REPORT #
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POTENTIAL CONTAMINATION OF SHALLOW AQUIFERS BY SURFACE MINING OF COAL

by

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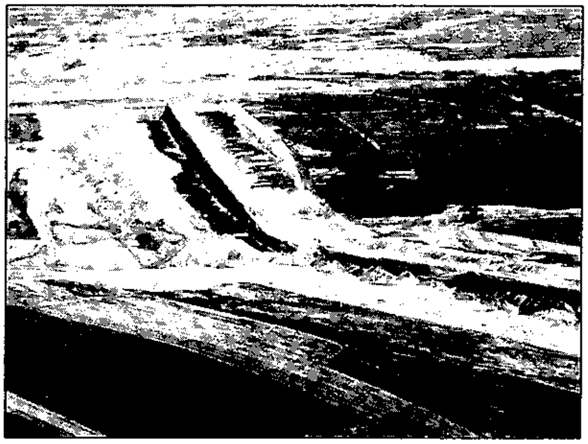

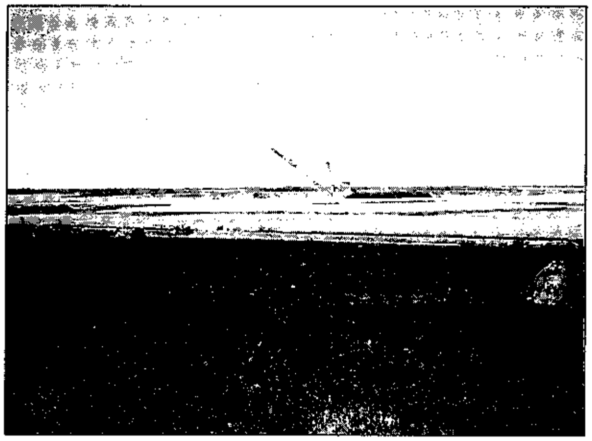

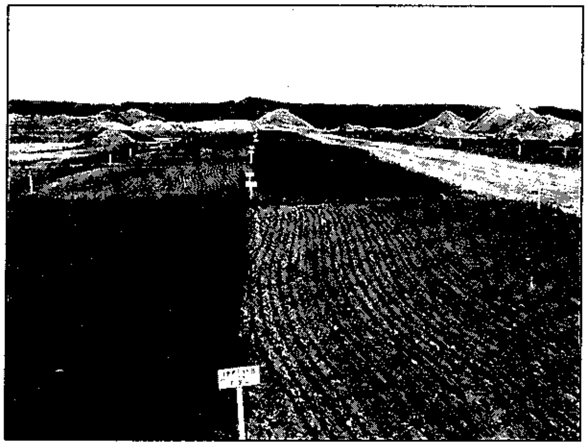

DISCLAIMER

This report is intended to provide government and industry staff with up-to-date technical information to assist in the preparation and review of Development and Reclamation Approvals, and development of guidelines and operating procedures. This report is also available to the public so that interested individuals similarly have access to the most current information on land reclamation topics.

The opinions, findings, conclusions, and recommendations expressed in this report are those of the author(s) and do not necessarily reflect the views of government or industry. In particular, the movement of a groundwater plume from the minesite into adjacent unmined land reported in this publication is considered to be a unique event, related to the specific geological and hydrological circumstances which occurred at the site. Mention of trade names or commercial products does not constitute endorsement, or recommendation for use, by government or industry.

REVIEWS

This report has been reviewed by members of the Reclamation Research Technical Advisory Committee and the Plains Coal Reclamation Research Program Committee.

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PREFACE

This is one of a series of reports that presents the findings of the Plains Hydrology and Reclamation Project (PHRP), an interdisciplinary study that focuses primarily on hydrologic aspects of the reclamation of surface coal mines in the Plains of Alberta. This research has been conducted by the Alberta Research Council, as part of the Alberta Government's Reclamation Research Program. The program is managed by the Land Conservation and Reclamation Council and is supported by the Alberta Heritage Savings Trust Fund.

The focus of the PHRP is to develop a predictive framework that will permit projection of success for reclamation and impact of mining on water resources on a long-term basis. The predictive framework is based on an understanding of processes acting within the landscape so that, in the future, mine sites that are not totally analogous to those that have been studied can be evaluated as well.

The project involves a holistic approach to reclamation by integration of studies of geology, hydrogeology, and soils, not only in the proposed mining area, but also in the adjoining unmined areas. This approach permits the assessment of impacts and of long-term performance, not only in reclaimed areas, but also in the surrounding area.

The research of the PHRP was directed toward the following two major objectives and eight subobjectives.

Objective A

To evaluate the potential for reclamation of lands to be surface mined. The focus is on features of the landscape that make it productive in a broad sense not restricted to revegetation. This objective was organized into five subobjectives.

1. To assess and evaluate the potential for long-term degradation of reclaimed soils through salt buildup.
2. To assess and evaluate the effectiveness of topographic modification and selective placement of

materials to mitigate deleterious impacts on chemical quality of groundwater.

3. To assess the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations.
4. To evaluate the productivity potential (capability) of post-mining landscapes and the significance of changes in capability as a result of mining.
5. To assess and evaluate limitations to post-mining land use posed by physical instability of cast overburden.

Objective B

To evaluate the long-term impact of mining and reclamation on water quantity and quality. This objective was organized into three subobjectives.

1. To assess and evaluate the long-term alteration of quality of groundwater in cast overburden and surface water fed from mine spoil as a result of the generation of weathering products.
2. To assess and evaluate infiltration, groundwater recharge, and groundwater-surface water interactions within cast overburden.
3. To characterize the groundwater chemistry generated within cast overburden.

Studies directed at these objectives began in 1979 at the Battle River site in east-central Alberta. Work began in 1982 at a second study area at Highvale Mine south of Lake Wabamun.

This report addresses Subobjective B-1, "to assess and evaluate the long-term alteration of quality of groundwater in cast overburden and surface water fed from mine spoil as a result of the generation of weathering products". It is fair to say that this particular investigation had not been conceived at the onset of the project. Conventional thinking clearly indicated that reclaimed surface coal mines would act as hydrologic sinks, certainly for a period of many years or decades after mining. The migration of spoil groundwater into unmined areas at the Battle River site arises from a collection of favourable geologic and hydrogeologic features that are presently unique to the Vesta Mine site. The key features required to produce this off-site migration, an elevated, ponded reclaimed landscape and adjacent permeable unmined aquifer, are potentially available at a number of mine sites. It is hoped that an awareness of the potential for off-site movement of spoil groundwater will have some influence on the design and construction of reclaimed landscapes in the future.

ABSTRACT

Groundwater migrating from the spoil of Vesta Mine in east-central Alberta has produced two plumes of spoil-contaminated groundwater, one plume in a thin surficial sand aquifer and another in a deeper coal aquifer. Major ion composition, salinity, and stable isotope makeup of the groundwater have been utilized to differentiate between natural and spoil-contaminated groundwater.

The groundwater in the reclaimed mine spoil is of $Na^+ - SO_4^{2-}$ composition with a mean total dissolved solids (TDS) of 7000 mg/L, and individual values ranging from 4000 to 14 000 mg/L. In the unmined coal adjacent to the mine the first plume of spoil-affected groundwater was detected, having a TDS of 2500 to 3200 mg/L, compared to natural values of 900 to 1700 mg/L. Sulfate concentrations increase from less than 50 mg/L in the natural groundwater to more than 1000 mg/L in this plume. There is a corresponding shift in composition from $Na^+ - HCO_3^-$ (natural) to $Na^+ - SO_4^{2-}$, HCO_3^- (contaminated). The plume of contaminated water is approximately 2 km long and 1 km wide, and is driven by hydraulic head within the reclaimed spoil that is 3 to 5 m higher than that in the unmined coal. This hydraulic head results from deep ponds in the reclaimed landscape that recharge the base of the spoil. The direction of spoil groundwater migration is opposite to the premining flow direction, and is controlled by the major axis of horizontal permeability in the coal. There is little or no migration in the direction of a regional groundwater drain, a major meltwater channel now occupied by the Battle River. It is likely that contamination by spoil groundwater will be insignificant at a distance of 1.5 to 2 km from Vesta Mine.

The second plume of spoil groundwater is in a thin (0 to 4 m) surficial sand aquifer adjacent to the mine, and has a salinity as high as 15 000 mg/L TDS, compared to the natural range of 600 to 2600 mg/L. Sulfate concentrations in this plume, at 2000 to 10 000 mg/L, are well above natural levels of less than 1200 mg/L.

There is a corresponding compositional shift from the natural Ca^{2+}, Mg^{2+} - HCO_3^- or Ca^{2+}, Mg^{2+} - HCO_3^-, SO_4^{2-} to the contaminated Na^+, Ca^{2+} - SO_4^{2-} or Ca^{2+}, Na^+ - SO_4^{2-}. This plume of contaminated water is approximately 2 km long and 2 km wide. The centroid of the plume is located approximately 1.2 km southwest of Vesta Mine. Upgradient from the centroid (toward Vesta Mine) TDS and sulfate concentrations decline, indicative of both rapid movement of the plume and a trend of improving groundwater quality with time in the discharge from the spoil. The direction of migration is to the southwest, toward an ephemeral stream channel that is underlain by glacio-fluvial sand. There is no evidence that spoil-contaminated groundwater is discharging to the ephemeral stream. The hydraulic potential for the migration of this plume is provided by a water table within the spoil that is 2 to 3 m above that in the sand. The high water table in the spoil is related to a reclaimed land surface that is, in places, 10 m above the undisturbed level, and to shallow ponds located high in the reclaimed landscape.

ACKNOWLEDGEMENTS

This study was supported by the Alberta Heritage Savings Trust Fund and administered by the Reclamation Research Technical Advisory Committee of the Alberta Land Conservation and Reclamation Council, Alberta Environment. Mr. K.E. Muncy of Paintearth County is gratefully acknowledged for providing access to his lands.

1. INTRODUCTION

Anomalously high-salinity groundwater with high concentrations of sulfate was first detected in wells completed in coal and surficial sand aquifers adjacent to Vesta Mine in 1981. To test the hypothesis that this water, which had a composition very similar to spoil groundwater, originated in the spoil at Vesta Mine and was migrating off-site to the west, additional test drilling and well installation was undertaken in 1982, 1983, and 1984 to define the extent of these spoil-derived groundwater plumes in the two aquifers. This report is a summary of the findings of this study.

The objective of this study was to evaluate the deterioration, as a result of surface coal mining and reclamation, of groundwater quality in undisturbed areas adjacent to Vesta Mine.

1.1 SITE DESCRIPTION

The Battle River mining area, which is located approximately 200 km southeast of Edmonton (Figure 1), is part of the Interior Plains Physiographic Province. The land is flat to gently rolling. The major topographic features are the deeply-incised valleys of the Battle River and Paintearth Creek.

The study site is located south of the Battle River, in an area of approximately 5.2 km^2 situated primarily in sections 14 and 23 (Tp 40, R 16, W 4; Figure 1); it is immediately west of Vesta Mine. The area is agricultural land, with approximately two-thirds in cereal grain production and one-third in pasture. Surface drainage within the study site is provided by the Battle River to the north, and by Slough Creek, an ephemeral stream that drains to the southeast (Figure 2).

1.2 GEOLOGY

Bedrock at the study site is sandstone, siltstone, shale, and coal of the Lower Horseshoe Canyon formation (Maslowski Schutze et al. 1986). The Battle River Bed, which is the coal seam exploited

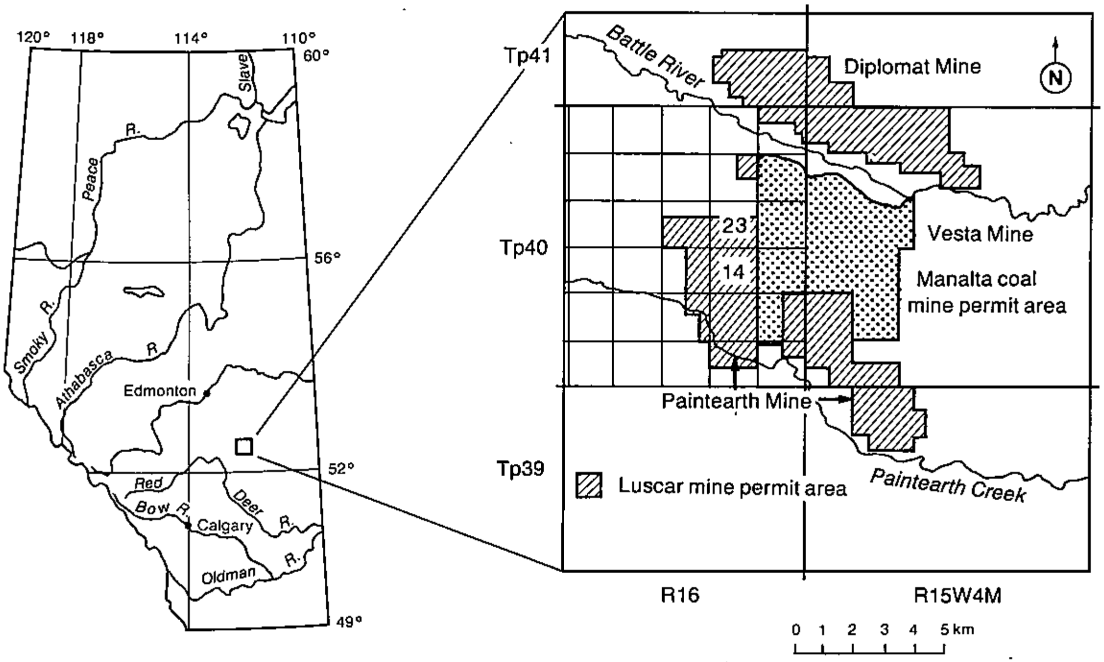

Figure 1. Map showing location of Battle River mining area and study site.

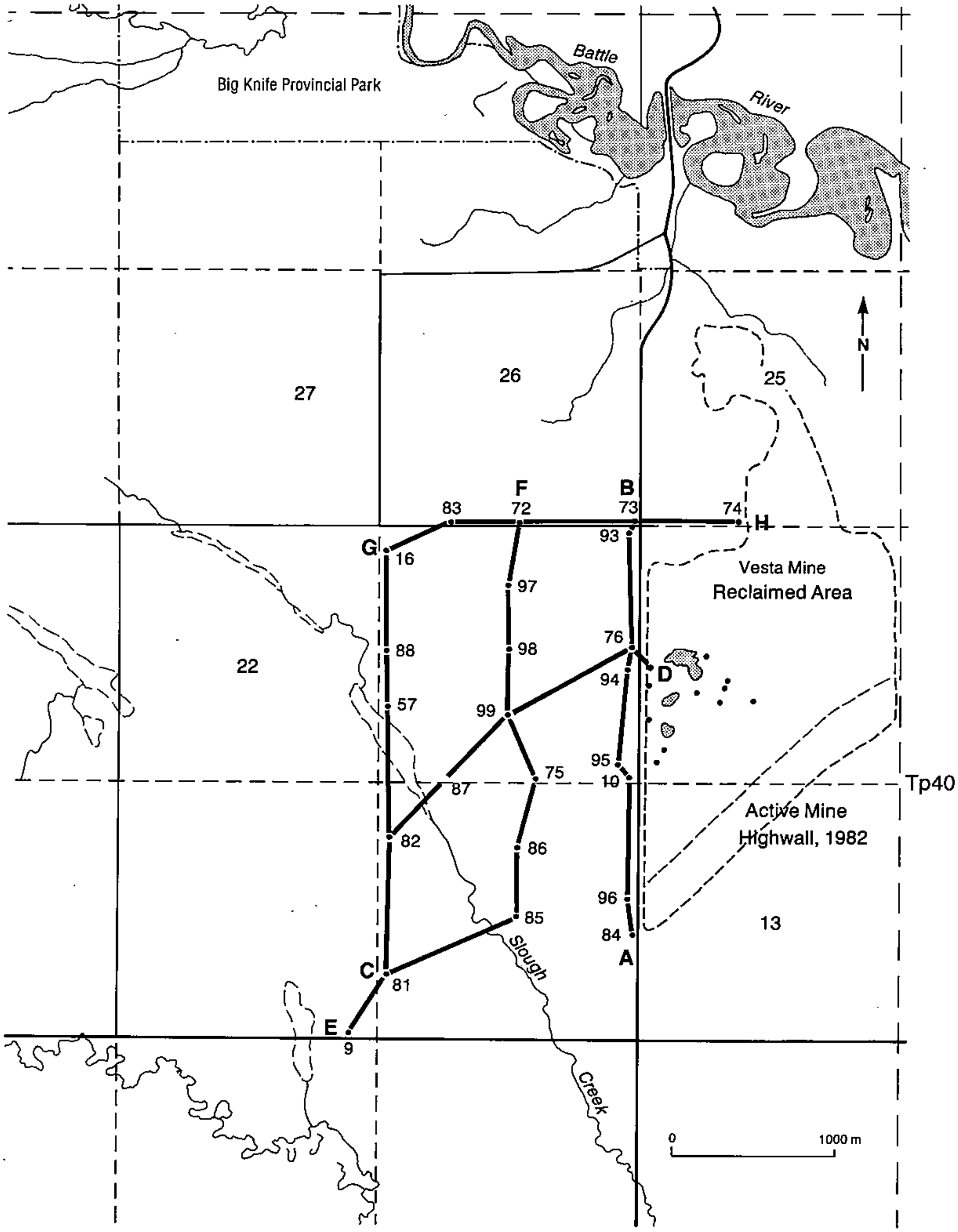

Figure 2. Map showing location of study site and geologic cross sections.

at Vesta Mine, is present from 13 to 29 m below ground surface, and is from 2.0 to 2.5 m thick.

The coal is fractured, with a major joint orientation of approximately 054° and a minor cleat orientation of approximately 144° (Vogwill 1976). The Battle River Bed is overlain by a sequence of interbedded shale, siltstone, and sandstone that forms the bedrock overburden.

The bedrock is overlain by glacial drift that ranges in thickness from 3.0 to 8.2 m (Figure 3) with a mean thickness of 5.4 m and a standard deviation of 1.6 ($n = 19$).

The surficial material in the study area, as shown in geologic cross sections (Figures 4 to 8), is characterized by a thin lower till unit 'B' overlying the bedrock that ranges in thickness from 0 to 2.4 m. The lower till is overlain by a sheet-like sand body from 0 to 4 m thick, that is stratigraphically continuous with a thick, sand-fill sequence in the valley of Slough Creek (Figures 5 and 6). Above the sheet-sand body is an upper till sequence 'A' that is 2 to 6 m thick, with numerous inclusions of lenticular sand bodies. In some locations, notably sites 9, 16, and 82 the upper till is overlain by fluvial sediment, primarily sand.

Through the centre of the study area, the sheet sand is laterally continuous north of Slough Creek, as shown in Cross Section E-F (Figure 6), although its thickness is quite variable. Along the western part of the study area (Cross Section C-G; Figure 8) the sheet sand is only present within 1 km of Slough Creek; in the northwest part of the study area the sheet sand is absent, as shown in Figures 7 and 9, although the sand is present along the northern boundary of the study area east of site 83 (Cross Section G-H; Figure 7). The southwest-northeast Cross Section C-D (Figure 5) shows both the height of the reclaimed land surface above the unmined plain as well as the continuity between the sheet sand and the spoil at Vesta Mine.

