a sonic log is available. This well encountered about 12 m net of Wabamun rock salt.



Alberta
Central Plains
Age 10⁶ yrs
Series
Period
Era
Drift
Hand Hills
Paskapoo
Edmonton Group
Belly River
Lea Park
La Biche Group
Colorado Shale
Colorado Shale
Fish Scale Zone
?
Mannville Group
Upper
Lower
detrital
Fernie
1.6
5.3
23.7
36.6
57.8
66.4
1st White Speckled Shale
2nd White Speckled Shale
Viking/ Pelican
97.5
Joli Fou
144
208
245
Upper
Late
Lower
Early
U
L
Middle
L
E
U
L
Middle
L
E
Q
TERTIARY
CRETACEOUS
JURASSIC
TRIASSIC
CENOZOIC
MESOZOIC
286
PERMIAN
320
PENNSYLVANIAN
Rundle
Banff
Exshaw
Wabamun
Winterburn
Woodbend Group
Ireton
Leduc
Duvennay
Cooking Lake
BHL
Waterways
Watt Mtn
Prairie
Winnipegosis
Contact Rapids
Cold Lake
Ernestina
Lotsberg
Granite Wash
360
Camrose
374
Slave Pt.
Ft. Vermillion
387
408
438
505
Finnegan
Deadwood
570
Pika
Earlie
Basal sst
U
L
L
E
Upper
Late
Middle
Lower
Early