A map of drift thickness (Figure 3) shows that a northeast-southwest trending depression in the bedrock surface is

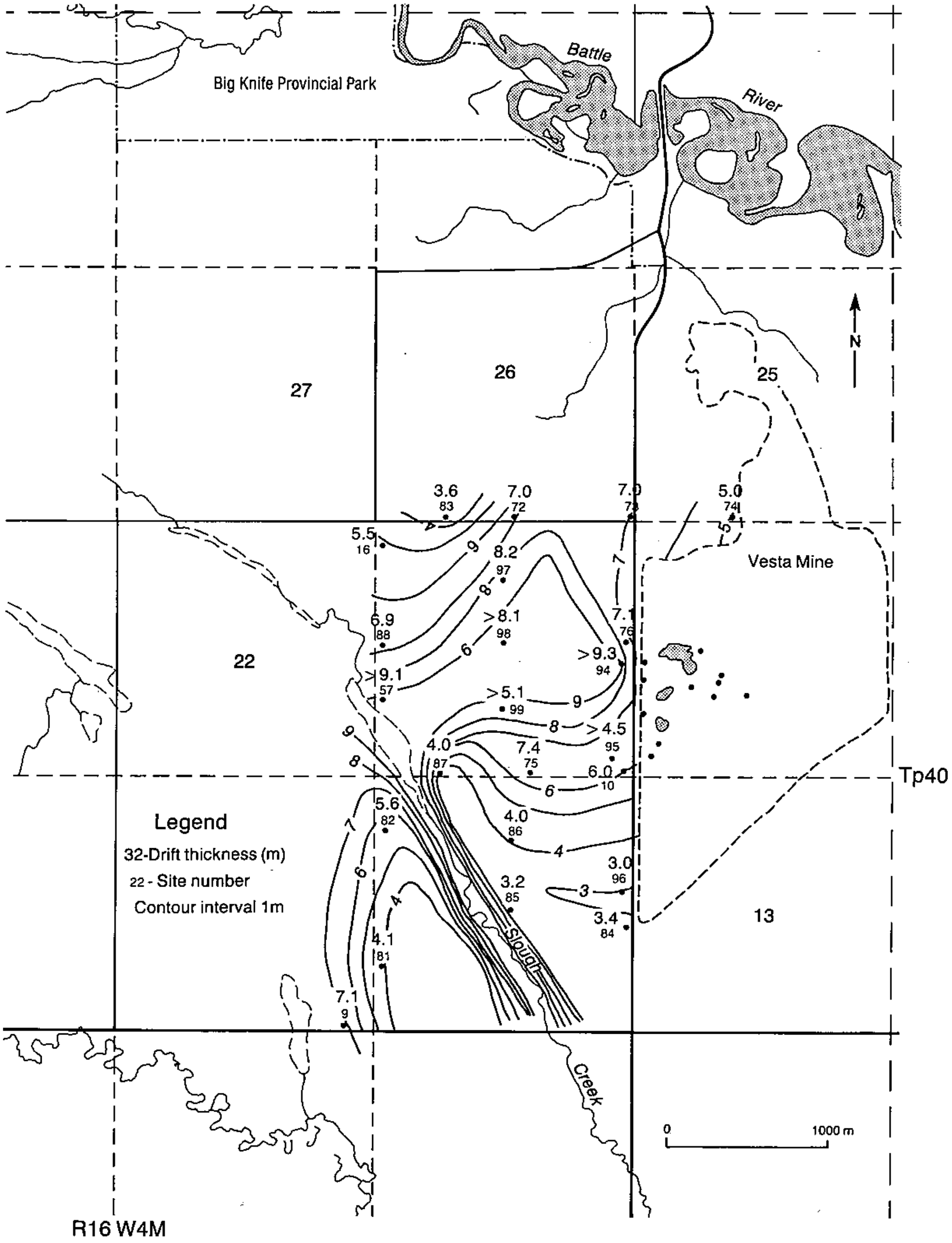

Figure 3. Map showing thickness of drift at the study site.

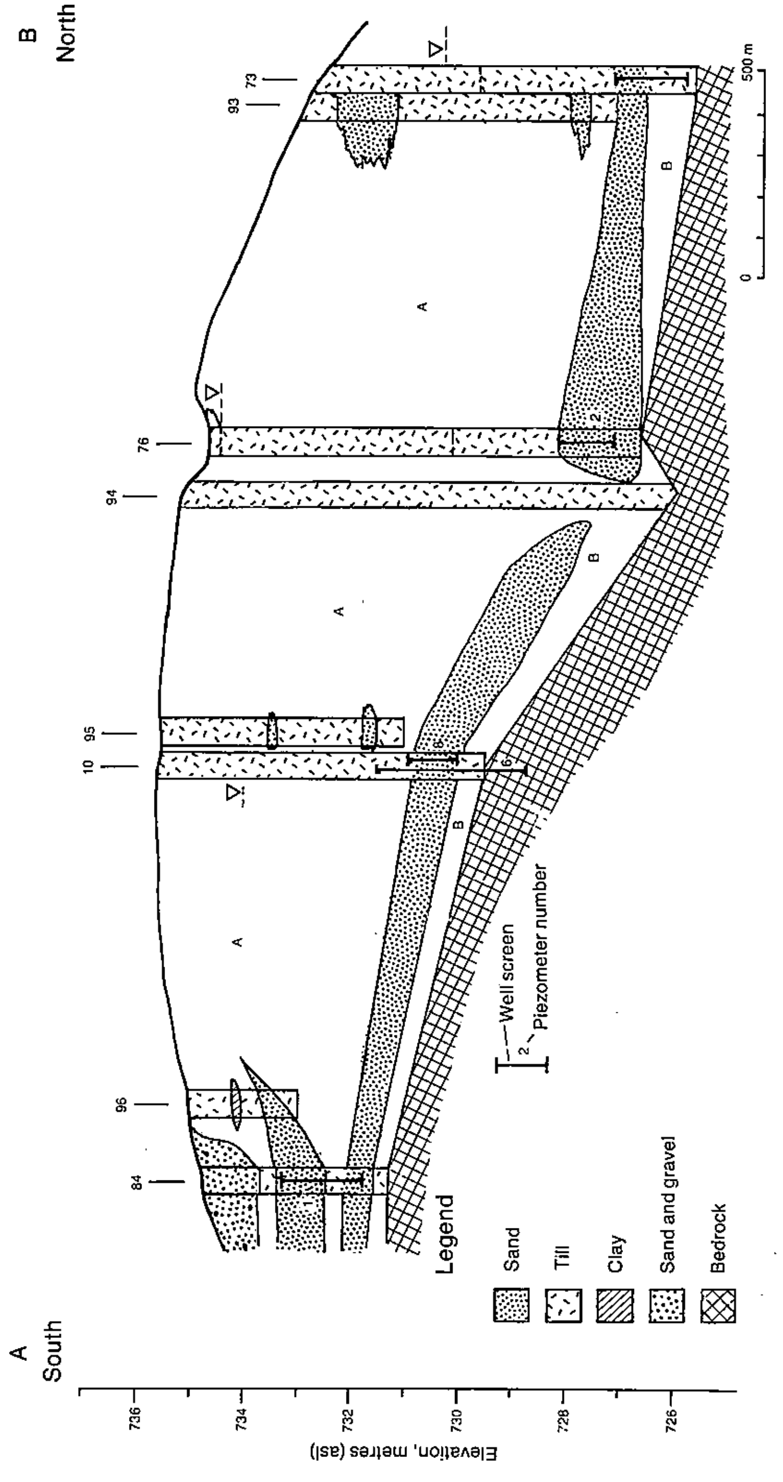

Figure 4. North-south geologic Cross Section A-B. Geologic units 'A' and 'B' represent upper and lower till units, respectively.

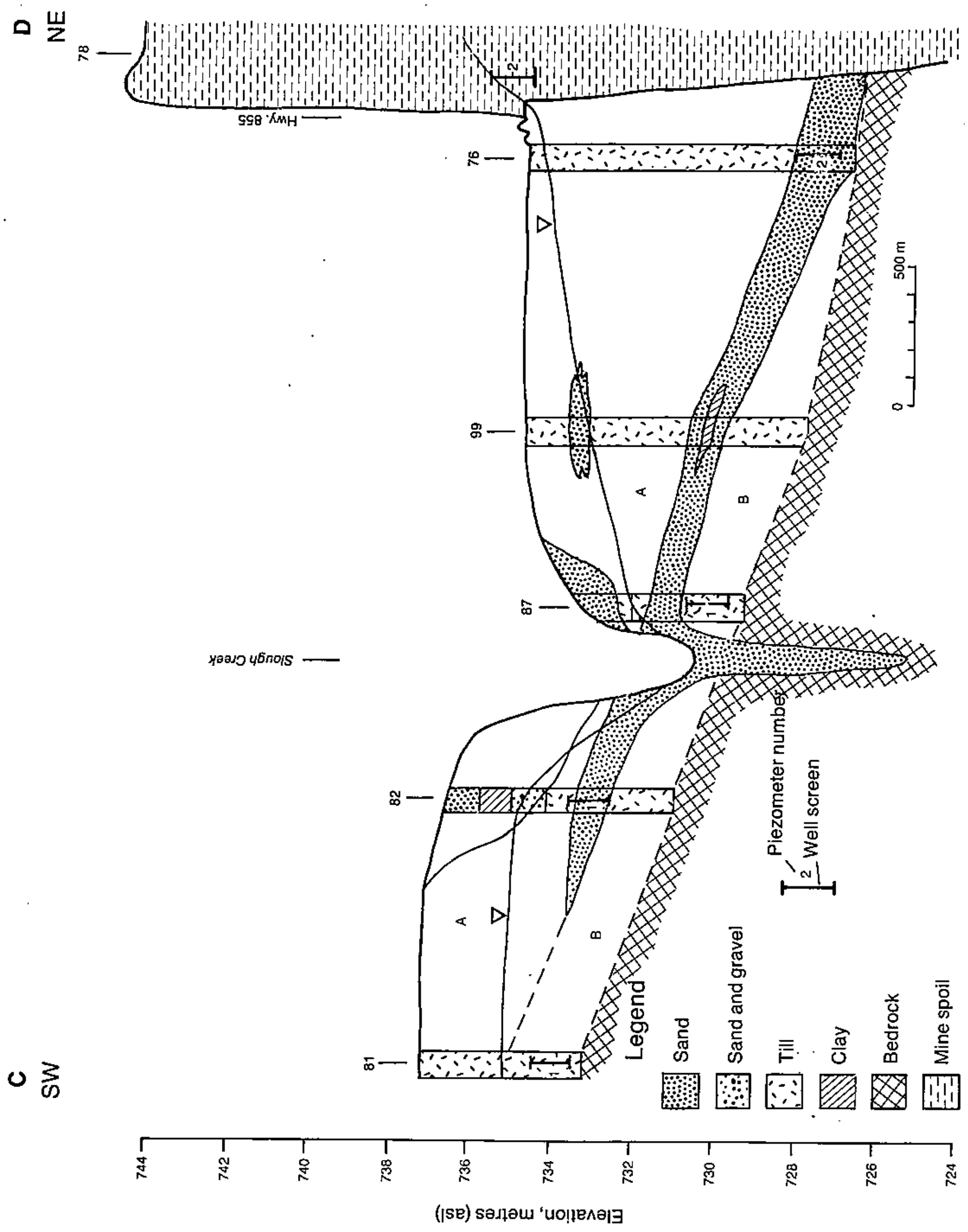

Figure 5. Southwest-northeast geologic Cross Section C-D. 'A' and 'B' refer to upper and lower till units, respectively.

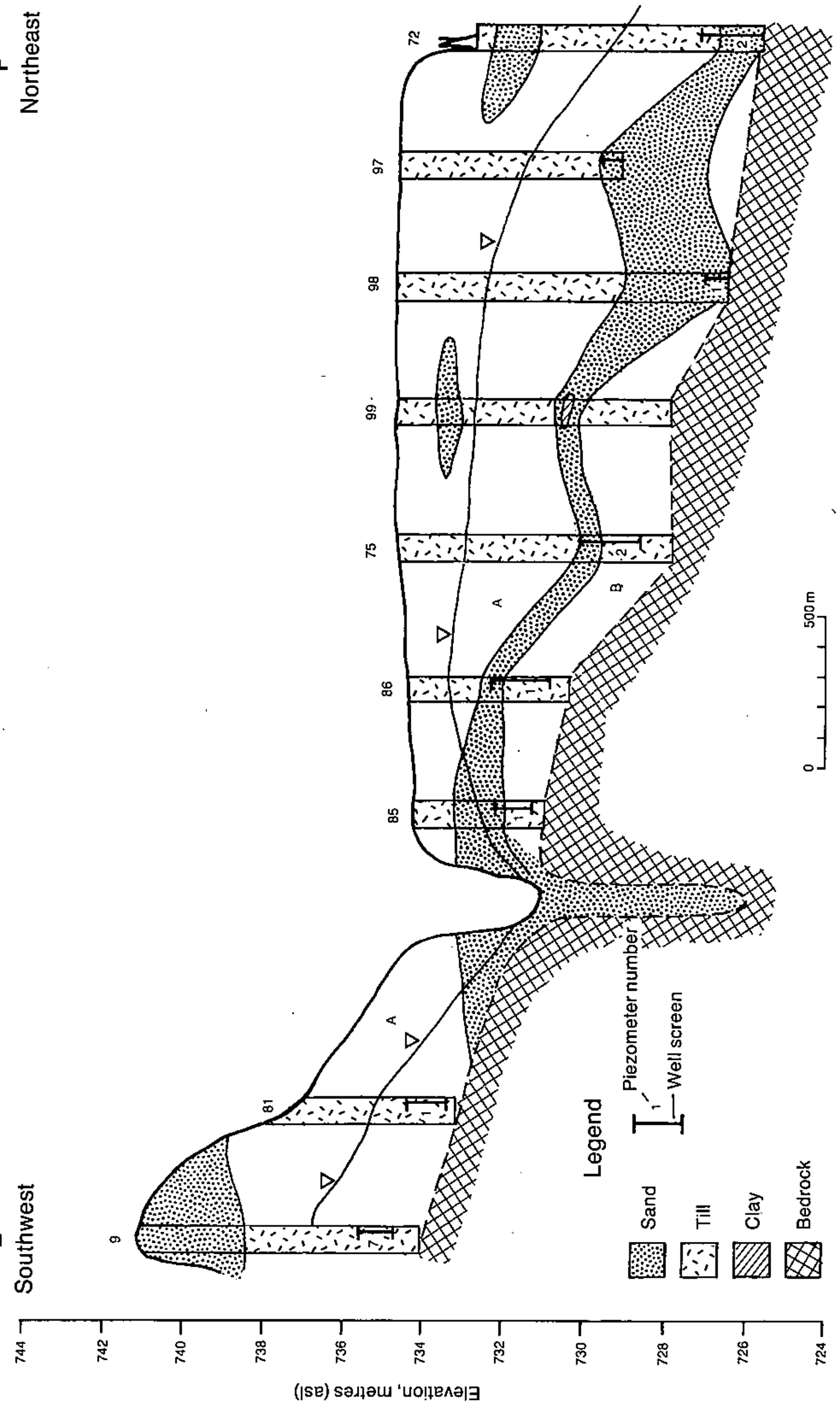

Figure 6. Southwest-northeast geologic Cross Section E-F. 'A' and 'B' refer to upper and lower till units, respectively.

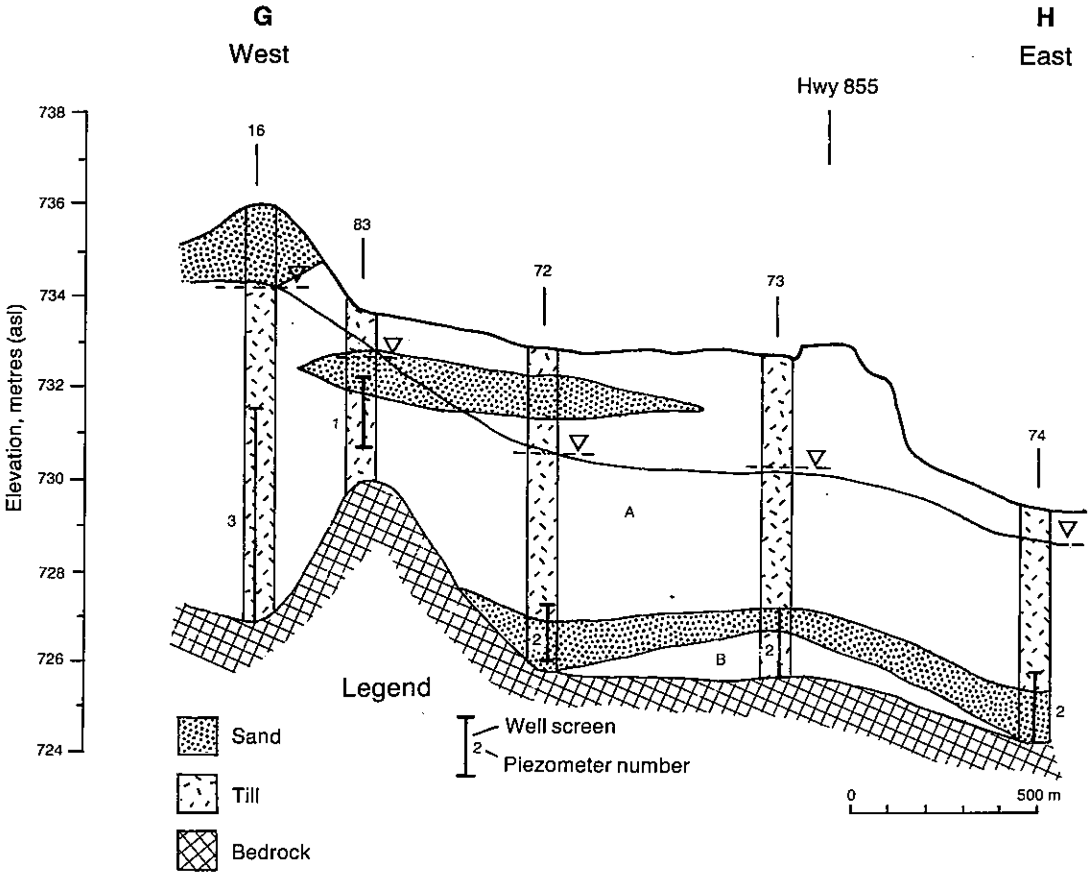

Figure 7. West-east geologic Cross Section G-H. 'A' and 'B' refer to upper and lower till units, respectively.

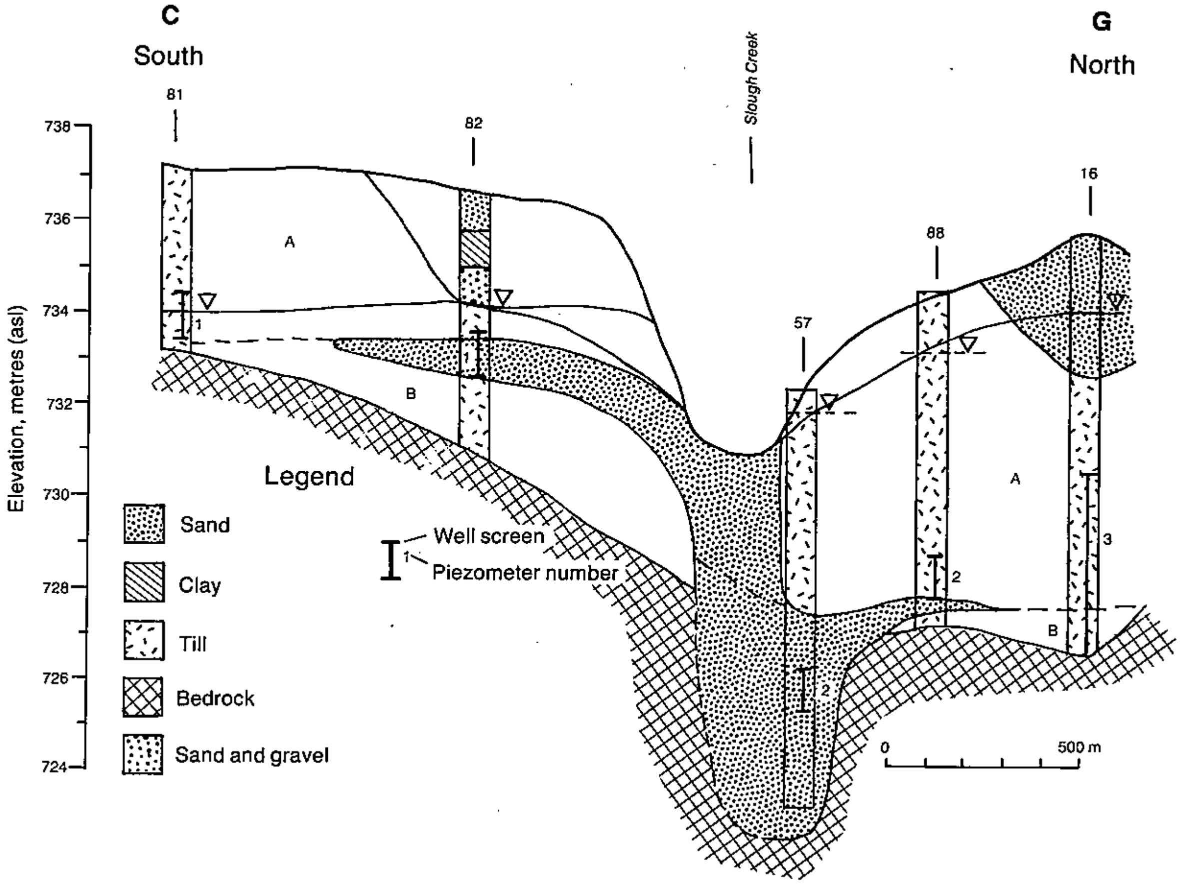

Figure 8. South-north geologic Cross Section C-G. 'A' and 'B' refer to upper and lower till units, respectively.

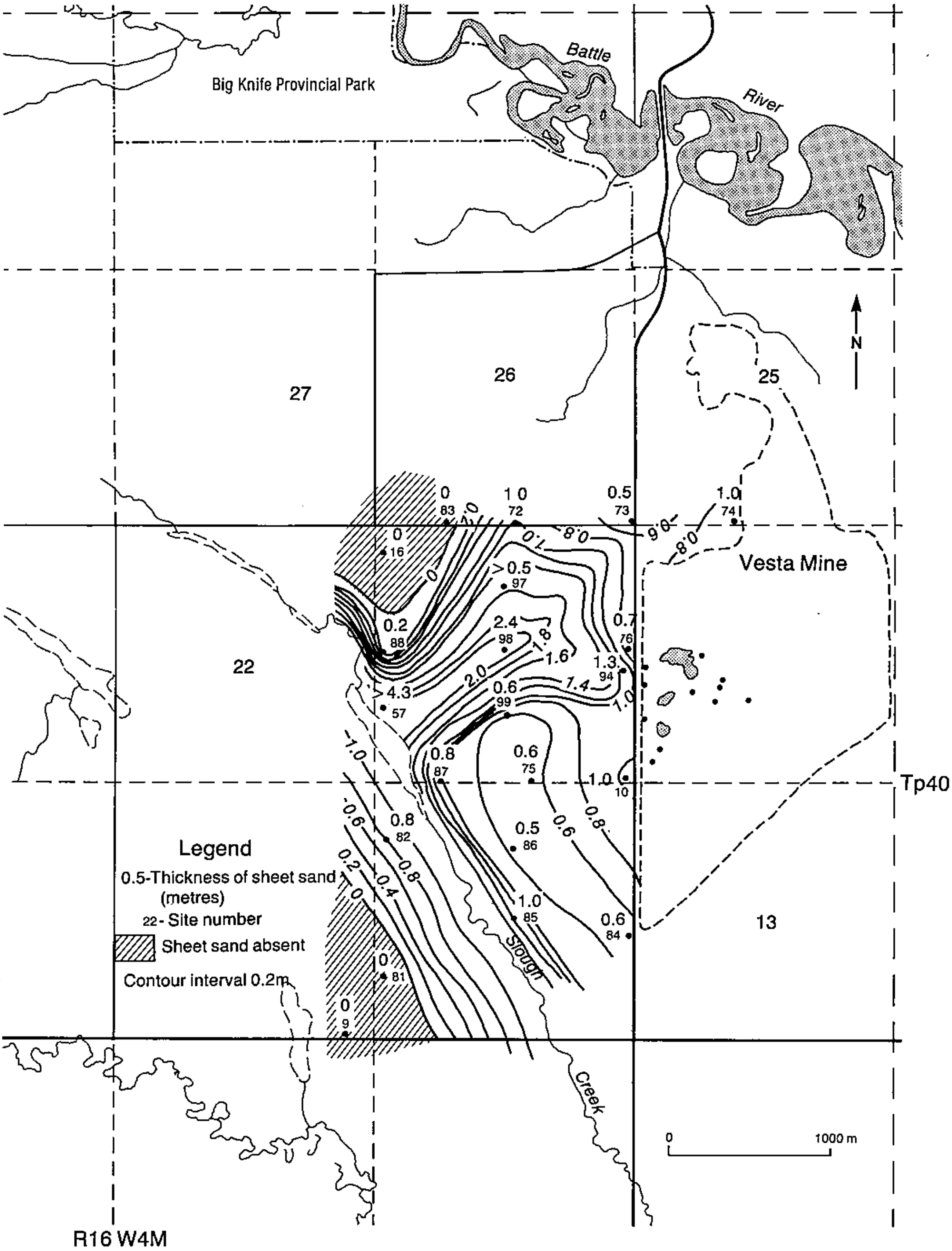

Figure 9. Map showing thickness of the sheet-sand unit in the glacial drift.

present between site 57 and sites 97 to 98. An isopach map of the sheet-sand body in the lower part of the drift (Figure 9) shows that this elongate depression in the bedrock surface coincides with an increased thickness of sand. This probably represents a buried tributary of Slough Creek that appears to have drained to the southwest. In addition to being thicker, the sand in the vicinity of site 98 is also coarser-grained; it is a medium-grained sand as opposed to the fine grained sand that is commonly found at nearby sites.

From a hydrogeologic point of view, this buried channel is significant because it is a potentially effective conduit for the movement of water and therefore the migration of spoil groundwater, from Vesta Mine toward Slough Creek.

At numerous locations discontinuous lenses of sand have been encountered at relatively shallow depths within the till (less than 3 m). These lenses, which appear to be typically a few metres across and less than 1 m thick, seem to be an artifact of the glacial history of the site. It is likely that the two till units represent two separate ice advances, separated by a period of fluvial sand deposition. The second ice advance, overriding the sheet sand, probably excavated blocks of this sand and incorporated them in the basal till of the second ice advance. These blocks of sand that were picked up from the sheet-sand body by the second ice advance form the present-day discontinuous sand lenses found in the upper till unit. Similarly, there are places, such as site 94, where the sheet sand is absent; these are areas where blocks of the entire sheet sand were excavated by the second ice advance, leaving the upper till lying directly on the lower till unit. For example, along the east side of the study area, as shown by Cross Section A-B (Figure 4) the sheet sand is continuous everywhere except at site BR94, where a small block has been removed.

2. GROUNDWATER FLOW CONDITIONS

Groundwater flow patterns in the drift are controlled to a large extent by relief and surface drainage features. In the Battle River Bed, groundwater flow is more complex, with regional drainage features, local drainage near the mine pit, and the anisotropy of hydraulic conductivity in the coal all impacting the pattern of groundwater flow.

A piezometric surface map for the Battle River Bed (Figure 10), including the base of the spoil at Vesta Mine (the post-mining stratigraphic equivalent of the Battle River Bed) shows that there is a significant component of groundwater flow directed from the spoil to the northwest, west and southwest into the Battle River Bed. Hydraulic head at the base of the spoil is as high as 729 to 734 m above sea level, compared to heads in the unmined coal that are typically 720 to 725 m above sea level. The high heads in the spoil are due to deep ponds that recharge the base of the spoil, and to a north-south trending berm approximately 10 m in height that is present along the western boundary of the mine. The natural direction of groundwater flow in the Battle River Bed is from southwest to northeast, with discharge occurring at the outcrop in the Battle River valley. In the vicinity of Vesta Mine drainage into the pit has lowered heads in the coal from 716 to 718 m above sea level. The resulting cone of depression extends 1 to 2 km to the southeast of the pit, and also to the southwest. This southwestern part of the cone of depression around the mine pit acts as the mechanism of discharge for the westward component of groundwater flow that originates in the older mine spoil to the north of the pit. In other words, groundwater that is directed from the spoil into the unmined coal to the west of Vesta Mine is drawn back into the mine because of the dewatering by the active pit situated to the south of the reclaimed area.

A water-table map for the drift (Figure 11) illustrates the potential for groundwater movement from the elevated area at Vesta Mine westward into the unmined drift. Water-table elevations of

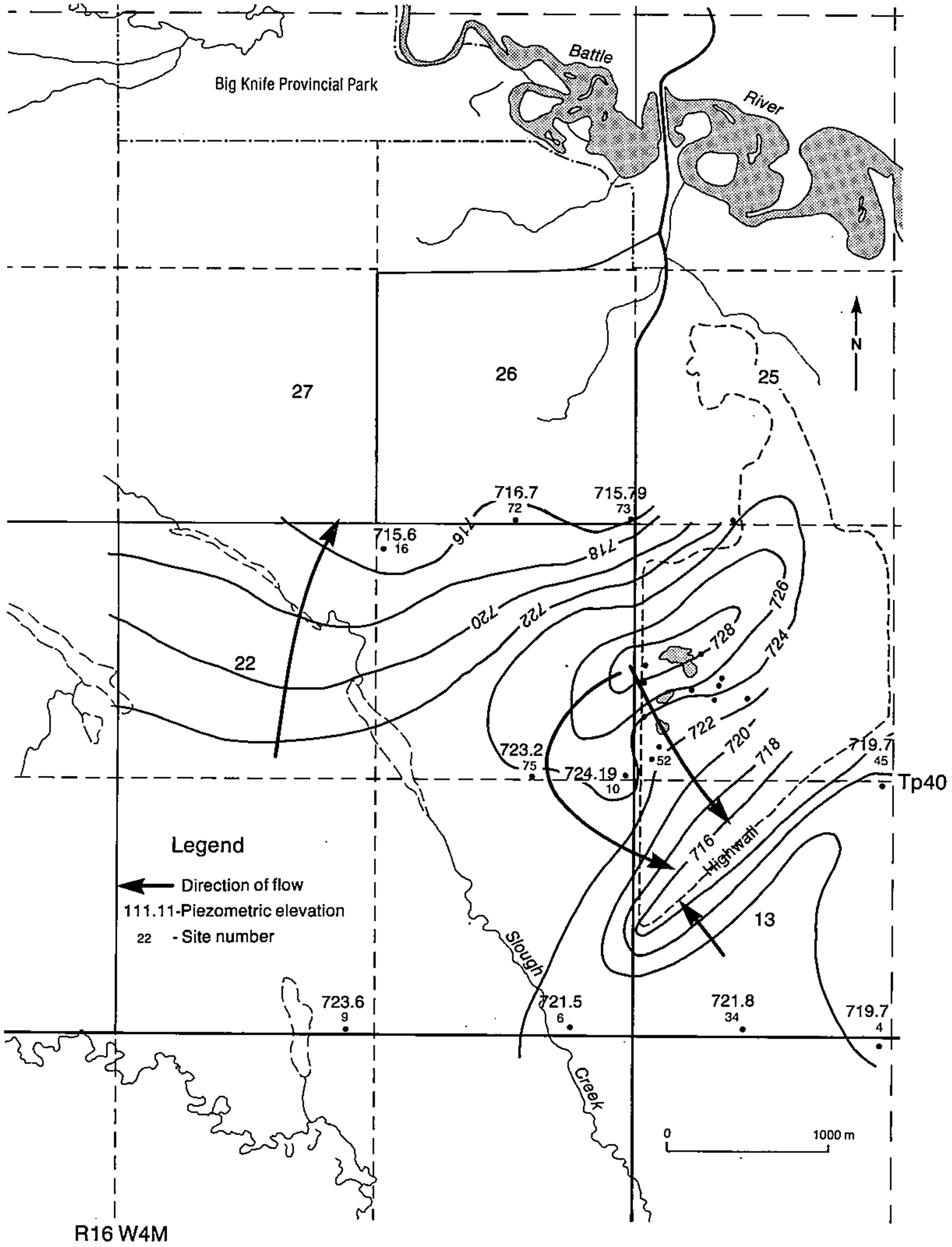

Figure 10. Piezometric surface map for the Battle River Bed.

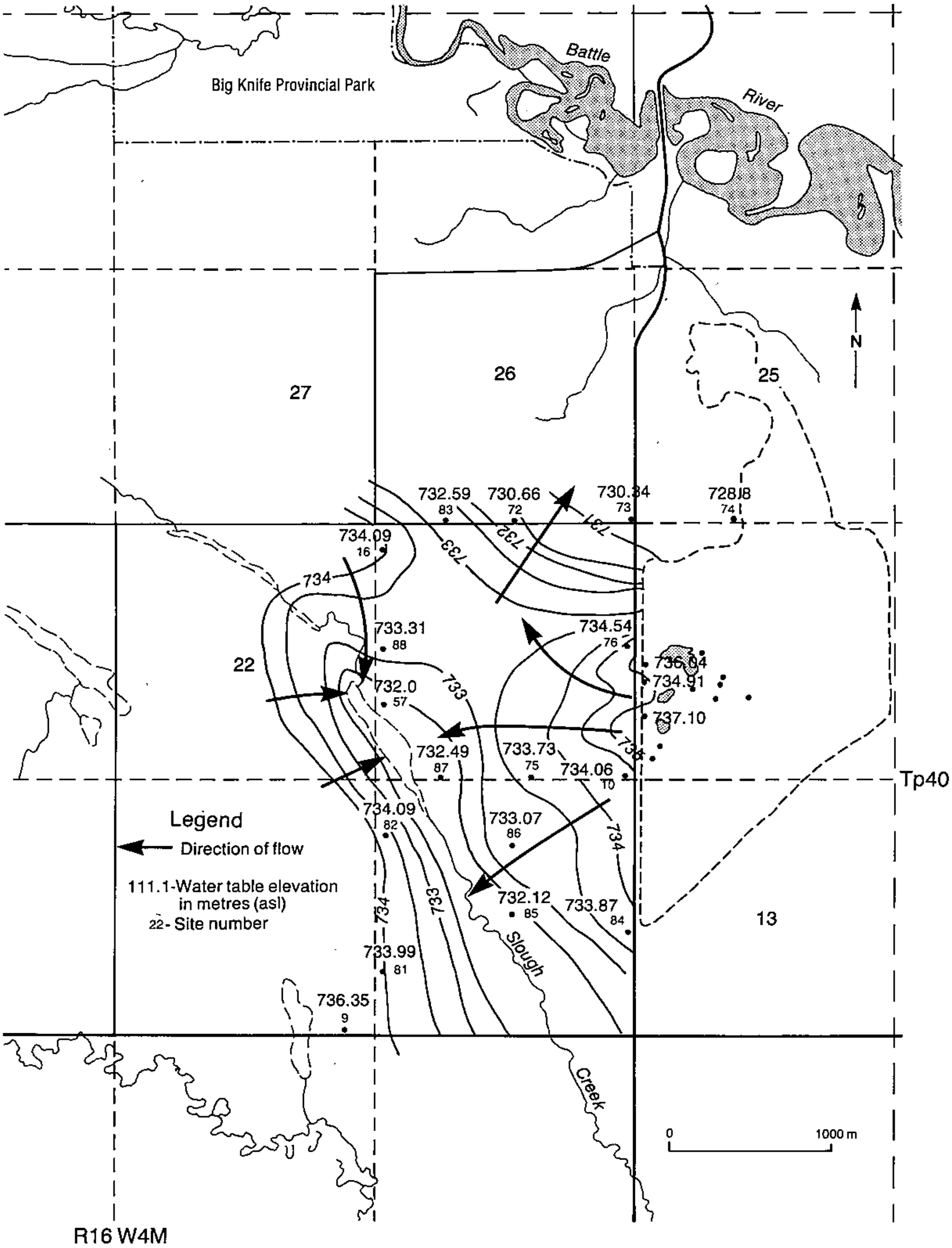

Figure 11. Water-table map for the drift.

approximately 735 to 737 m above sea level are present in the reclaimed spoil, compared to 733 to 734 m above sea level in the drift west of the mine. A groundwater divide trending northwest-southeast bisects Sec 23, separating groundwater flow at the water table into a north and northeast component, directed toward the Battle River valley, and a southwest component, with flow toward Slough Creek. At site BR85, where the drift is 3.2 m thick (Figure 3), the water table is below the drift for much of the year. In the period from June to December 1983, for example, the water table was more than 3 m below ground surface except from early July to early September. This lack of hydraulic continuity with the rest of the drift groundwater-flow system probably results in the bulk of drift groundwater movement around this site, to the north and west. Horizontal hydraulic gradients in the drift range from 0.0015 to 0.01, with most values at about 0.003.

Slough Creek probably functions as a hydraulic drain, not by surface discharge, but by subsurface flow in the unconsolidated sand that infills the stream channel to a depth of approximately 9 m. The northward-directed groundwater flow component discharges approximately 2 km to the north at the outcrop of the drift in the valley of the Battle River.

3. GROUNDWATER CHEMISTRY AND PLUME DELINEATION

The potential for migration of groundwater from the spoil at Vesta Mine into the unmined drift and coal west of the mine is confirmed by the presence of high salinity, sodium-calcium-sulfate water in unmined aquifers adjacent to the mine.

3.1 BATTLE RIVER BED PLUME

Wells installed in the Battle River Bed at six sites located immediately west of Vesta Mine were sampled in order to determine the extent of lateral migration of spoil groundwater into the coal.

On the basis of major ion chemistry (Table 1), spoil-derived groundwater has been detected at two sites west of Vesta Mine, 10 and 75. The delineation of the plume is best illustrated by the distribution of sulfate, which is at levels of 950 to 2600 mg/L in the plume, compared to 6 to 200 mg/L in the natural groundwater in the Battle River Bed (Figure 12; Table 1). The mean sulfate concentration of 3900 mg/L in the spoil groundwater at Vesta Mine suggests that a significant degree of mixing of groundwater from the spoil with groundwater from the coal has taken place within the plume, resulting in the levels of sulfate observed in the plume.