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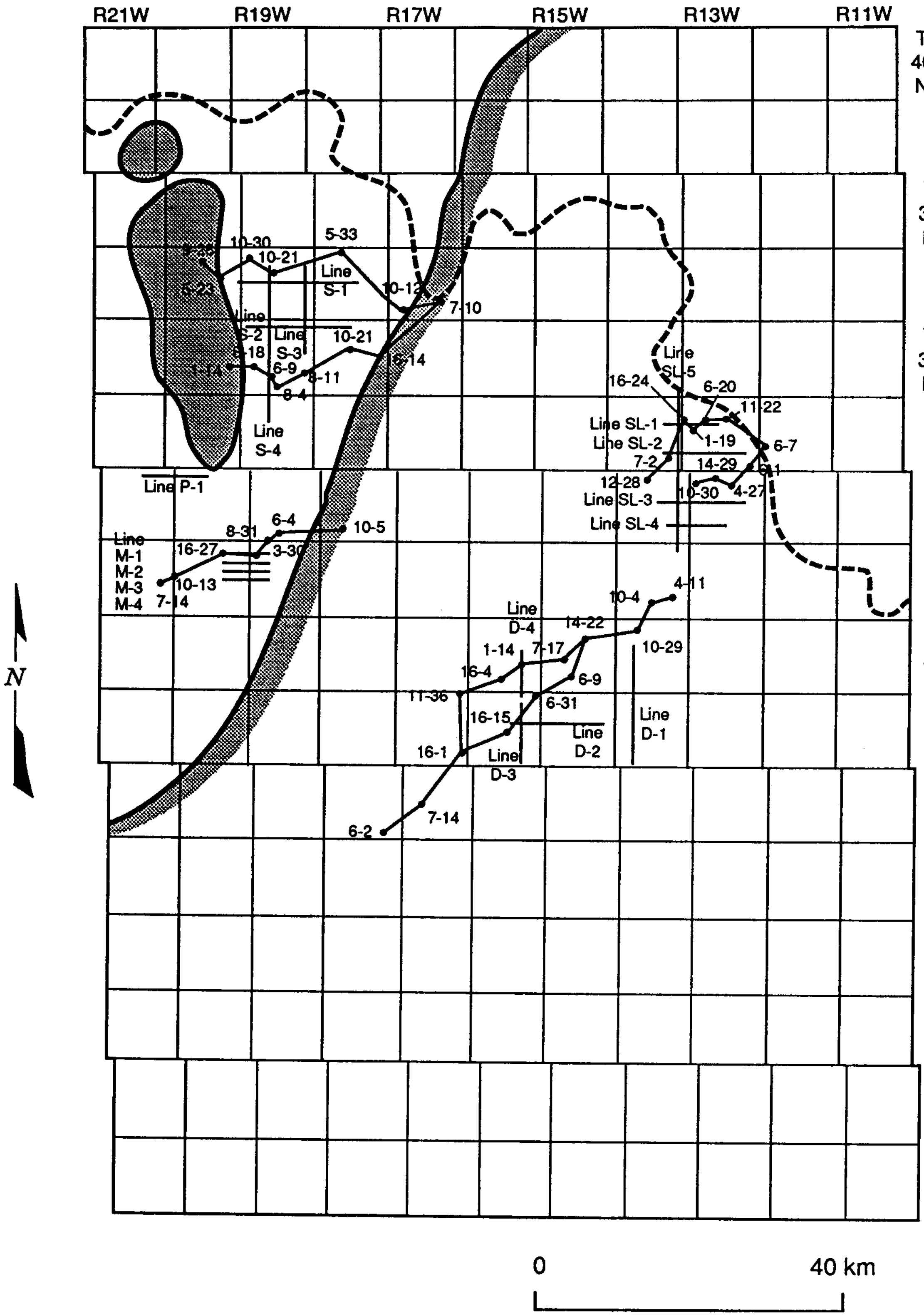
DEVONIAN
ORDOVICIAN
CAMBRIAN
PALEOZOIC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R17W
R15W
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T 26 N
N
5-33
10-30
10-21
5-26
5-23
Line S-1
10-12
7-10
Line S-2
Line S-3
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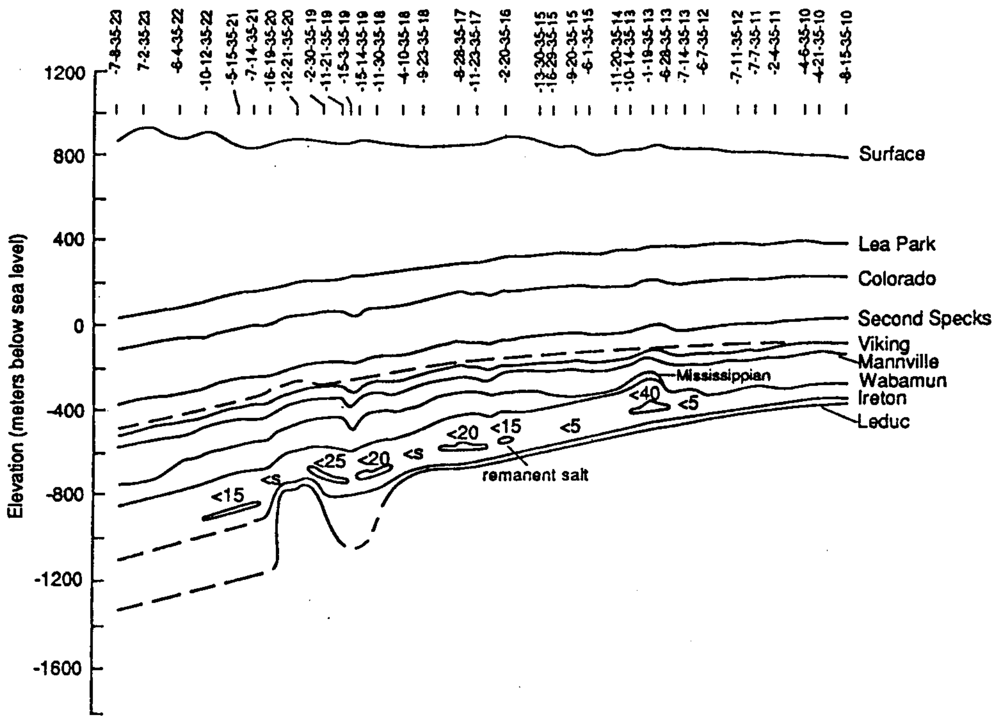
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-8-15-35-10
1200
800
400
0
-400
-800
-1200
-1600