The chemical composition of groundwater in the spoil derived plume is quite similar to that of groundwater from the spoil at Vesta Mine, and bears little resemblance to the natural groundwater from the Battle River Bed. The composition of unaffected groundwater from the coal in the vicinity of Vesta Mine is Na^+ - HCO_3^- to Na^+ - HCO_3^-, Cl^-, with TDS ranging from 800 to 1900 mg/L (Figures 13 and 14). Sodium makes up over 90% of the cation composition and bicarbonate composes over 65% of the anionic component. Chloride is a secondary constituent, making up as much as 35% of the anion composition. Sulfate makes up less than 20% of the anions in almost all cases. In the plume, on the other hand, the groundwater is of Na^+ - SO_4^{2-}, HCO_3^- composition, with TDS ranging from 2515 to 3134 mg/L. Sodium makes up from 65 to 70% of the cation fractions,

Table 1. Chemical and isotopic characteristics of natural and contaminated groundwater from the Battle River Bed.

Well ID	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	CO_3^{2-}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	NO_3^{-}	F^{-}	pH	$\delta^{18}O$	δD	^{3}H	Gypsum SI	Ca/Mg	Na/K
	←					mg/L					→							
Natural																		
4-2-1	2937	6.8	0.9	553	2.3	0.0	2133	212.0	21.0	0.3	0.28	8.55	-[a]	-	-	-2.53	4.58	408.9
5-2-1	2424	9.7	1.4	719	3.8	11.5	1347	21.0	285.0	15.0	0.7	8.55	-16.2	-131.6	-	-3.31	4.21	321.8
6-3-1	1502	3.6	0.8	373	2.9	0.0	952	46.7	58.0	59.0	0.9	7.78	-17.9	-138.8	-	-3.23	2.73	218.8
9-4-1	1554	38.0	0.3	428	1.7	19.8	998	14.5	44.0	3.9	0.9	8.42	-18.4	-136.1	-	-2.77	76.8	428.2
15-2-1	1725	9.2	0.3	494	1.7	13.9	1083	46.5	68.0	1.2	0.9	8.42	-16.0	-120.5	-	-2.91	18.6	494.2
16-5-1	1047	3.0	0.2	292	0.7	6.5	679	8.2	14.4	31.8	1.10	8.04	-	-	-	-4.00	9.10	709.5
17-3-1	925	11.3	2.6	266	3.8	17.7	483	135.0	2.0	1.0	0.30	8.42	-20.4	-151.0	-	-2.25	2.64	119.1
23-3-1	1557	8.3	1.2	465	2.3	24.0	870	29.0	142.0	5.1	0.60	8.45	-18.2	-140.1	-	-3.12	4.20	343.9
24-3-1	1783	5.6	0.7	550	1.7	75.0	990	34.0	97.0	12.2	0.7	8.49	-17.0	-136.4	43	-3.26	4.85	550.2
45-1-1	1301	7.9	0.8	440	2.9	399.0	306	39.0	92.0	0.5	0.5	11.27	-16.5	-134.5	10	-	-	-
46-2-1	1431	7.5	1.4	419	5.4	74.6	737	94.0	82.0	2.5	0.7	8.66	-12.2	- 30.8	45	-2.67	3.25	132.0
72-1-1	1132	6.2	1.0	322	2.2	15.4	748	9.0	10.0	1.3	1.5	8.60	-	-	-	-3.68	3.76	248.9
73-1	826	8.5	1.0	226	2.5	6.0	548	13.0	5.0	0.8	1.0	8.50	-	-	-	-	-	-
74-1	1266	4.2	1.1	401	1.6	21.6	888	27.0	15.0	3.0	1.0	8.49	-	-	-	-3.41	2.32	426.0
76-1	1305	5.3	1.3	379	1.9	22.6	910	17.0	11.0	2.1	0.7	8.52	-	-	-	-3.51	2.47	339.0
Mean	1514	9.0	1.0	422	2.5	47.2	911	49.7	63.1	9.3	0.79	8.61	-17.0	-124.2	33	-3.13	10.73	364.7
Std Dev	555	8.4	0.6	126	1.2	100.0	424	56.5	74.3	16.1	0.31	0.77	2.3	36.0	20	0.49	20.33	166.3
Contaminated																		
10-3-1	3134	187.0	31.2	725	12.5	0.0	407	1750.0	5.4	6.2	0.2	8.09	-22.1	-168.9	24	-0.398	3.64	98.6
75-1-1	2515	45.0	6.8	643	4.1	6.2	524	953.0	2.0	0.9	0.3	8.40	-	-	-	-1.10	4.04	266.7
Vesta Spoil																		
Mean	7035	264.0	130.0	1678	19.5		1019	3909.0	9.1	2.8			-20.1	-154.3	42	-0.278	1.748	209.0
Std Dev													1.0	7.8				

Symbols: [a] - , not determined.

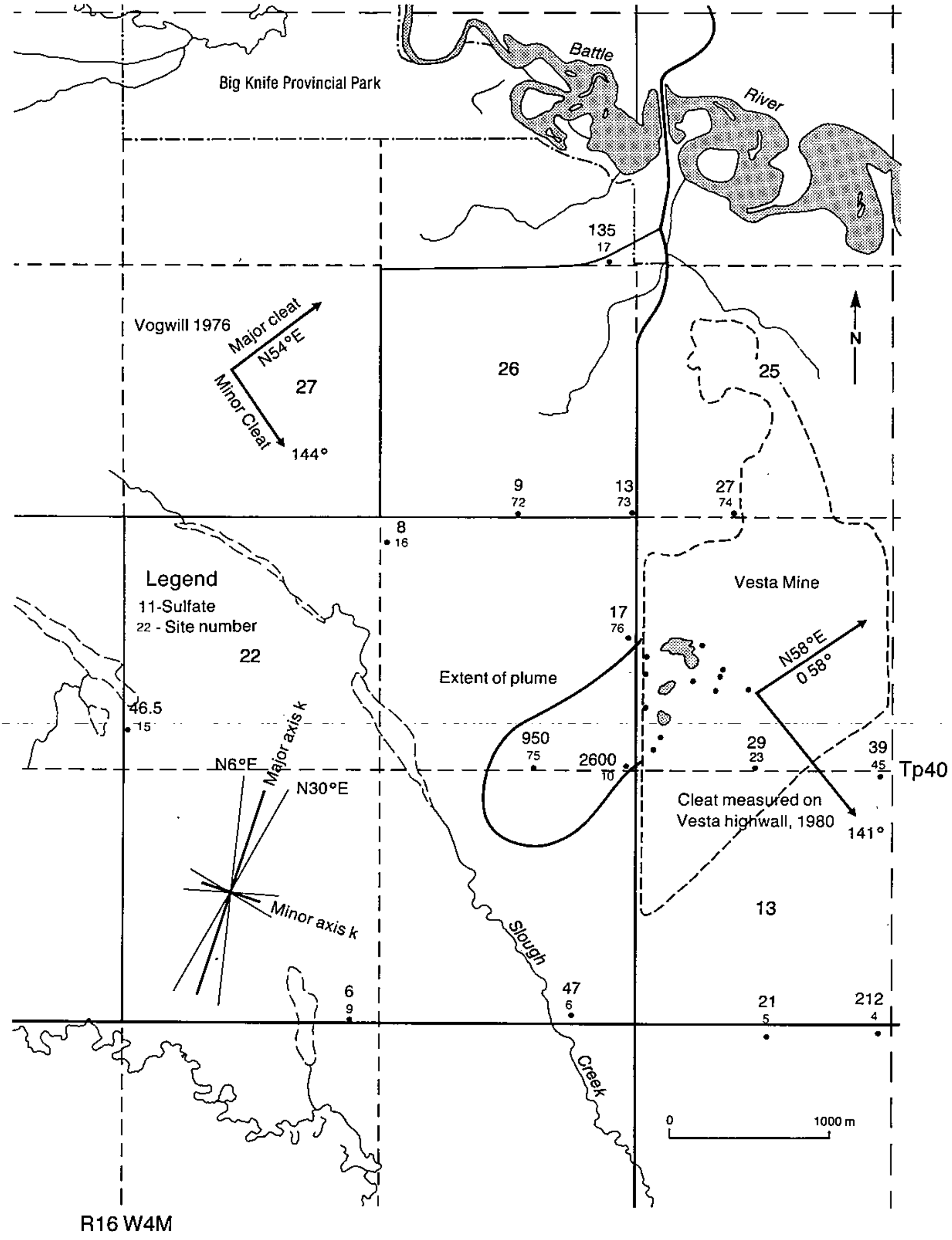

Figure 12. Map showing concentration of sulfate in groundwater from the Battle River Bed.

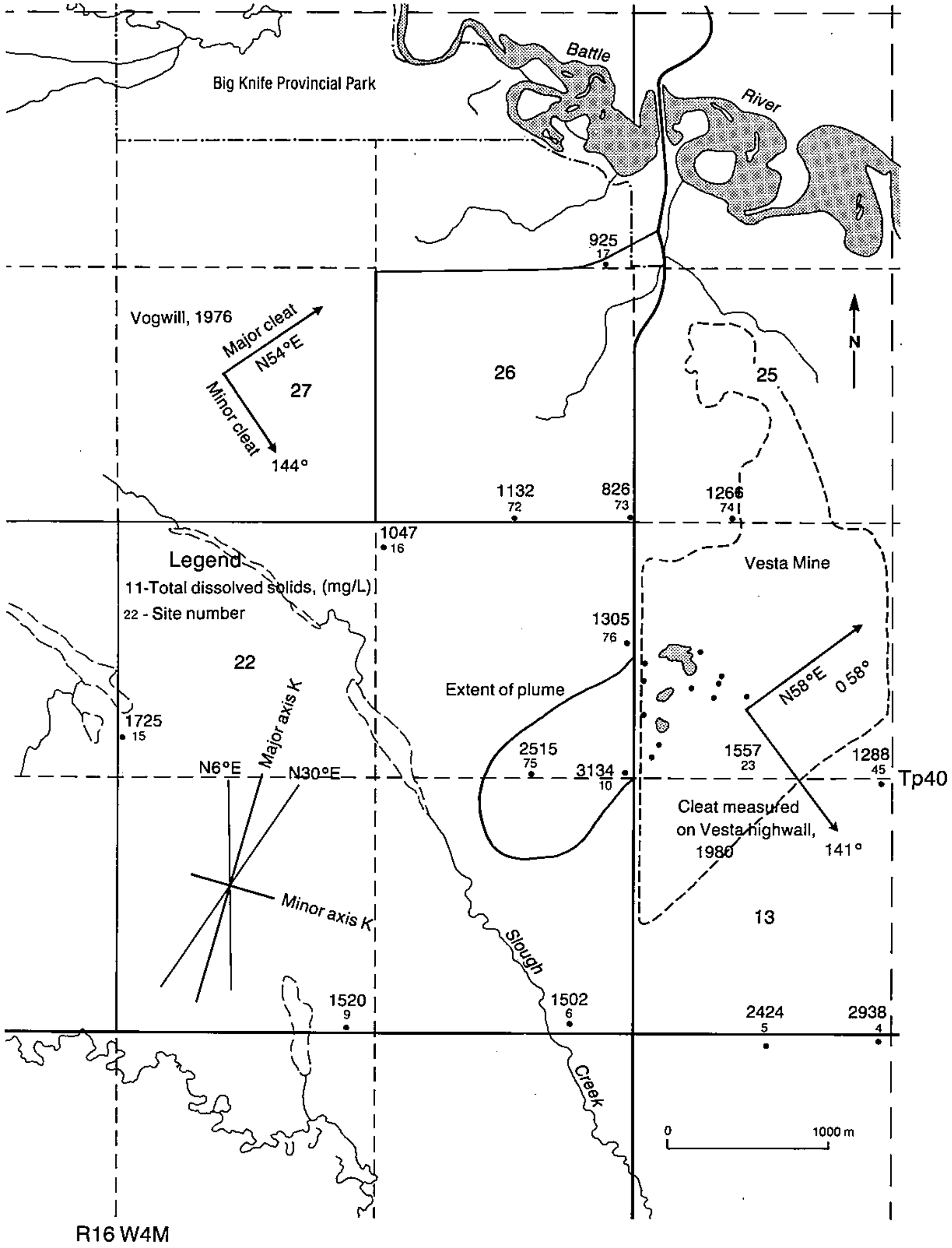

Figure 13. Map showing concentration of total dissolved solids in groundwater from the Battle River Bed.

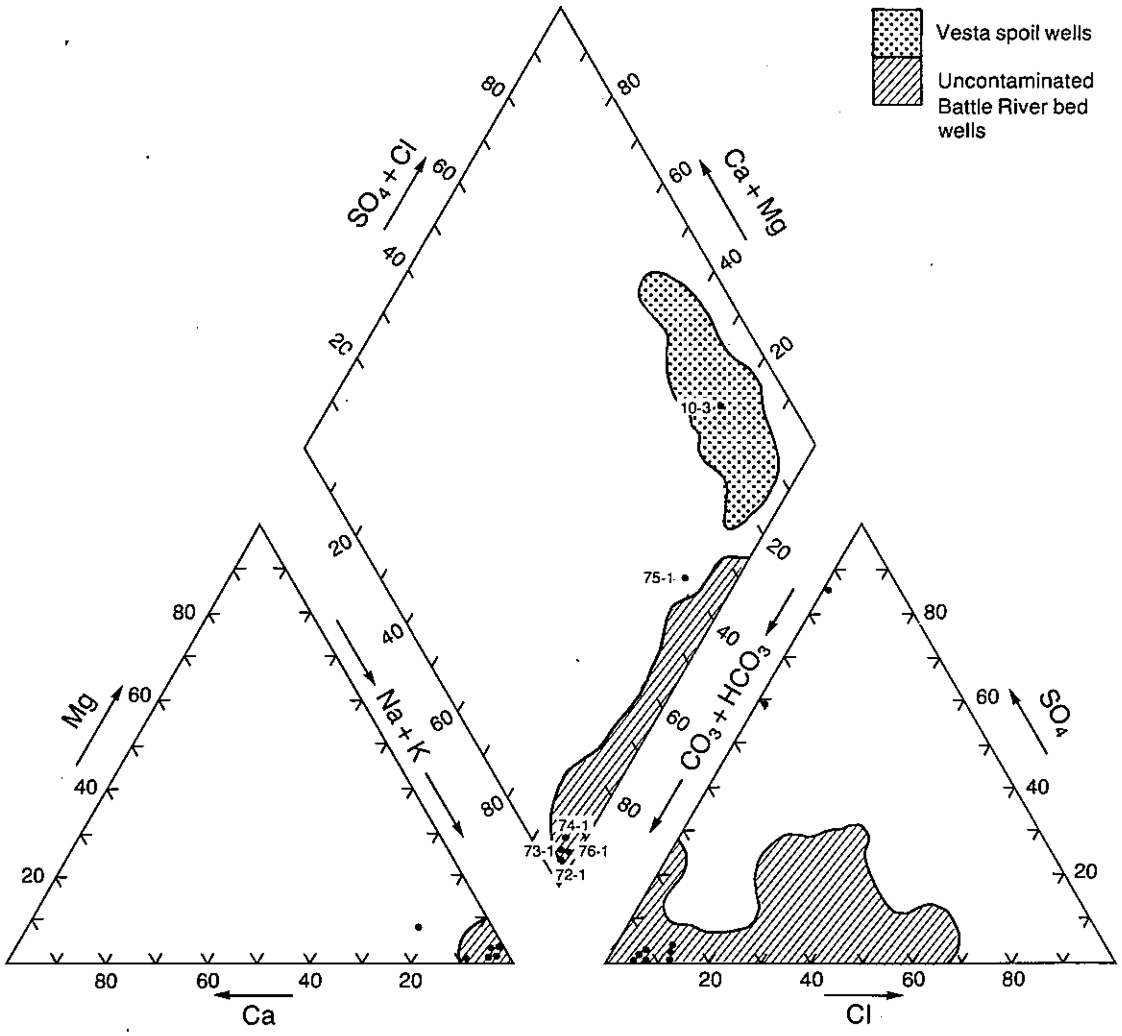

Figure 14. Piper trilinear diagram for groundwater samples from the Battle River Bed.

whereas the remaining 10 to 35% is primarily calcium. Sulfate is the dominant anion, composing 60 to 90% of the anion fraction, and chloride is almost negligible at less than 5% of the anion component. As shown in Figure 14, the composition of the plume sample from site 10 is indistinguishable from the spoil groundwater at Vesta Mine (which has 75 to 95% sulfate and 45 to 95% sodium), although it is somewhat less saline. The plume sample from site 75, however, is compositionally intermediate between the spoil groundwater and the natural Battle River Bed groundwater, suggesting mixing or dilution.

The extent of mixing and dilution of the spoil groundwater plume at site 75 is not certain, but estimates indicate that the groundwater in the Battle River Bed at site 75 is made up of approximately 24% spoil groundwater. These estimates are based on a simple mixing of the mean sulfate concentration of spoil groundwater with the mean sulfate concentrations of water from the Battle River Bed in the vicinity of site 75. Since the influence of the spoil groundwater is reduced by roughly 75% at a distance of approximately 1 km from the mine, it is likely that contamination by spoil groundwater will be insignificant at a distance of approximately 1.5 to 2 km.

The absence of spoil-derived groundwater in the Battle River Bed at site 76, immediately west of Vesta Mine, is an unexpected finding that is related to the direction of migration of groundwater from the mine. The apparent direction of spoil groundwater migration is to the south-southwest, with virtually no movement detected in either north or west directions. The explanation of this phenomenon is based on the fracture pattern in the coal, and resulting anisotropy of hydraulic conductivity in the horizontal plane. The average orientation of the major vertical cleat in the Battle River Bed is 054° (N54°E; Vogwill 1976) to 058° (N58°E; measured at the Vesta Mine Highwall 1980), as shown in Figures 12 and 13. The minor cleat in the coal is at 144° (N36°W; Vogwill 1976) to 141° (N39°W; measured at the Vesta Mine Highwall 1980) also as shown in Figures 12 and 13. The major axis of hydraulic conductivity, based on aquifer tests in the eastern part of Vesta Mine, has an average direction of 018° (N18°E), with measured values ranging from 006° (N6°E) to 030° (N30°E) (Vogwill 1976), with the minor axis of hydraulic conductivity at right angles to these directions (Figures 12 and 13). The major axis of hydraulic conductivity corresponds to a resultant of the two cleat directions (Vogwill 1976). Because of this anisotropy of hydraulic conductivity there is a strong tendency for groundwater to flow preferentially in the direction of the major axis of hydraulic conductivity, that is, from Vesta Mine to the south-southwest. As the flow progresses through the coal, dispersion causes the plume to increase in size in both longitudinal and transverse directions, which acts to increase its east-west dimension. Consequently, if the plume in the Battle River Bed originated in the deep ponds of Vesta Mine located just east and south of site 76, then the direction of migration, including the dispersive component, will be away from site 76 to the southwest, toward sites 10 and 75.

Other chemical parameters provide indications as to the origin of the groundwater in the plume. Calcium concentrations in the plume are from 45 to 187 mg/L, compared to the natural range of values from 3.0 to 11.3 (Table 1). Similarly, the concentration of magnesium in the plume is from 6.8 to 31.2 mg/L, compared to a maximum concentration in the natural groundwater of 2.6 mg/L (Table 1). In both of these cases, the concentrations are intermediate between those in the coal and those in the spoil groundwater, indicating some degree of mixing. The same general observation is true for values of gypsum saturation index, Ca^{2+}/Mg^{2+} ratios and Na^{+}/K^{+} ratios (Table 1).

Stable isotope and tritium data for this group of samples is somewhat sparse, although the one oxygen-18 and deuterium analysis that is available for the plume (from site BR10) is isotopically lighter than any of the natural Battle River Bed samples, and well within the range of values that is typical of spoil groundwater from Vesta Mine (Table 1).

3.2 DRIFT PLUME

The natural groundwater in the drift has a chemical makeup that can be broken down into three major groups (Table 2; Figure 15). The first has bicarbonate as the major anion, with either calcium or sodium as the dominant cation. The TDS concentrations in this group are low, ranging from 400 to 1300 mg/L, as are the sulfate concentrations, which range from 20 to 220 mg/L. The second major type of water has sulfate as the principal anion, and calcium plus magnesium making up more than 70% of the cation component. In this group of samples, TDS concentrations are low to moderate, ranging from 600 to 2500 mg/L, and sulfate concentrations are moderate, ranging from 100 to 1200 mg/L. The third major type of naturally-occurring groundwater in the drift also is dominated by sulfate, at 70 to 80% of the anionic component; sodium makes up from 40 to 80% of the cation fraction. In these samples TDS concentrations are moderate (2200 to 3200 mg/L), as are sulfate concentrations, which range from 1000 to 1500 mg/L.

The samples of drift groundwater that are indicative of contamination by spoil groundwater are similar in composition to the third group of natural drift groundwater samples but are higher in sulfate and much more saline. The composition of the contaminated samples (Figure 15) is dominated by sodium (35 to 90% of the cation fraction) and sulfate (80 to 95% of the anion fraction). The TDS concentrations range from 4100 to 14 900 mg/L, with most values between 5000 to 8000 mg/L (Table 3). Similarly, sulfate concentrations range from 2400 to 9600 mg/L, with most values between 3000 to 6000 mg/L (Table 3).

The spatial distribution of TDS and sulfate concentrations in the lower sand horizon of the drift can be used to delineate the extent of the spoil groundwater plume in the drift (Figures 16 and 17; Tables 2 and 3). On a contour map of TDS in the drift groundwater (Figure 16) the spoil groundwater plume corresponds approximately to the 4000 mg/L contour. A zone of mixing of the two sources of water probably exists between the 3000 and 4000 mg/L

Table 2. Chemical and isotopic characteristics of natural drift groundwater.

Well ID	(d/mo/y)	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	SiO_2	F^-	pH	$\delta^{18}O$	δ^2H	^3H	Gypsum SI	Ca/Mg	Na/K
		<					mg/L					>							
Group I: Ca^{2+}, Mg^{2+} - HCO_3^- to Na^+, Ca^{2+} - HCO_3^- Type																			
17-7	23/06/82	1000	169	40.9	28	5.4	700	39	2.2	1.4	14.0	0.3	7.90	-17.6	-141.1	0	-1.756	2.48	8.65
49-4	12/11/81	1172	119	34.0	138	16.2	665	136	43.0	0.6	19.6	0.4	7.85	-18.0	-146.4	-[a]	-1.366	2.10	14.48
82-1	14/06/83	501	22	6.5	107	2.8	269	44	2.0	7.2	20.0	0.6	7.88	-25.9	-201.3	51	-2.175	2.05	65.00
84-1	15/06/83	614	41	15.0	103	1.4	405	33	2.0	1.2	11.0	0.6	7.66	-23.8	-199.5	39	-2.089	1.66	12.50
84-1	25/06/84	545	41	14.0	82	1.1	366	21	4.7	3.2	12.0	0.4	7.14	-	-	-	-2.435	1.77	126.70
84-1	09/08/85	448	36	11.0	139	1.1	470	35	4.0	5.2	14.0	0.3	7.45	-	-	-	-2.298	1.98	214.80
85-1	03/08/83	898	106	36.0	74	8.8	588	52	9.0	4.1	20.0	0.5	7.11	-26.8	-206.9	91	-1.593	1.79	14.30
85-1	27/06/84	685	64	27.0	78	5.9	395	92	4.0	4.2	15.0	0.4	7.82	-	-	-	-1.689	1.43	22.50
85-1	09/08/85	481	63	21.0	28	4.8	302	44	1.3	4.0	13.0	0.2	7.23	-	-	-	-1.956	1.82	9.91
96-1	01/05/84	1217	53	15.0	265	8.1	581	211	6.8	49.0	13.0	0.5	7.70	-	-	-	-1.489	2.14	55.60
Group II: Ca^{2+} - SO_4^{2-}, HCO_3^- Type																			
72-2	14/12/82	1627	251	81.0	128	5.8	372	873	0.0	3.0	12.7	0.3	7.60	-	-	-	-0.456	1.86	37.52
72-2	31/05/83	1888	280	89.0	119	6.4	427	945	0.0	6.7	15.0	0.3	7.19	-24.0	-149.5	122	-0.219	1.91	36.60
73-2	07/04/83	989	164	50.0	41	3.3	285	420	4.0	4.3	18.0	0.3	7.69	-23.1	-157.0	-	-0.801	1.97	21.12
73-2	31/05/83	941	164	41.0	32	4.0	376	300	2.0	3.3	19.0	0.3	7.49	-23.2	-159.6	131	-0.741	2.42	13.60
73-2	22/06/84	900	147	45.0	28	3.6	302	348	6.3	1.6	18.0	0.2	7.28	-	-	-	-0.897	1.98	13.22
73-2	07/08/85	784	134	33.0	23	3.4	312	255	4.7	1.6	17.0	0.2	7.30	-	-	-	-1.026	2.46	11.50
83-1	16/06/83	2431	425	91.0	144	2.4	525	1200	2.0	24.0	17.0	1.2	7.47	-22.7	-172.1	78	-0.016	2.83	10.20
93-1	03/05/84	597	91	26.0	23	2.9	265	113	6.8	51.0	17.0	0.5	7.27	-19.2	-154.2	168	-1.451	2.12	13.48
99-1	09/05/84	1366	215	94.0	25	6.1	443	550	7.4	4.8	21.0	0.3	7.09	-20.5	-161.5	54	-0.659	1.38	6.96
Group III: Na^+, Ca^{2+} - SO_4^{2-} Type																			
9-7	26/02/81	3210	314	82.0	452	10.0	1108	1225	2.0	0.52	15.5	0.3	7.66	-	-	-	-0.336	2.30	76.84
9-7	01/06/83	2626	270	78.0	370	8.4	531	1350	0.0	2.6	16.0	0.6	7.78	-21.8	-163.7	113	-0.158	2.10	74.90
16-3	21/04/82	2270	100	20.0	550	5.1	549	1000	4.6	14.6	15.6	0.3	8.03	-21.5	-162.2	-	-0.792	3.00	183.30
16-3	31/05/83	2275	106	20.0	530	6.0	461	1020	0.01	25.0	7.6	0.3	6.93	-23.3	-178.6	49	-0.579	3.22	150.20
81-1	29/06/83	2624	118	89.0	590	10.0	354	1425	12.0	8.9	16.0	0.5	7.59	-24.0	-186.6	-	-0.484	0.80	10.00

Symbols: [a] - , not determined.

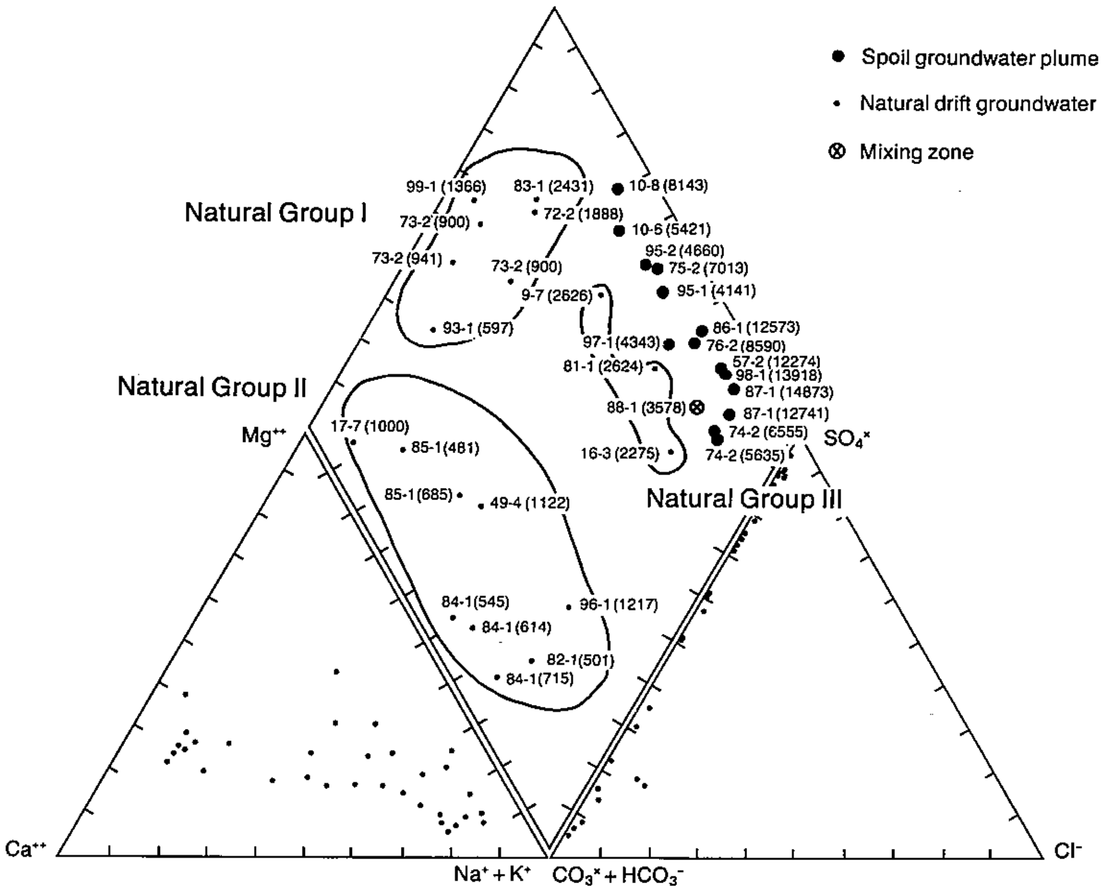

Figure 15. Piper trilinear diagram for drift groundwater samples. The labels attached to each point indicate the well number, and in parentheses, the total dissolved solids.

Table 2. Chemical and isotopic characteristics of natural drift groundwater.

Well ID	(d/mo/y)	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	SiO_2	F^-	pH	$\delta^{18}O$	δ^2H	^3H	Gypsum SI	Ca/Mg	Na/K
		←					mg/L					→							
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49-4	12/11/81	1172	119	34.0	138	16.2	665	136	43.0	0.6	19.6	0.4	7.85	-18.0	-146.4	-[a]	-1.366	2.10	14.48
82-1	14/06/83	501	22	6.5	107	2.8	269	44	2.0	7.2	20.0	0.6	7.88	-25.9	-201.3	51	-2.175	2.05	65.00
84-1	15/06/83	614	41	15.0	103	1.4	405	33	2.0	1.2	11.0	0.6	7.66	-23.8	-199.5	39	-2.089	1.66	12.50
84-1	25/06/84	545	41	14.0	82	1.1	366	21	4.7	3.2	12.0	0.4	7.14	-	-	-	-2.435	1.77	126.70
84-1	09/08/85	448	36	11.0	139	1.1	470	35	4.0	5.2	14.0	0.3	7.45	-	-	-	-2.298	1.98	214.80
85-1	03/08/83	898	106	36.0	74	8.8	588	52	9.0	4.1	20.0	0.5	7.11	-26.8	-206.9	91	-1.593	1.79	14.30
85-1	27/06/84	685	64	27.0	78	5.9	395	92	4.0	4.2	15.0	0.4	7.82	-	-	-	-1.689	1.43	22.50
85-1	09/08/85	481	63	21.0	28	4.8	302	44	1.3	4.0	13.0	0.2	7.23	-	-	-	-1.956	1.82	9.91
96-1	01/05/84	1217	53	15.0	265	8.1	581	211	6.8	49.0	13.0	0.5	7.70	-	-	-	-1.489	2.14	55.60
Group II: Ca^{2+} - SO_4^{2-}, HCO_3^- Type																			
72-2	14/12/82	1627	251	81.0	128	5.8	372	873	0.0	3.0	12.7	0.3	7.60	-	-	-	-0.456	1.86	37.52
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73-2	07/04/83	989	164	50.0	41	3.3	285	420	4.0	4.3	18.0	0.3	7.69	-23.1	-157.0	-	-0.801	1.97	21.12
73-2	31/05/83	941	164	41.0	32	4.0	376	300	2.0	3.3	19.0	0.3	7.49	-23.2	-159.6	131	-0.741	2.42	13.60
73-2	22/06/84	900	147	45.0	28	3.6	302	348	6.3	1.6	18.0	0.2	7.28	-	-	-	-0.897	1.98	13.22
73-2	07/08/85	784	134	33.0	23	3.4	312	255	4.7	1.6	17.0	0.2	7.30	-	-	-	-1.026	2.46	11.50
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93-1	03/05/84	597	91	26.0	23	2.9	265	113	6.8	51.0	17.0	0.5	7.27	-19.2	-154.2	168	-1.451	2.12	13.48
99-1	09/05/84	1366	215	94.0	25	6.1	443	550	7.4	4.8	21.0	0.3	7.09	-20.5	-161.5	54	-0.659	1.38	6.96
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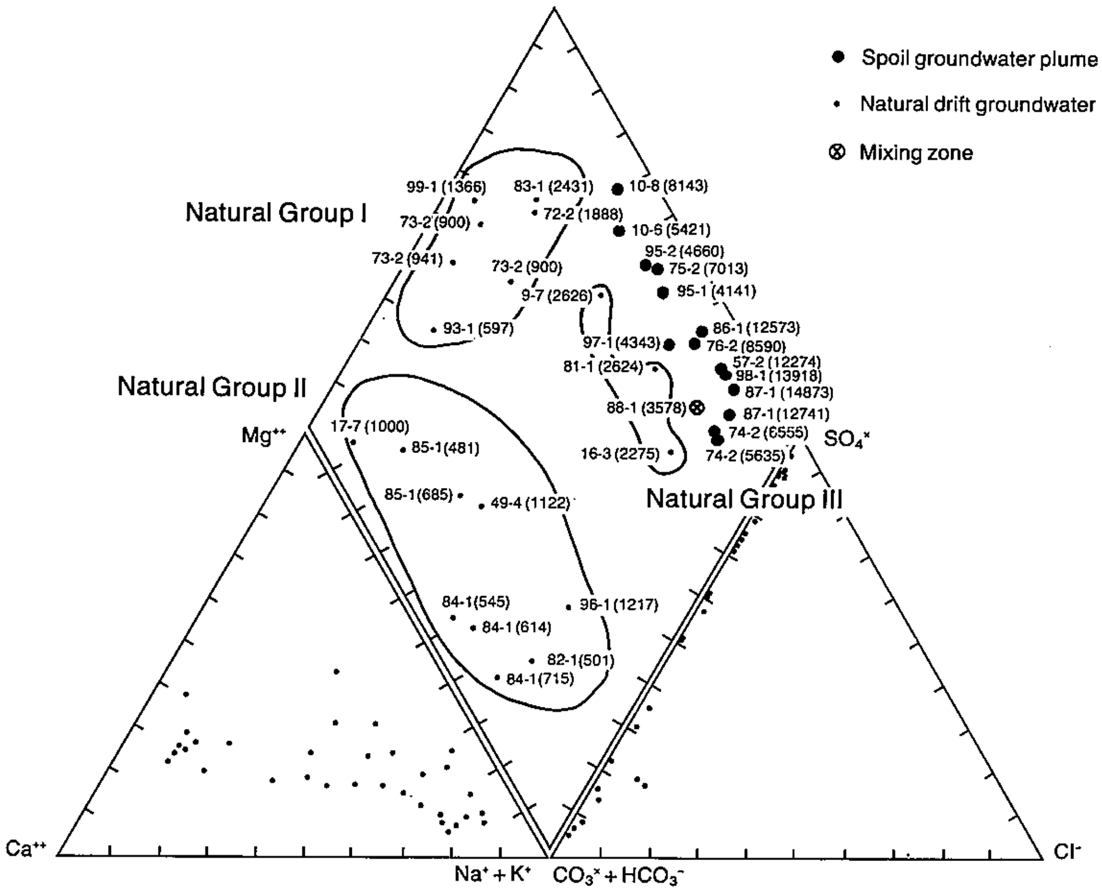
9-7	01/06/83	2626	270	78.0	370	8.4	531	1350	0.0	2.6	16.0	0.6	7.78	-21.8	-163.7	113	-0.158	2.10	74.90
16-3	21/04/82	2270	100	20.0	550	5.1	549	1000	4.6	14.6	15.6	0.3	8.03	-21.5	-162.2	-	-0.792	3.00	183.30
16-3	31/05/83	2275	106	20.0	530	6.0	461	1020	0.01	25.0	7.6	0.3	6.93	-23.3	-178.6	49	-0.579	3.22	150.20
81-1	29/06/83	2624	118	89.0	590	10.0	354	1425	12.0	8.9	16.0	0.5	7.59	-24.0	-186.6	-	-0.484	0.80	10.00

Symbols: [a] - , not determined.