Elevation (meters below sea level)
Surface
Lea Park
Colorado
Second Specks
Viking
Mannville
Mississippian
Wabamun
Ireton
Leduc
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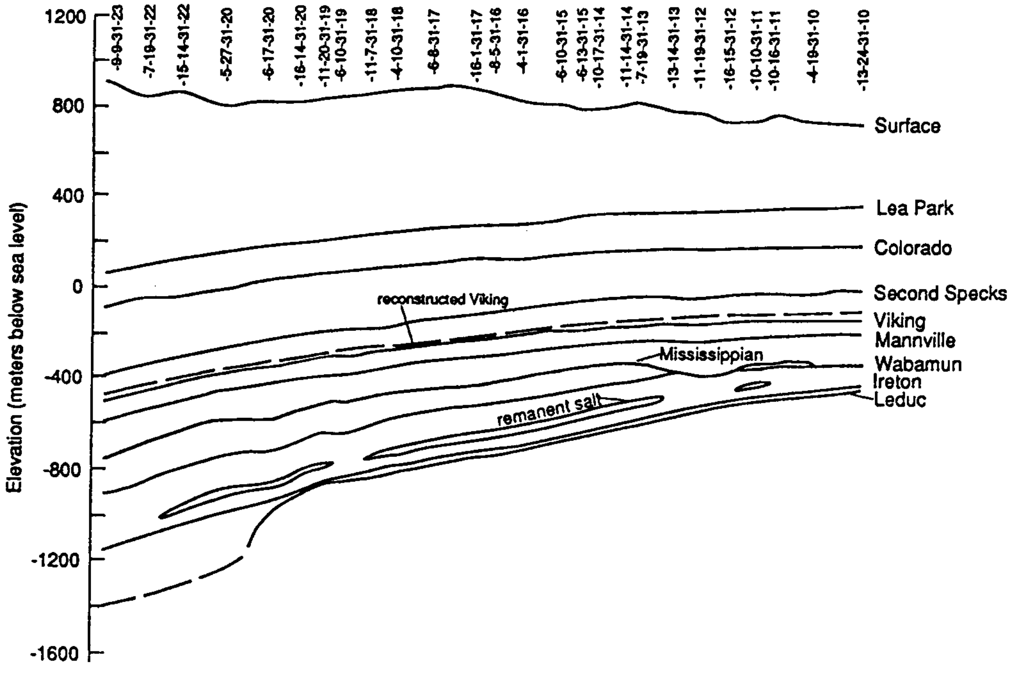
remanent salt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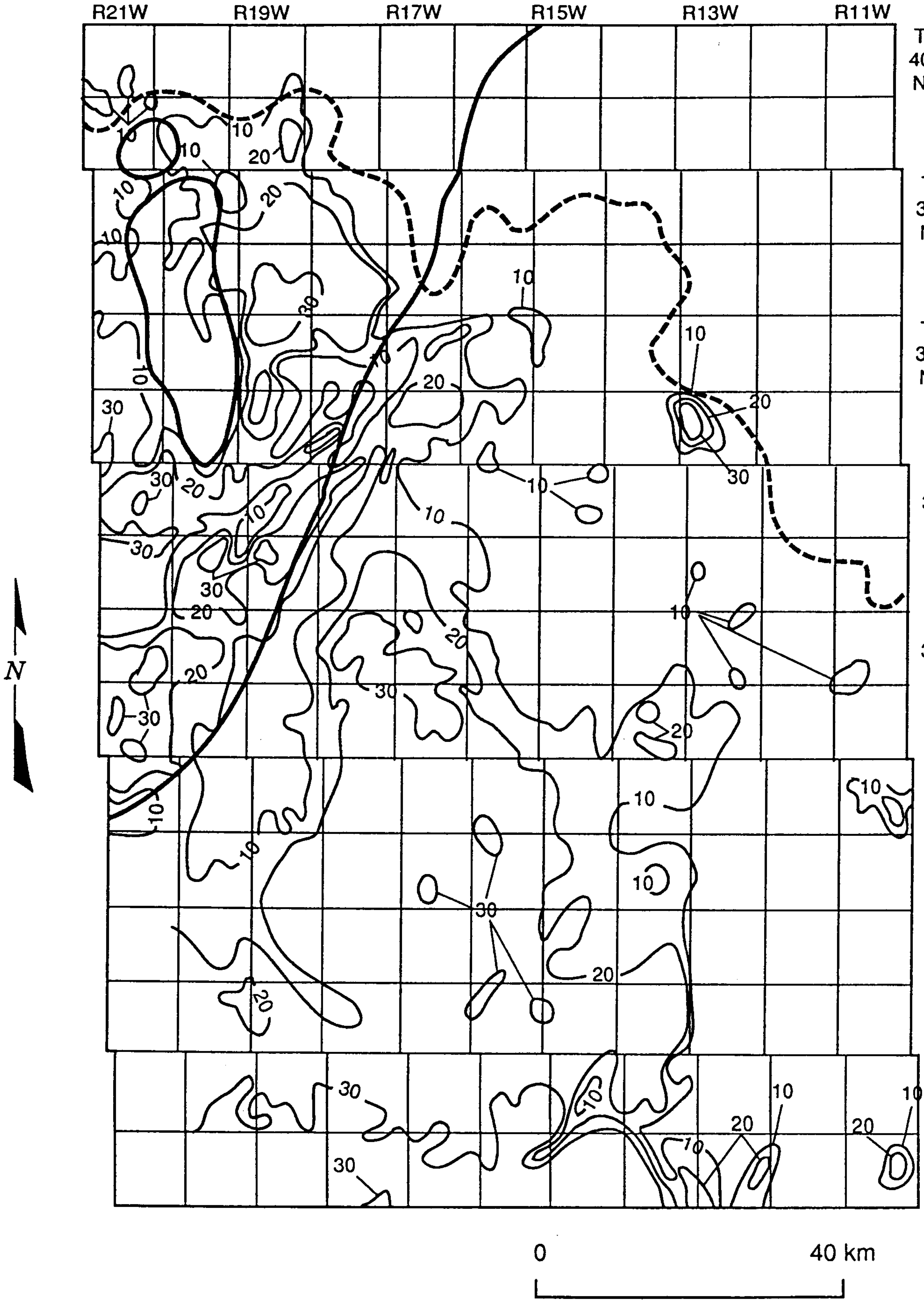
-10-16-31-11
-4-19-31-10
-13-24-31-10
1200
800
400
0
-400
-800
-1200
-1600
Elevation (meters below sea level)
Surface
Lea Park
Colorado
Second Specks
reconstructed Viking
Viking
Mannville
Mississippian
Wabamun
Ireton
Leduc
remanent salt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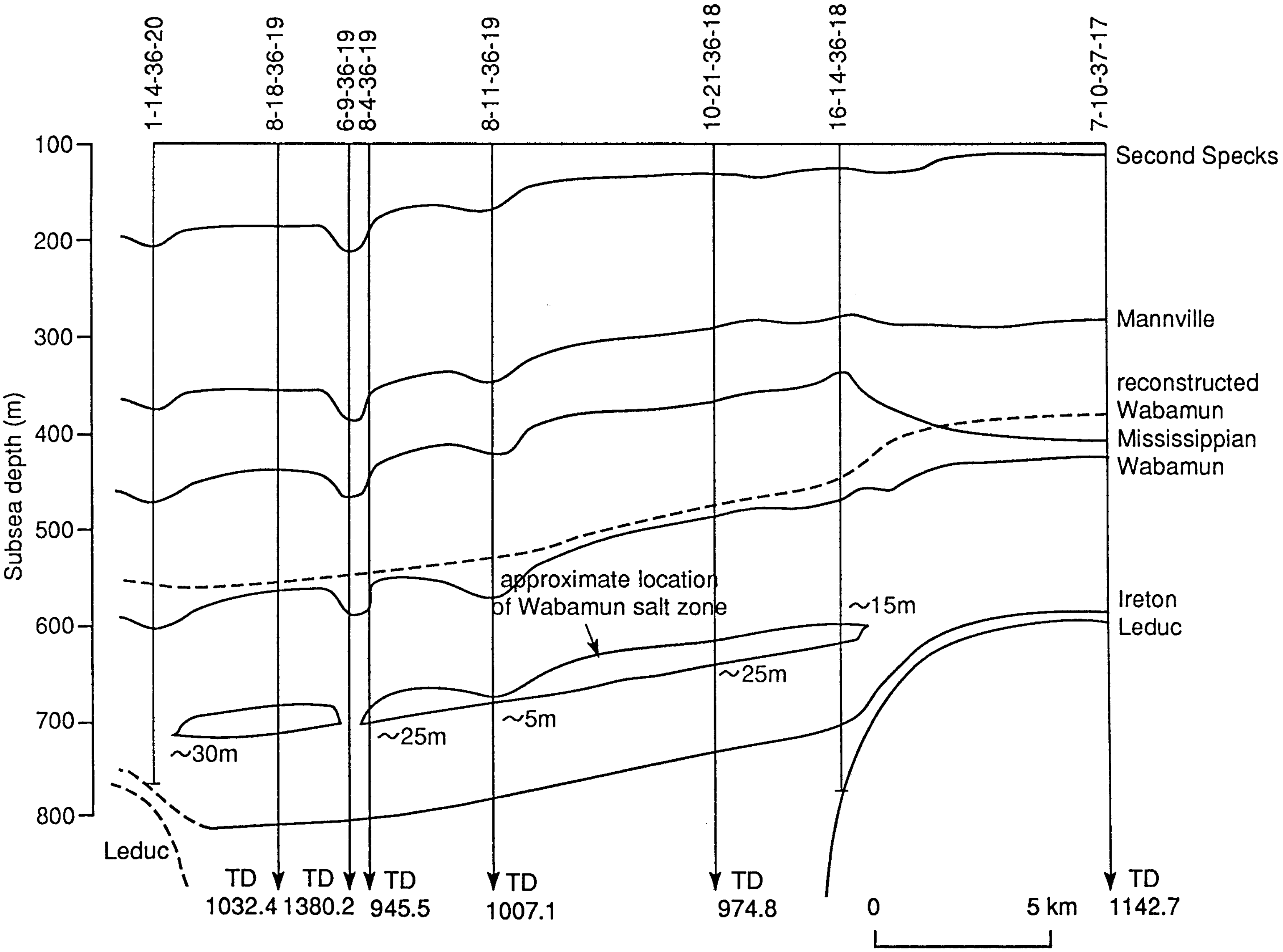
40 km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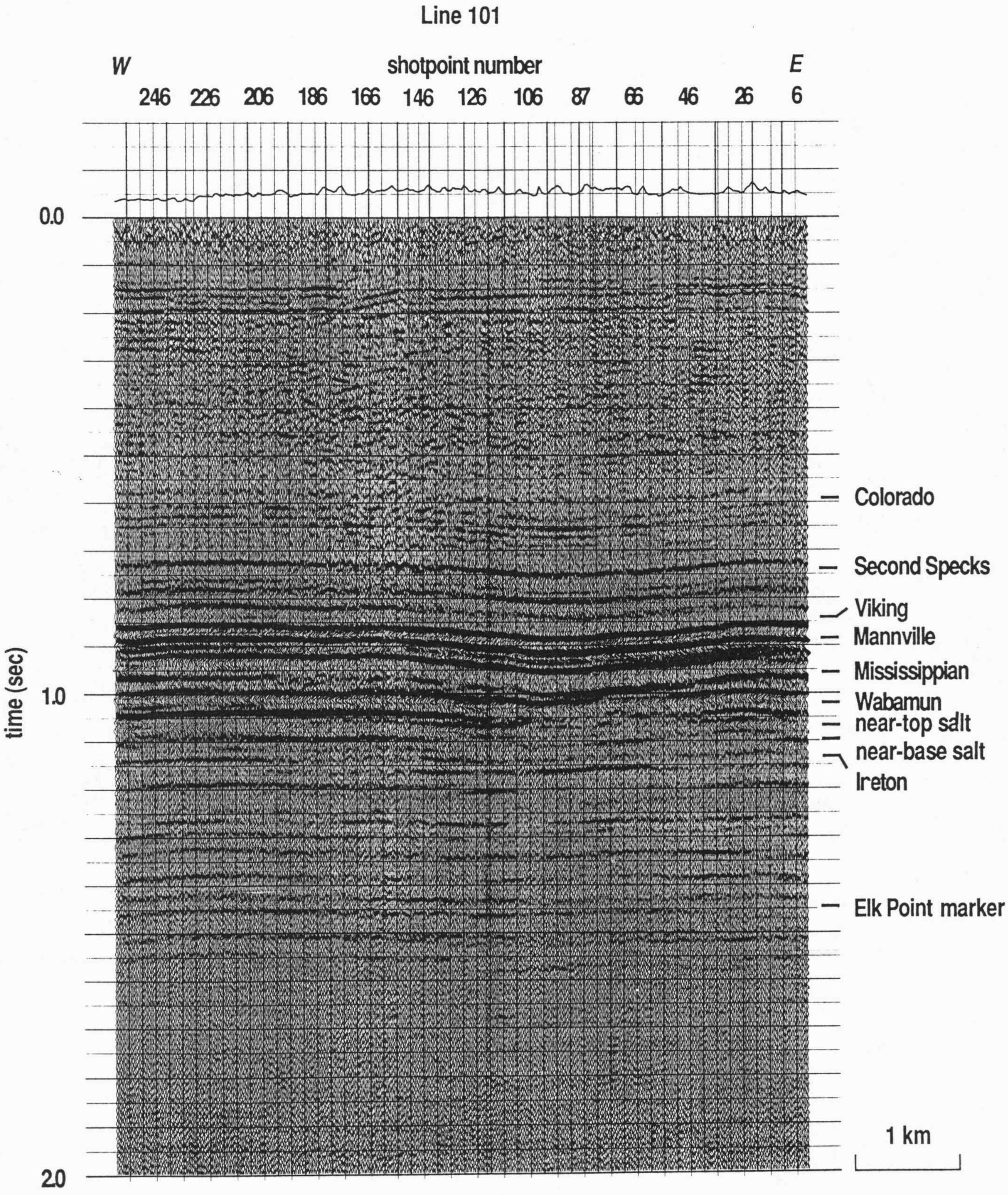
8-11-36-19
10-21-36-18
16-14-36-18
7-10-37-17
Subsea depth (m)
100
200
300
400
500
600
700
800
Second Specks
Mannville
reconstructed Wabamun
Mississippian
Wabamun
Ireton
Leduc