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		< mg/L >																	
10-6	29/10/81	5284	379	262	775	10.4	539	3193	4.0	2.0	18.8	0.8	7.79	-21.5	-167.0	0	-0.060	0.87	126.3
10-6	01/06/83	5421	415	300	745	9.8	562	3360	2.0	6.7	20.0	0.8	7.52	-22.6	-195.5	19	0.161	0.84	129.3
10-8	29/10/81	8330	495	530	1044	14.0	578	5060	2.8	29.0	23.0	0.7	7.99	-21.2	-162.3	67	0.100	0.56	129.7
10-8	01/06/83	8143	490	630	965	11.0	552	5460	0.0	17.0	19.0	0.6	7.81	-23.1	-201.3	55	0.285	0.48	149.2
57-2	27/10/81	14606	390	306	3738	29.0	926	9040	7.6	0.4	13.0	0.3	7.79	-15.8	-128.2	0	0.071	0.76	224.2
57-2	01/06/83	13114	370	310	3275	25.0	894	8220	4.0	2.2	13.0	0.3	7.81	-17.7	-154.3	15	0.214	0.72	222.8
74-2	17/12/82	6852	75	65	2109	8.9	944	3711	0.0	4.8	17.5	0.4	7.25	-[a]	-	-	-0.733	0.69	401.8
74-2	01/06/83	6555	165	76	1640	7.3	926	3720	0.0	0.8	19.0	0.3	7.38	-22.2	-197.7	7	-0.208	1.32	382.1
74-2	28/06/84	5635	131	63	1580	8.0	771	3060	3.5	2.9	16.0	0.2	8.10	-	-	-	-0.512	1.26	335.8
74-2	07/08/85	5939	124	61	1580	5.8	727	3420	1.5	1.8	17.0	0.3	7.07	-	-	-	-0.510	1.23	463.1
75-2	17/12/82	7066	435	289	1398	12.5	578	4335	0.0	2.2	16.6	0.3	7.36	-	-	-	0.034	0.90	189.6
75-2	01/06/83	7013	510	295	1140	12.0	596	4440	0.0	0.61	19.0	0.3	7.30	-22.9	-182.4	39	0.286	1.05	161.6
76-2	16/12/82	12450	330	694	2726	24.0	723	7687	25.0	1.6	13.0	0.4	7.44	-	-	-	-0.033	0.28	192.6
76-2	01/06/83	7687	200	425	1440	106.0	339	5160	8.0	1.0	7.7	0.3	9.07	-20.8	-158.4	45	-0.095	0.28	231.1
76-2	28/06/84	8590	159	390	1920	188.0	675	5220	13.0	2.6	8.8	0.5	8.34	-	-	-	-0.381	0.25	17.4
76-2	07/08/85	6834	178	270	1380	142.0	459	4380	12.0	2.2	11.0	0.3	8.10	-	-	-	-0.332	0.40	16.5
86-1	16/06/83	14403	340	555	3280	17.0	588	9600	2.0	1.7	18.0	0.9	7.85	-22.8	-176.3	133	0.196	0.37	328.2
86-1	28/06/84	12754	335	490	3020	19.0	705	8160	3.1	4.3	17.0	0.7	8.00	-	-	-	-0.008	0.41	270.2
86-1	09/08/85	11981	320	420	2700	14.0	707	7800	0.8	1.6	18.0	0.5	7.12	-	-	-	-0.024	0.46	327.8
87-1	16/06/83	14873	355	240	3920	20.0	954	9360	6.0	1.4	15.0	0.6	7.79	-21.1	-168.4	7	0.207	0.90	333.4
87-1	28/06/84	12741	270	175	3620	19.0	1132	7500	7.7	0.2	17.0	0.4	7.50	-	-	-	-0.109	0.93	323.9
87-1	09/08/85	11699	235	160	3100	16.0	1027	7140	5.3	1.2	15.0	0.3	7.90	-	-	-	-0.166	0.89	329.4
88-1	16/06/83	3578	154	39	890	7.5	490	1965	2.0	8.6	15.0	0.3	7.40	-23.3	-181.0	24	-0.040	2.40	201.8
95-1	04/05/84	4141	245	200	815	21.0	354	2420	2.0	66.0	17.0	0.5	6.98	-18.1	-148.9	43	-0.283	0.74	66.0
95-2	04/05/84	4660	260	250	735	9.3	415	2640	1.0	38.0	16.0	0.7	7.44	-19.7	-148.7	55	-0.247	0.63	134.3
97-1	04/05/84	4343	270	120	910	9.3	531	2470	4.7	9.6	18.0	0.2	7.08	-20.8	-154.2	-	-0.231	1.36	166.3
98-1	04/05/84	13918	470	245	3760	18.0	801	8610	4.2	0.9	9.0	0.2	7.49	-20.6	-154.2	4	+0.146	1.16	355.1

Symbols: [a] - , not determined.

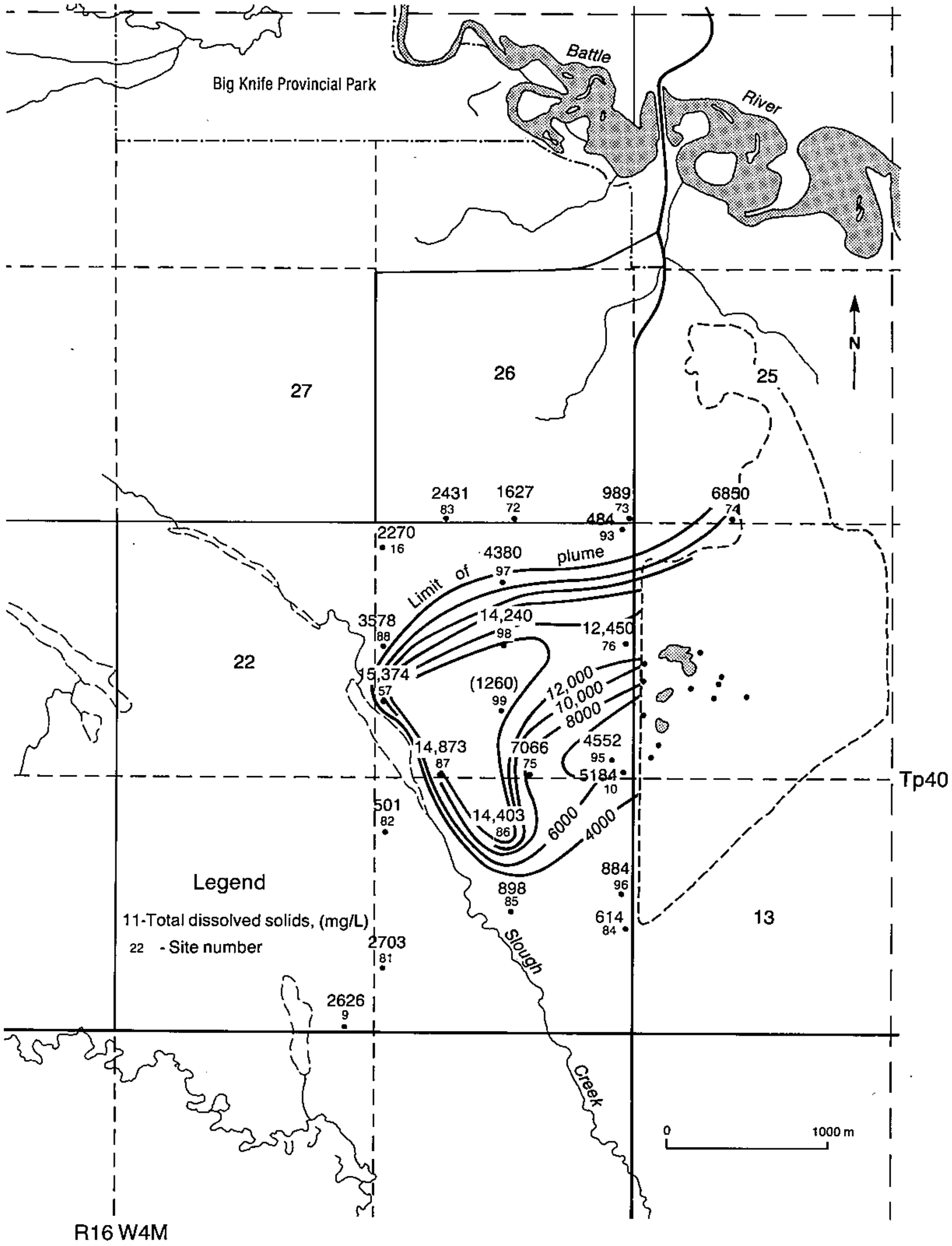

Figure 16. Map showing concentration of total dissolved solids in groundwater from the drift.

Table 3. Chemical and isotopic characteristics of contaminated drift groundwater.

Well ID	(d/mo/y)	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	SiO_2	F^-	pH	$\delta^{18}O$	δ^2H	^3H	Gypsum SI	Ca/Mg	Na/K
		<					mg/L					>							
10-6	29/10/81	5284	379	262	775	10.4	539	3193	4.0	2.0	18.8	0.8	7.79	-21.5	-167.0	0	-0.060	0.87	126.3
10-6	01/06/83	5421	415	300	745	9.8	562	3360	2.0	6.7	20.0	0.8	7.52	-22.6	-195.5	19	0.161	0.84	129.3
10-8	29/10/81	8330	495	530	1044	14.0	578	5060	2.8	29.0	23.0	0.7	7.99	-21.2	-162.3	67	0.100	0.56	129.7
10-8	01/06/83	8143	490	630	965	11.0	552	5460	0.0	17.0	19.0	0.6	7.81	-23.1	-201.3	55	0.285	0.48	149.2
57-2	27/10/81	14606	390	306	3738	29.0	926	9040	7.6	0.4	13.0	0.3	7.79	-15.8	-128.2	0	0.071	0.76	224.2
57-2	01/06/83	13114	370	310	3275	25.0	894	8220	4.0	2.2	13.0	0.3	7.81	-17.7	-154.3	15	0.214	0.72	222.8
74-2	17/12/82	6852	75	65	2109	8.9	944	3711	0.0	4.8	17.5	0.4	7.25	-[a]	-	-	-0.733	0.69	401.8
74-2	01/06/83	6555	165	76	1640	7.3	926	3720	0.0	0.8	19.0	0.3	7.38	-22.2	-197.7	7	-0.208	1.32	382.1
74-2	28/06/84	5635	131	63	1580	8.0	771	3060	3.5	2.9	16.0	0.2	8.10	-	-	-	-0.512	1.26	335.8
74-2	07/08/85	5939	124	61	1580	5.8	727	3420	1.5	1.8	17.0	0.3	7.07	-	-	-	-0.510	1.23	463.1
75-2	17/12/82	7066	435	289	1398	12.5	578	4335	0.0	2.2	16.6	0.3	7.36	-	-	-	0.034	0.90	189.6
75-2	01/06/83	7013	510	295	1140	12.0	596	4440	0.0	0.61	19.0	0.3	7.30	-22.9	-182.4	39	0.286	1.05	161.6
76-2	16/12/82	12450	330	694	2726	24.0	723	7687	25.0	1.6	13.0	0.4	7.44	-	-	-	-0.033	0.28	192.6
76-2	01/06/83	7687	200	425	1440	106.0	339	5160	8.0	1.0	7.7	0.3	9.07	-20.8	-158.4	45	-0.095	0.28	231.1
76-2	28/06/84	8590	159	390	1920	188.0	675	5220	13.0	2.6	8.8	0.5	8.34	-	-	-	-0.381	0.25	17.4
76-2	07/08/85	6834	178	270	1380	142.0	459	4380	12.0	2.2	11.0	0.3	8.10	-	-	-	-0.332	0.40	16.5
86-1	16/06/83	14403	340	555	3280	17.0	588	9600	2.0	1.7	18.0	0.9	7.85	-22.8	-176.3	133	0.196	0.37	328.2
86-1	28/06/84	12754	335	490	3020	19.0	705	8160	3.1	4.3	17.0	0.7	8.00	-	-	-	-0.008	0.41	270.2
86-1	09/08/85	11981	320	420	2700	14.0	707	7800	0.8	1.6	18.0	0.5	7.12	-	-	-	-0.024	0.46	327.8
87-1	16/06/83	14873	355	240	3920	20.0	954	9360	6.0	1.4	15.0	0.6	7.79	-21.1	-168.4	7	0.207	0.90	333.4
87-1	28/06/84	12741	270	175	3620	19.0	1132	7500	7.7	0.2	17.0	0.4	7.50	-	-	-	-0.109	0.93	323.9
87-1	09/08/85	11699	235	160	3100	16.0	1027	7140	5.3	1.2	15.0	0.3	7.90	-	-	-	-0.166	0.89	329.4
88-1	16/06/83	3578	154	39	890	7.5	490	1965	2.0	8.6	15.0	0.3	7.40	-23.3	-181.0	24	-0.040	2.40	201.8
95-1	04/05/84	4141	245	200	815	21.0	354	2420	2.0	66.0	17.0	0.5	6.98	-18.1	-148.9	43	-0.283	0.74	66.0
95-2	04/05/84	4660	260	250	735	9.3	415	2640	1.0	38.0	16.0	0.7	7.44	-19.7	-148.7	55	-0.247	0.63	134.3
97-1	04/05/84	4343	270	120	910	9.3	531	2470	4.7	9.6	18.0	0.2	7.08	-20.8	-154.2	-	-0.231	1.36	166.3
98-1	04/05/84	13918	470	245	3760	18.0	801	8610	4.2	0.9	9.0	0.2	7.49	-20.6	-154.2	4	+0.146	1.16	355.1

Symbols: [a] - , not determined.

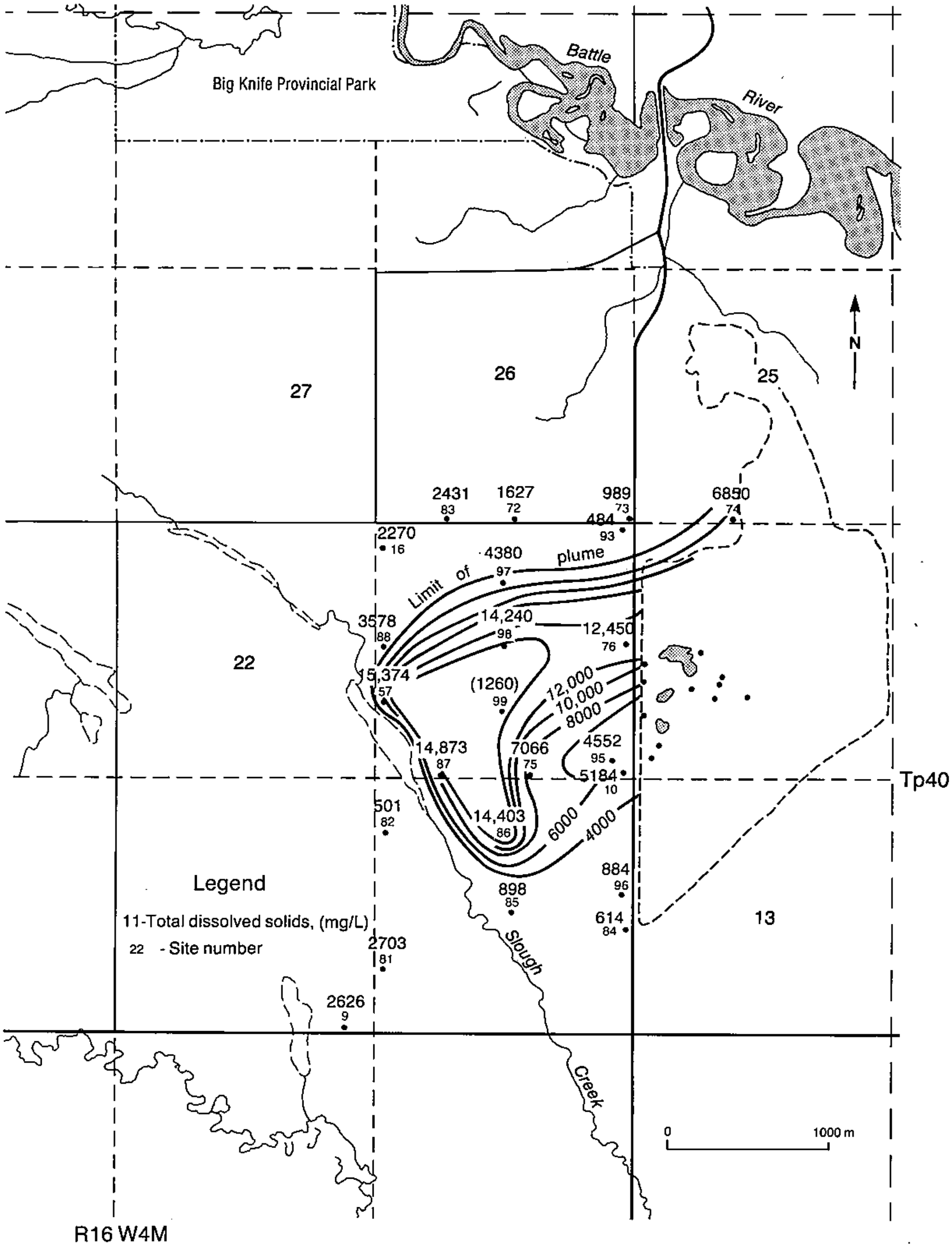

Figure 16. Map showing concentration of total dissolved solids in groundwater from the drift.

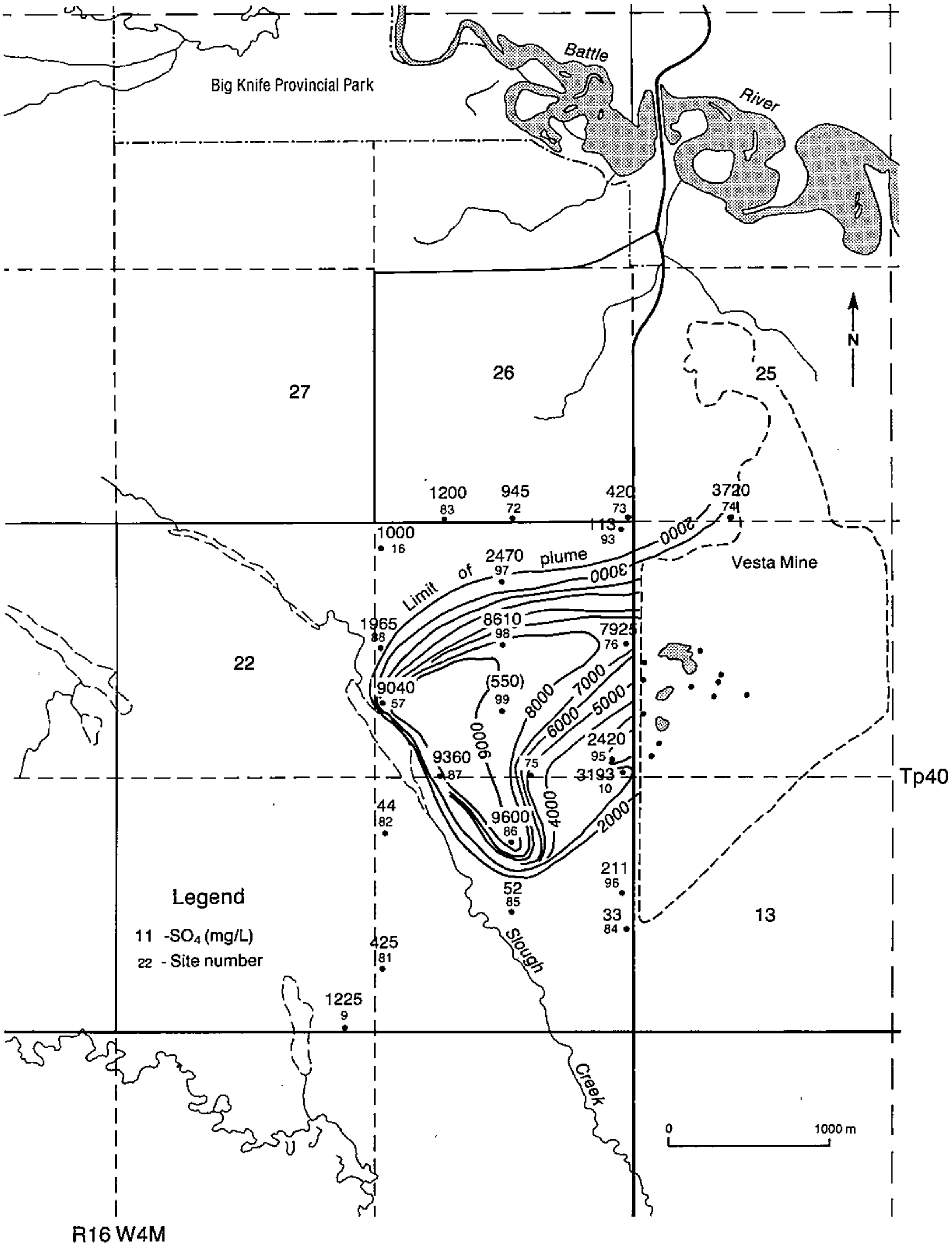

Figure 17. Map showing concentration of sulfate in groundwater from the drift.

contours. The highest TDS concentrations (13 100 to 14 900 mg/L) occur at sites 57, 86, and 87, closest to the discharge zone in Slough Creek. The TDS contours tail off toward Vesta Mine; along the mine boundary TDS values range from 5100 to 12 400 mg/L. The shape of the TDS contours, with the highest concentrations at some distance from the mine, suggest that the present-day plume represents the tail end of a highly saline slug of water released from the mine spoil at some time in the past. The 14 000 to 15 000 mg/L zone of the present plume may represent the centroid of the original plume. This original plume may have resulted from an initial flushing of highly soluble sodium sulfate salts from the spoil, whereas the present-day release represents a less saline sodium-calcium-sulfate composition.