approximate location of Wabamun salt zone
~15m
~25m
~5m
~25m
~30m
Leduc
TD 1032.4
TD 1380.2
TD 945.5
TD 1007.1
TD 974.8
TD 1142.7
0
5 km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E
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226
206
186
166
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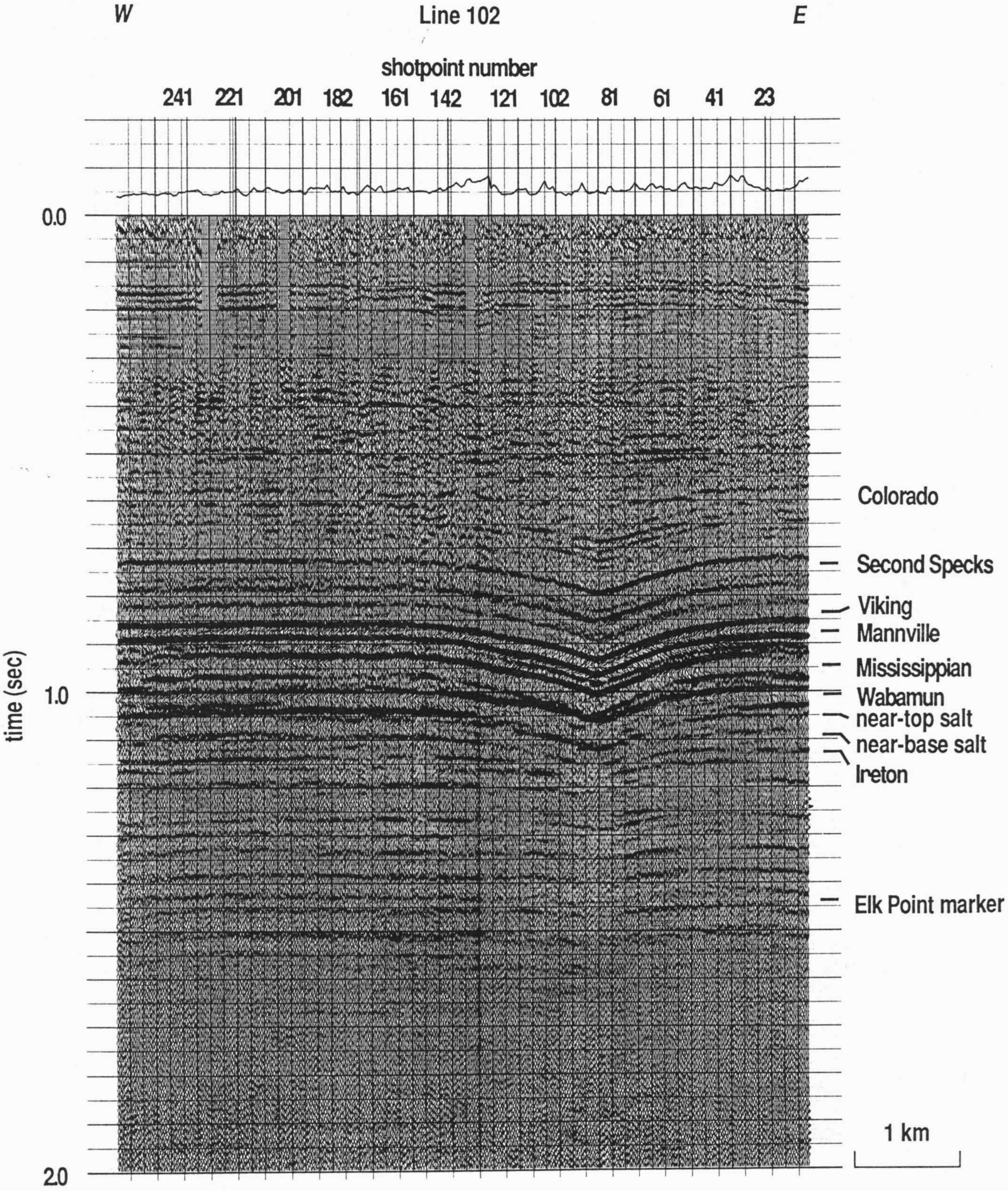
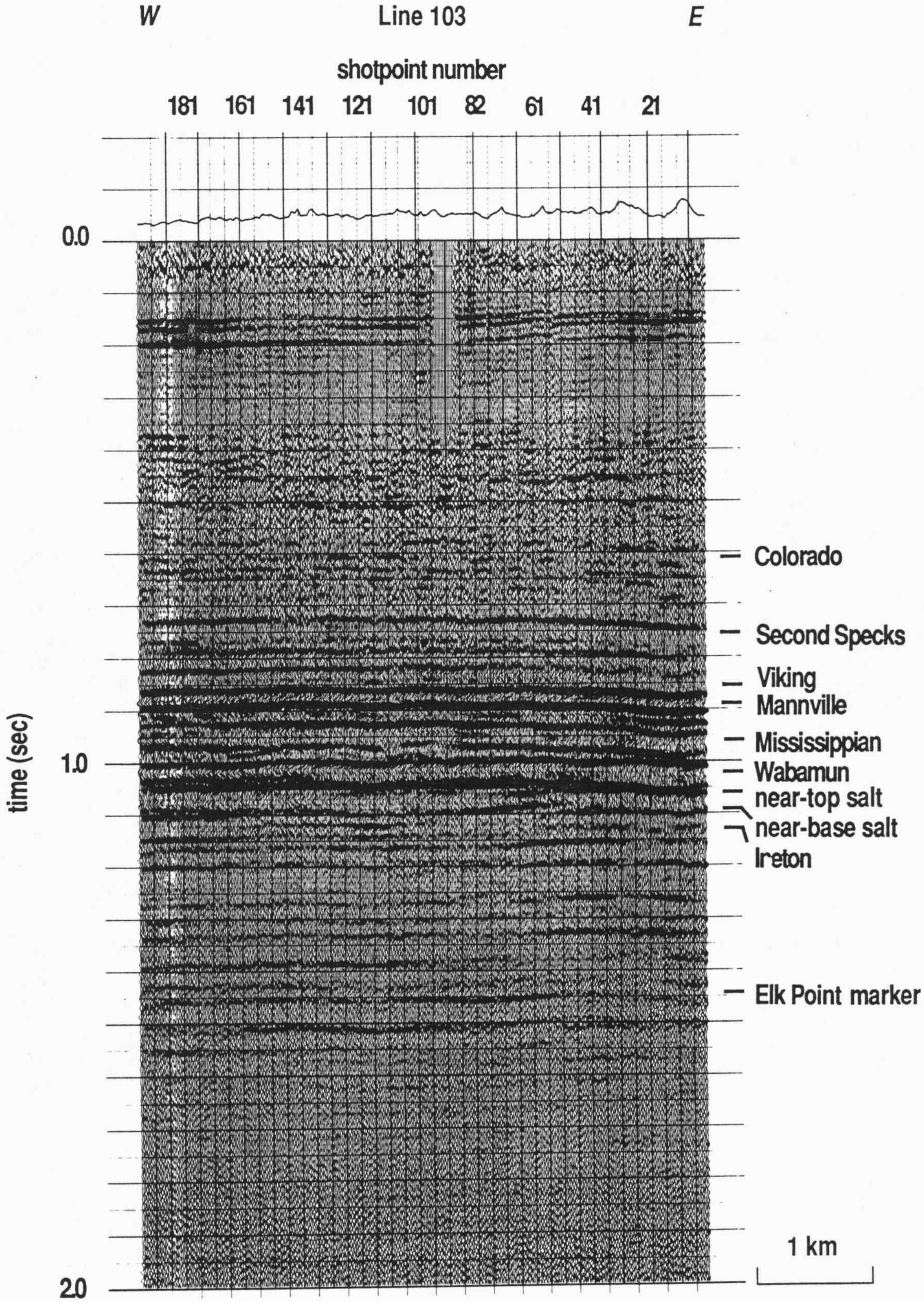
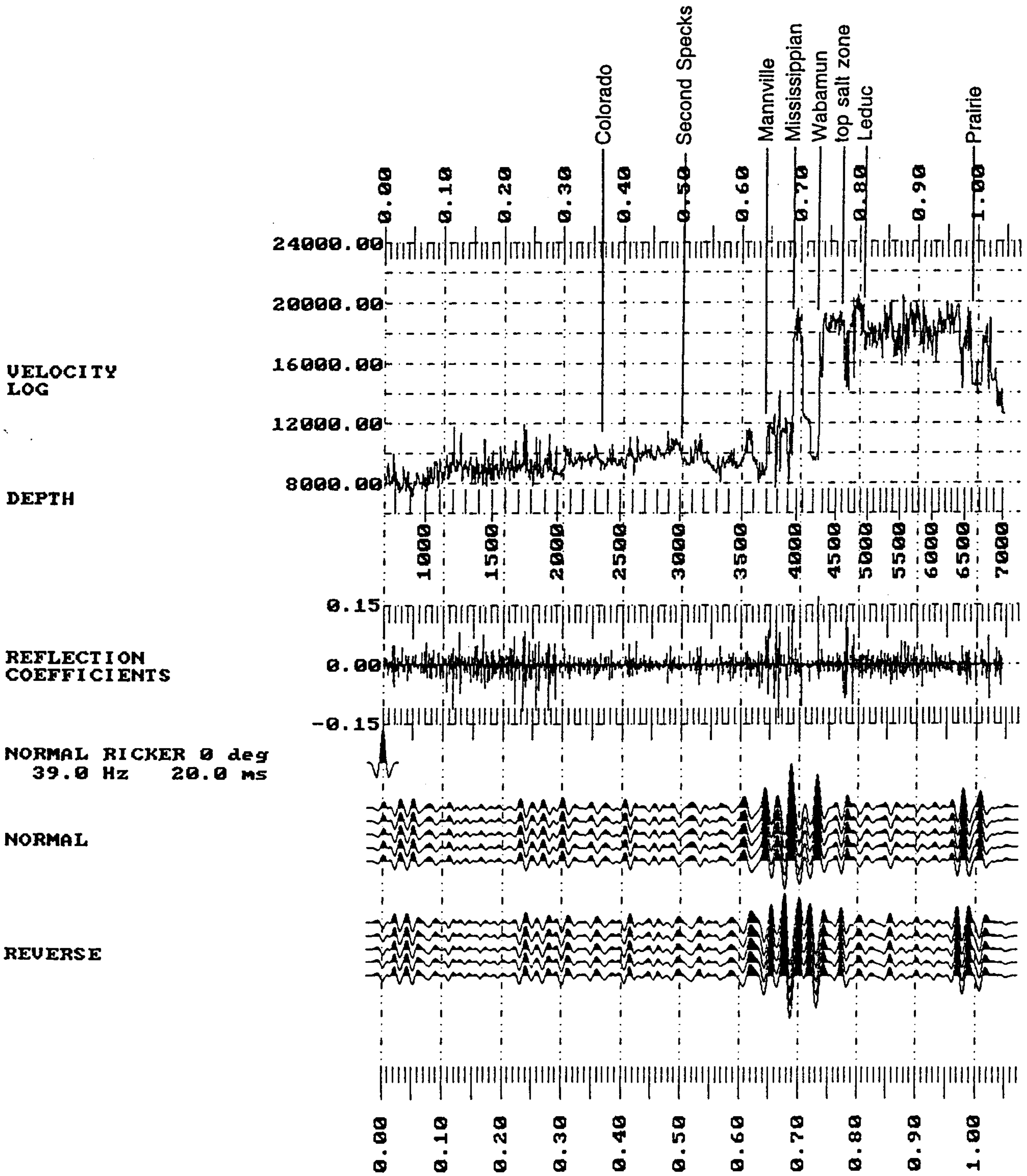
126
106
87
66
46
26
6
0.0
1.0
2.0
time (sec)
Colorado
Second Specks
Viking
Mannville
Mississippian
Wabamun
near-top salt
near-base salt
Ireton
Elk Point marker
1 km


W
Line 102
E
shotpoint number
241
221
201
182
161
142
121
102
81
61
41
23
0.0
1.0
2.0
time (sec)
Colorado
Second Specks
Viking
Mannville
Mississippian
Wabamun
near-top salt
near-base salt
Ireton
Elk Point marker
1 km


W
Line 103
E
shotpoint number
181
161
141
121
101
82
61
41
21
0.0
1.0
2.0
time (sec)
Colorado
Second Specks
Viking
Mannville
Mississippian
Wabamun
near-top salt
near-base salt
Ireton
Elk Point marker
1 km



Colorado
Second Specks
Mannville
Mississippian
Wabamun
top salt zone
Leduc
Prairie
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
24000.00
20000.00
16000.00
12000.00
8000.00
VELOCITY LOG
DEPTH
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
0.15
REFLECTION COEFFICIENTS
0.00
-0.15
NORMAL RICKER 0 deg
39.0 Hz 20.0 ms
NORMAL
REVERSE
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00