Essentially the same pattern is illustrated by a contour map of sulfate concentrations in the drift groundwater (Figure 17). In this case, the 2000 mg/L contour approximately defines the extent of the plume and corresponds very closely to the plume defined by the 4000 mg/L contour of TDS. The sulfate plume also tails off toward Vesta Mine, with concentrations declining from over 9000 mg/L near Slough Creek, to 3100 to 8000 mg/L along the mine boundary. This pattern also suggests that the observed plume represents a remnant of an older, high salinity slug of water in addition to the present moderate salinity release.

The plume of spoil-affected groundwater in the drift has many chemical characteristics in common with the spoil groundwater at Vesta Mine, and these characteristics help to differentiate the spoil-derived groundwater from the most saline of the natural drift groundwater.

For example, gypsum saturation index (SI) values in natural drift groundwater (Table 2) indicate that in all cases the water is undersaturated with respect to gypsum. In the plume, 46% of the wells have groundwater supersaturated with respect to gypsum, and 62% of the samples have a gypsum SI value greater (i.e., more positive) than -0.2. This is similar to the spoil groundwater at Vesta Mine, in which 73% of the groundwater samples have gypsum SI values greater than -0.2. Only 7% of the natural drift groundwater samples, on the other hand, have gypsum SI values greater than -0.2. Thirty-four percent of the spoil groundwater samples are supersaturated with gypsum, compared to 46% of the plume samples. This difference is attributable to the large reservoir of available calcium associated with the abundant carbonate minerals in the drift. Relatively small concentrations of Ca^{2+} from carbonate mineral dissolution, in combination with very high concentrations of SO_4^{2-} from the spoil groundwater, result in saturation or supersaturation with gypsum, particularly since the spoil groundwater is at or near gypsum saturation as it enters the drift.

The mole ratios of Ca^{2+}/Mg^{2+} are also distinctive in the plume groundwater (Tables 2 and 3). The mean Ca^{2+}/Mg^{2+} ratio of the natural groundwater from drift wells is 2.06 (standard deviation = 0.55, n = 14). In the plume the mean Ca^{2+}/Mg^{2+} ratio is 0.82, with a standard deviation of 0.29 (n = 13). In the spoil groundwater at Vesta Mine the mean Ca^{2+}/Mg^{2+} ratio is 1.75 (standard deviation = 1.09, n = 41), which is intermediate between that of the natural and plume groundwaters. The reduction of the Ca^{2+}/Mg^{2+} ratio in the plume relative to the spoil groundwater is probably a reflection of gypsum precipitation in the plume. Since the plume groundwater is in many cases supersaturated with gypsum, active precipitation of gypsum in the plume is likely. This will remove Ca^{2+} from the groundwater, thereby reducing the Ca^{2+}/Mg^{2+} ratio.

The mole ratio of Na^+/K^+ in the plume groundwater is also closely related to that in the spoil groundwater, and is distinct from that of the natural drift groundwater (Tables 2 and 3). In the spoil groundwater at Vesta Mine the Na^+/K^+ ratio typically ranges from approximately 150 to 350, with a mean of 209.0 and a standard deviation of 76.0 (n = 41). Such high Na^+/K^+ ratios are typical of groundwater in the Horseshoe Canyon formation at the Battle River site (mean Na^+/K^+ ratio = 204, standard deviation = 145, n = 34) and probably reflect the greater abundance of sodium in the rock, and the increased affinity of K^+ for adsorption onto clay mineral exchange sites compared to sodium (Freeze and Cherry 1979). The plume of contaminated groundwater has a mean Na^+/K^+ ratio of 211 (standard deviation = 100, n = 13) which reflects its source in the spoil at Vesta Mine. The mean Na^+/K^+ ratio of natural drift groundwater at 43.8 (standard deviation = 46.7, n = 14) is only one-fifth that of the ratio in the plume, and reflects a different material of origin, that is, glacial till and sand as opposed to bedrock of the Horseshoe Canyon formation.

Several wells within the plume of spoil groundwater were sampled repeatedly between 1981 and 1986 (Figure 18). In well 74-2 TDS concentrations showed a gradual decline between December 1982 and June 1984, and a slight increase by August 1985. At site 76 the maximum TDS concentration of over 12 000 mg/L occurred in 1982, and declined significantly to less than 8000 mg/L by 1983. Since 1983 TDS concentrations at this site have fluctuated between 7000 and 9000 mg/L. This pattern is consistent with the interpretation that a high salinity initial pulse was released from the spoil at Vesta Mine, the tail end of which was passing through site 76 in 1982. The subsequent release of groundwater from Vesta Mine, after the initial 'flushing', was more representative of present-day spoil groundwater, which has a mean TDS concentration of 7400 mg/L. This is typical of the post-1982 TDS levels at site 76. Groundwater samples from wells 86-1 and 87-1, which were first sampled in June 1983, showed maximum TDS concentrations in the initial samples, with decreasing concentrations in 1984 and 1985. In 1986, well 86-1 showed a further decline in TDS of over 1000 mg/L, whereas the TDS concentration in well 87-1 increased by nearly 1000 mg/L. The overall trend, however, shows a general decrease in concentrations with time, consistent with the migration of the saline initial plume, and flushing with less saline, present-day spoil groundwater. Limited data available from sites 10 and 57 are inconclusive. Repeat sampling of wells 10-6 and 10-8 in October 1981 and June 1983 show small but contradictory changes in TDS concentrations. From these samples, well 10-6 showed a 137 mg/L increase in TDS concentration, whereas well 10-8 showed a

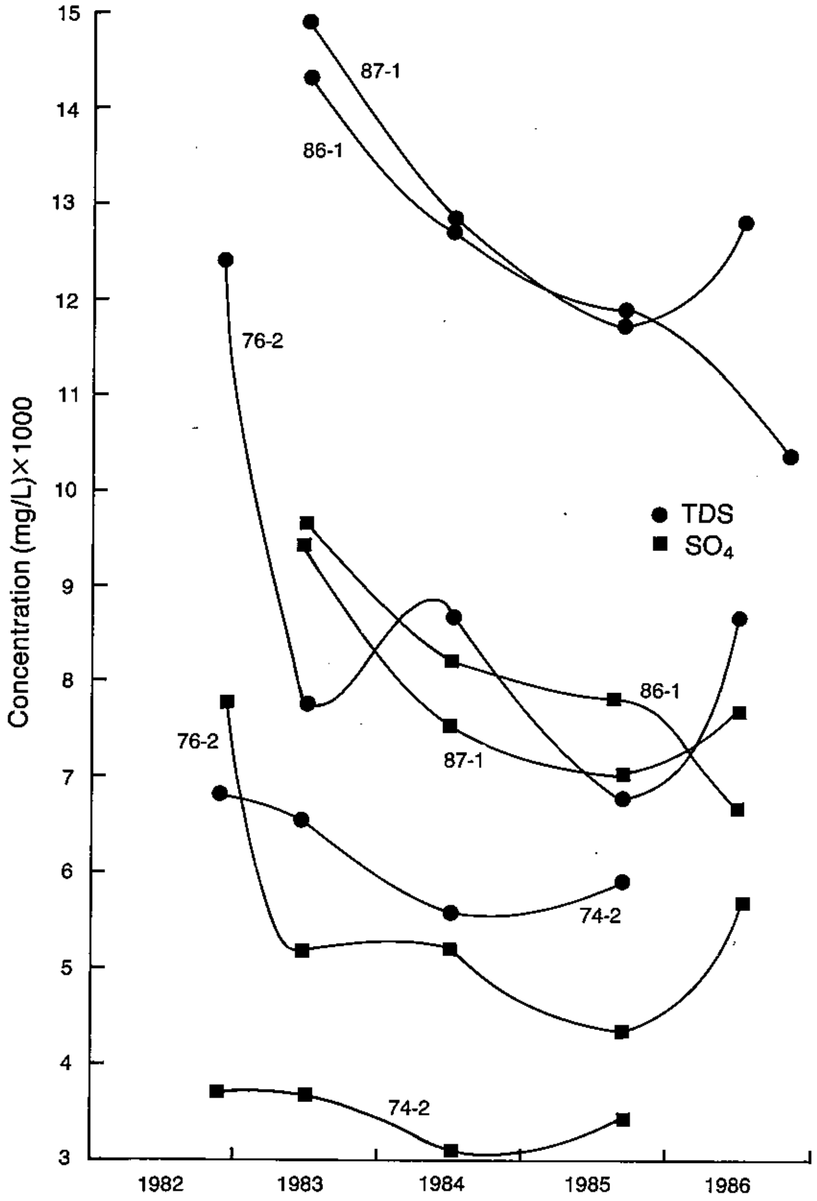

Figure 18. Changes in total dissolved solids and sulfate concentrations for selected wells, 1980 to 1985.

187 mg/L decrease. Over the same time period, TDS concentrations in well 57-2 decreased by 1492 mg/L, which is consistent with the hypothesis that general decreases in salinity are associated with the migration of the plume. Although there is good evidence to show that groundwater is being flushed through the plume, additional evidence indicates that the lateral extent of the plume has remained essentially constant with time. Two samples from well 88-1, located in the mixing zone along the northwest border of the plume (Figures 16 and 17), collected in 1983 and 1986 show very little change, suggesting that the plume is not expanding in that direction. Furthermore, none of the sites originally characterized as having natural drift groundwater have been found to subsequently become affected by spoil groundwater.

Stable isotope data for the drift groundwater illustrates two important characteristics (Figure 19). First, groundwater in the drift is primarily meteoric in origin, and there is no consistent difference in isotopic composition between natural and contaminated drift groundwater and Vesta spoil groundwater. Second, there is almost no evidence of evaporation shown by the stable isotope data; therefore, evaporative concentration of naturally derived salts is not the mechanism responsible for the high salinity groundwater in the drift. Plots of TDS and Na^+ versus ^{18}O (Figures 20 and 21) also show this. Since sodium salts are all very soluble, the concentration of sodium in groundwater is unlikely to be affected by mineral precipitation associated with evaporative concentration. In Figures 20 and 21 it can be seen that the concentration of both TDS and sodium in the drift groundwater are independent of ^{18}O. Under conditions of evaporative concentration, a linear relationship between $\delta^{18}O$ and either sodium or TDS would be expected. One sample, from well 57-2, does show some evidence of slight evaporative concentration. The value of $\delta^{18}O$ for sample 57-2-2 is -17.7 per mille compared to -22 to -24 per mille for most of the other samples. In addition, the sample plots to the right of the meteoric water line (Figure 19) in a position characteristic of

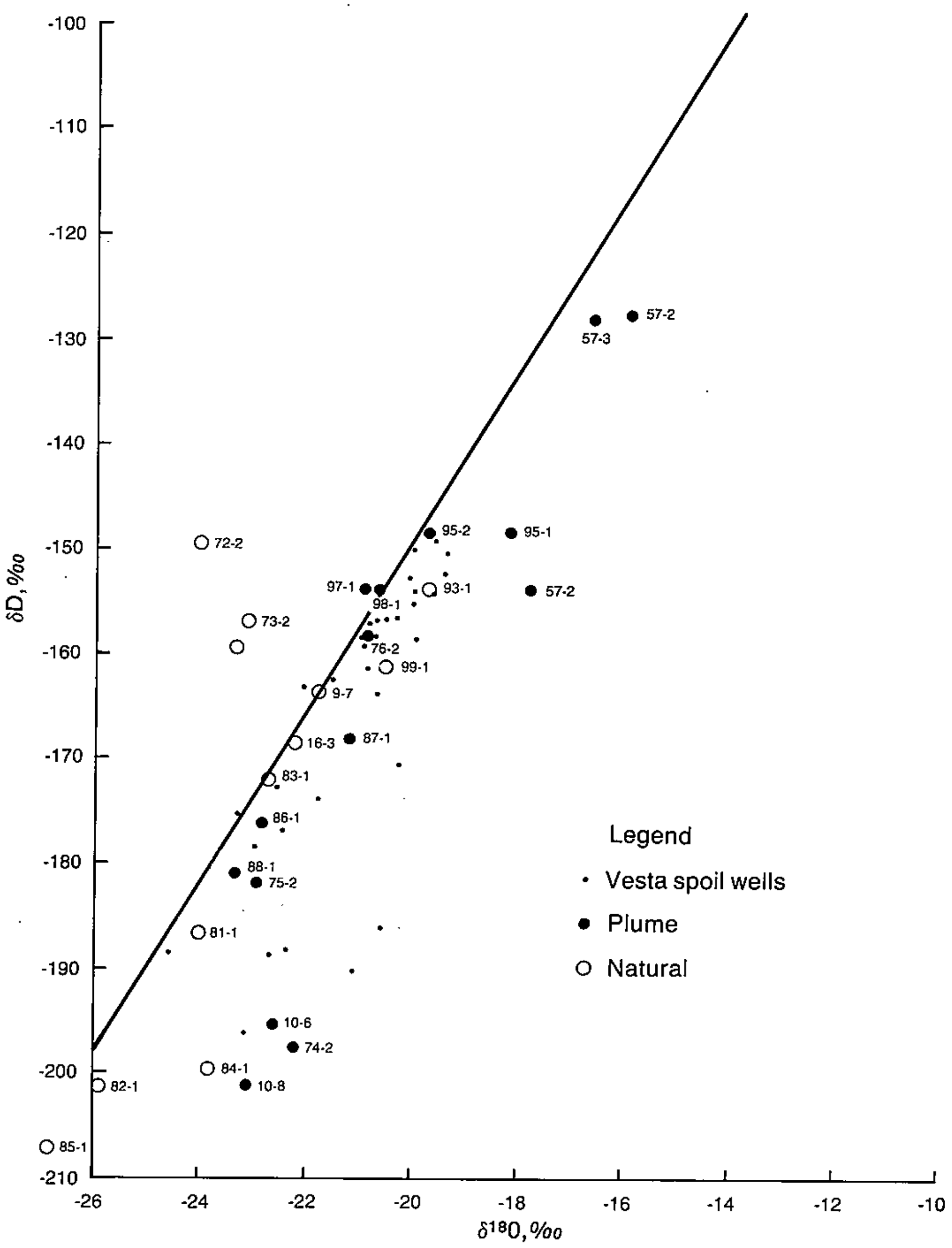

Figure 19. Deuterium versus oxygen-18 for groundwater from drift, including spoil groundwater from Vesta Mine.

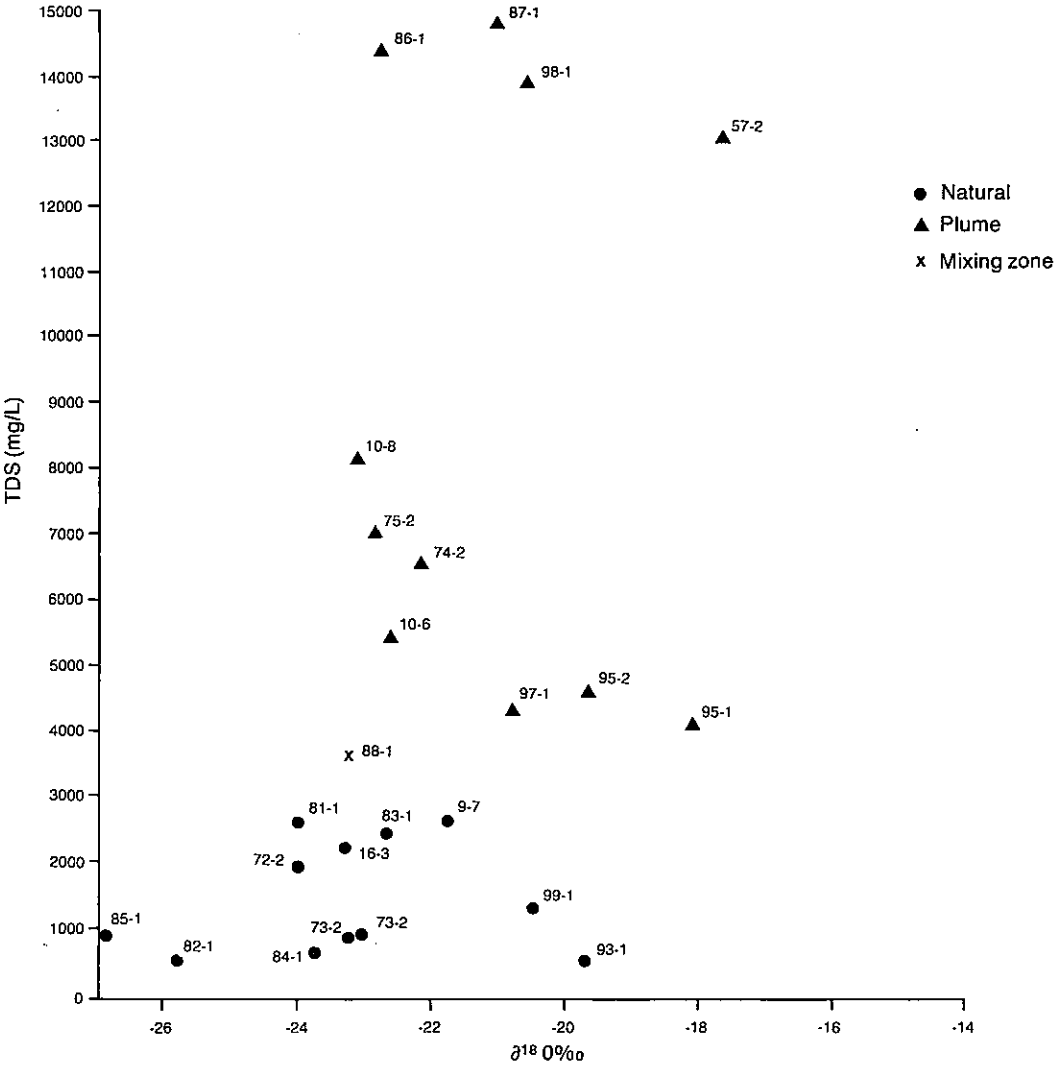

Figure 20. Total dissolved solids concentration versus oxygen-18 for groundwater from the drift.

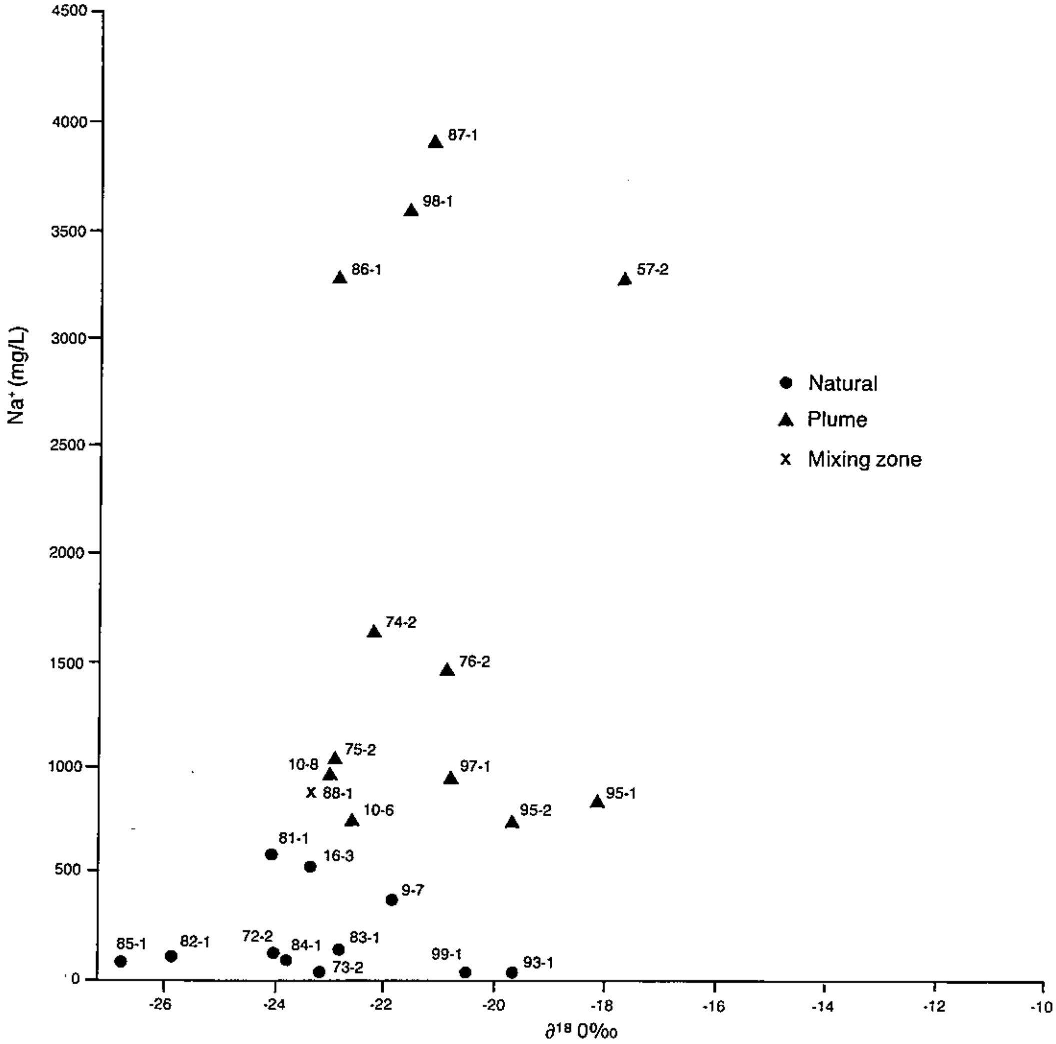

Figure 21. Sodium concentration versus oxygen-18 for groundwater from the drift.

evaporation observed in ponds at the Battle River mining area (Trudell et al. 1987). Consequently, at least a portion of the high salinity in this sample is due to evaporation.

Samples from both natural and contaminated drift groundwater, as well as spoil groundwater from Vesta Mine, were analysed for tritium (Tables 2 and 3). Tritium is the radioactive isotope of hydrogen (atomic mass = 3 amu) present in water. Precipitation since the early 1950s has had relatively high concentrations of tritium as a result of atmospheric testing of thermonuclear devices. The concentration of tritium in precipitation measured in Edmonton reached a peak in 1963 at 4022 tritium units (TU, where 1 TU = 1 ^{3}H atom in 10^{18} hydrogen atoms; Brown 1970) and has since undergone an exponential decline, with present-day precipitation at approximately 42 TU (Trudell et al. 1988). Groundwater recharged from precipitation prior to 1952 will have a tritium content of approximately 5 to 10 TU (Egboka et al. 1983) and, given analytical precision and potential contamination, measured values of less than 20 to 25 TU may be considered to be from pre-1952 water.

On the basis of tritium concentrations, all of the natural drift groundwater (with the exception of one sample, from well 17-7; Table 2) is judged to be post-1952 in age, with a mean tritium concentration of 90 TU (standard deviation = 41, n = 10), and values ranging from 39 to 168 TU. The spoil groundwater at Vesta Mine, on the other hand, has both recent (post-1952) and old (pre-1952) water, as well as water that may be a mixture of the two. Approximately 78% of the samples from Vesta Mine have tritium concentrations above 26 TU, reflecting recently recharged water. Of this 78%, 22% of the samples are between 88 to 171 TU, and 56% are between 26 and 58 TU. The remaining 22% represents pre-1952 water, and may reflect undiluted groundwater from the Battle River Bed that recharged the base of the spoil immediately after mining. The mean tritium concentration of the Vesta spoil groundwater is 42 TU (standard deviation = 33, n = 32) and probably represents a mixing of high tritium, recent water that recharged through the spoil with low tritium, older water that was introduced into the spoil by lateral inflow from the unmined coal. This mixed nature of the spoil groundwater is also typical of the groundwater in the plume. The mean tritium concentration of groundwater from the plume is 34 TU, with a standard deviation of 34 (n = 15). Forty-seven percent of the plume samples are post-1952 water, on the basis of tritium concentrations, with the remaining 53% of the samples having less than 25 TU. The range of individual values, from 0 to 133 TU, is also much like that in the Vesta spoil groundwater, in which tritium values range from 0 to 171 TU. Considering that there is little difference in depth between the natural drift groundwater samples (mean depth = 5.2 m) and the drift plume groundwater samples (mean depth = 5.6 m) it is unlikely that the observed difference in tritium concentrations between the two groups is due to natural differences in the age of the recharge water.

Given this range of parameters to characterize the spoil-derived groundwater plume and delineate it from the natural drift groundwater, it is evident that the origin of the plume is the spoil groundwater at Vesta Mine. As shown in Figures 16 and 17 the spoil groundwater plume extends for a distance of 1.7 km to the southwest of Vesta Mine, and has a width of approximately 1.4 to 1.6 km.

4. EFFECTS OF SPOIL GROUNDWATER MIGRATION ON SOIL SALINITY

An accumulation of salts has been observed at the soil surface above the plume of spoil-derived groundwater along Highway 855 immediately west of the mine in Sec 23, Tp 40, R 16, W 4. According to the landowner, this accumulation appears to be worsening with time.

The objective of this segment of the investigation was to characterize the soil salinity, particularly in Sec 23, Tp 40, R 16, W 4 and to identify the source of that salinity.

The field program to accomplish this objective had two components: (1) soil core sampling to a depth of 2 m and analysis of saturated paste extracts along four east-west transects including affected and nonaffected areas, and (2) soil salinity mapping using electromagnetic induction profiles.

4.1 SOIL CORE SAMPLING

Fourteen soil cores were collected along four transects perpendicular to the western edge of Vesta Mine, in Sec 23, Tp 40, R 16, W 4 (Figure 22). Samples were collected to a depth of 2 m. The four transects were designed to include two salt-affected areas (transects BR94 and 95) and two nonaffected areas (transects BR93 and 96). Within the salt-affected areas, the transects included at least two sites within the fringe of noticeable salt accumulation along the eastern boundary of the section, and at least one site beyond the salt-affected fringe, toward the middle of the section. In addition to these transects, soil samples were collected from three additional sites along the north-south quarter-section line of section 23, sites BR97, 98, and 99 (Figure 22). Of the 188 soil samples that were collected, 168 samples were suitable for saturation extract analysis. The extracts were analysed for pH, electrical conductance (EC), and soluble salts. Samples were collected at 15 cm intervals from surface to 1.5 m depth, and at approximately 30 cm intervals from 1.5 to 2.0 m depth.

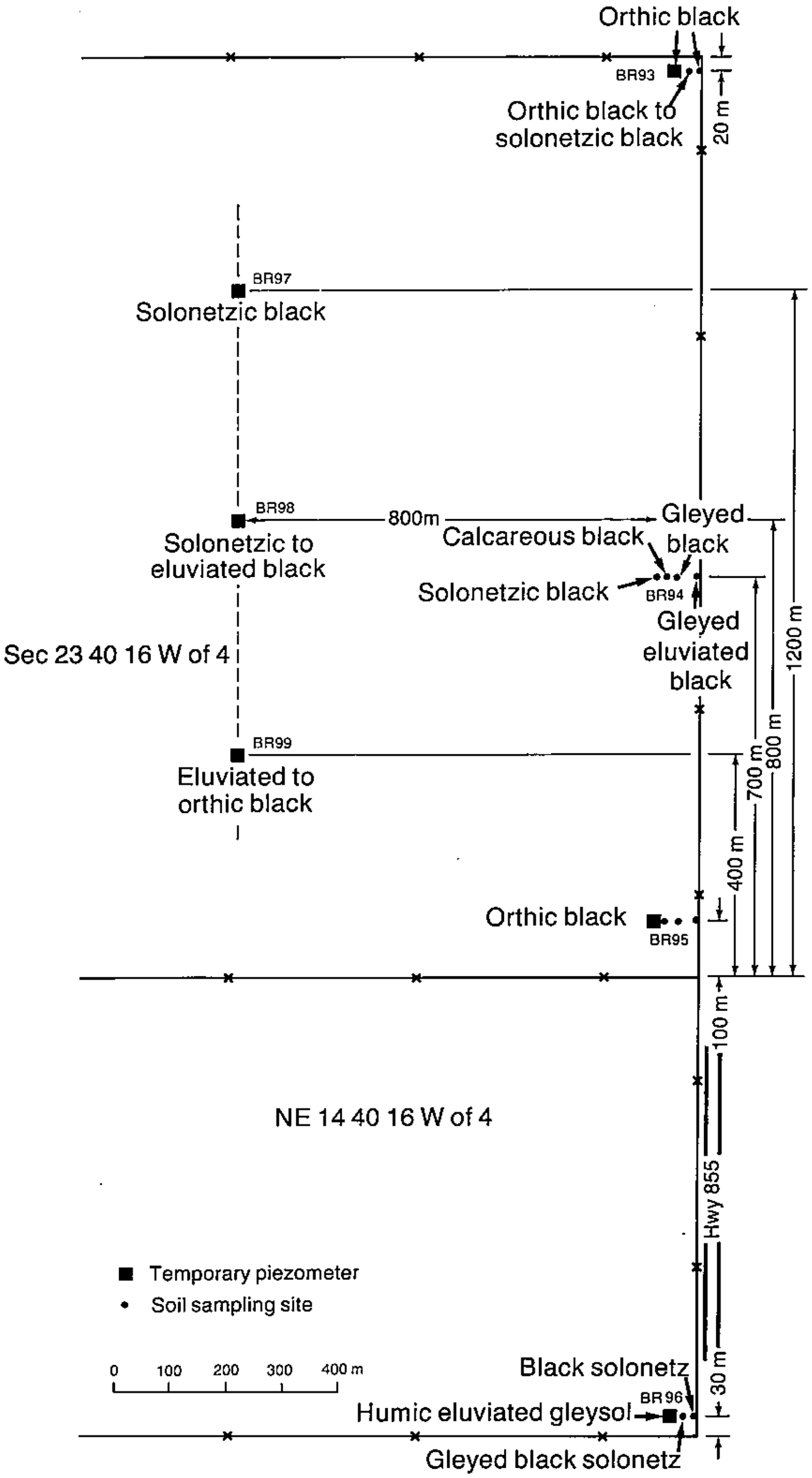

Figure 22. Map showing location of soil sampling transects and temporary piezometer locations.

In order to differentiate between salt accumulation caused by natural soil forming processes from that produced by artificially elevated water-table conditions, detailed soil descriptions and classification were conducted in 1985 along each of the four transects shown in Figure 22. The soils in the study area are quite variable. At the south end (BR96) the soils are predominantly Solonetzic and imperfectly to poorly drained. The remainder of the soils in this quarter section (NE14, Tp 40, R 16, W 4) appear to be dominantly Solonetzic as well. At the north end of the study site (BR93) the soils are predominantly orthic and eluviated Chernozemic with essentially no evidence of indigenous (natural) salinity. The area between these transects reflects a degree of variability. Along transect BR95 the soils are dominantly orthic with no evidence of salinity. Along transect 94 there is some evidence of salinity. The area adjacent to the ditch along Highway 855 appears to be just slightly lower in elevation relative to the rest of the field, and more poorly drained and carbonated soils are present parallel to the ditch in the vicinity of BR94. Sites 97, 98, and 99 indicate that saline or Solonetzic soils are not predominant and do not represent a major concern in that portion of the field.

4.1.1 Soil Core Data

Figure 23 shows the vertical profiles of EC, SO_4^{2-}, and SAR in soil cores along transect 93. The soil EC levels are generally less than 1 dS/m, and show little change with depth. The only vertical trend along this transect is a tendency for EC to decrease slightly with depth, as shown in cores 93-1 and 93-3 (Figure 23).

Sulfate profiles along transect 93 are variable both in the magnitude of sulfate levels, and in the pattern of the vertical distribution of sulfate (Figure 23). In core 93-1, sulfate concentrations are highest (approximately 400 mg/L) at shallow depths (less than 0.4 m) and decrease with greater depth. In core 93-2, sulfate concentrations are higher than the other two cores along transect 93, with values ranging from 100 to 500 mg/L. Although

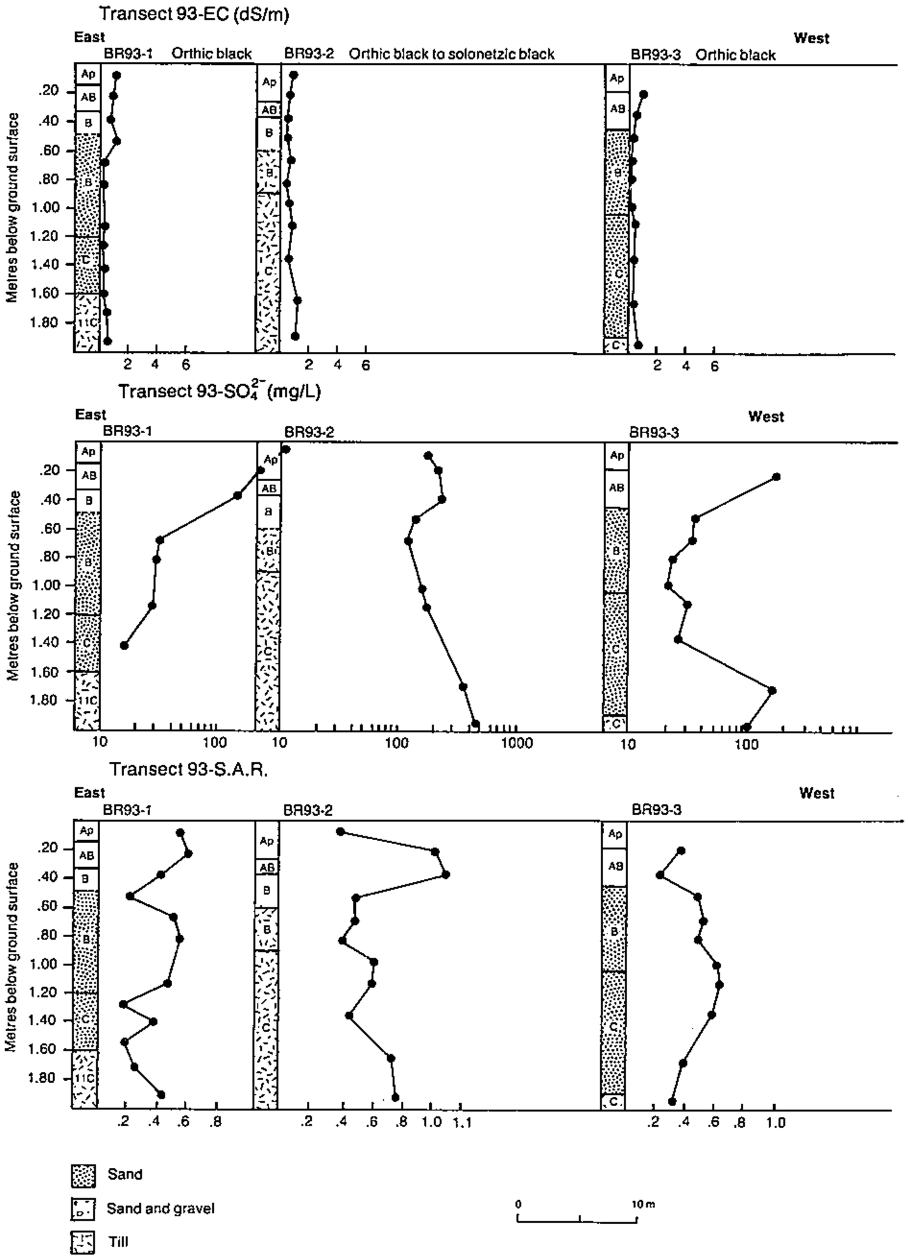

Figure 23. Vertical profiles of electrical conductance, sulfate, and sodium adsorption ratio in soil extracts, transect 93.

there is an overall tendency for sulfate concentration to increase with depth in this core there is a bulge in the vertical sulfate profile at 0.2 to 0.5 m depth that may be associated with a salt accumulation process, for example, evapotranspiration. Core 93-2 also differs from the other cores along transect 93 in that no sand was encountered in the upper 2 m of material, compared to 1.1 m and 1.4 m of sand in cores 93-1 and 93-3, respectively. Lower sulfate concentrations in core 93-3 tend to parallel the sand distribution; highest sulfate levels (over 100 mg/L) are present in the topsoil above the sand, and in the till below the sand, whereas within the sand horizon sulfate concentrations are typically less than 30 mg/L. This general pattern also applies to the vertical sulfate profile in core 93-1, although analysis of samples from below the sand horizon are not available.

SAR values along transect 93 are in all cases extremely low, with the maximum SAR approximately 1.0 (Figure 23). In general, the SAR levels along this transect are an order of magnitude lower than those found in other parts of study area.

Transect 94 was located approximately 900 m south of transect 93, and included an area in which salt accumulation was observed on the soil surface during the spring of 1984. Cores 94-1 and 94-2 were situated within the area of observed salt accumulation. Cores 94-3 and 94-4 were located in an area with no visible salt accumulation, west of the observed salt fringe. Figure 24 shows the vertical profiles of EC, SO_4^{2-}, and SAR for transect 94. Surprisingly, extracts of the two cores from within the salt fringe showed lower EC levels than those in the 'nonaffected' area (Figure 24). EC values in the Ap horizon at 94-1 and 94-2 (visibly affected) were 2 to 4 dS/m, whereas cores 94-3 and 94-4 (not visibly affected) had Ap horizon EC levels of approximately 3 to 8 dS/m. In contrast to the topsoil salinities, the EC levels in the till parent material are highest in the easternmost core (94-1), with values of 6 to 8 dS/m. Cores 94-2 and 94-3 showed intermediate salinity levels,

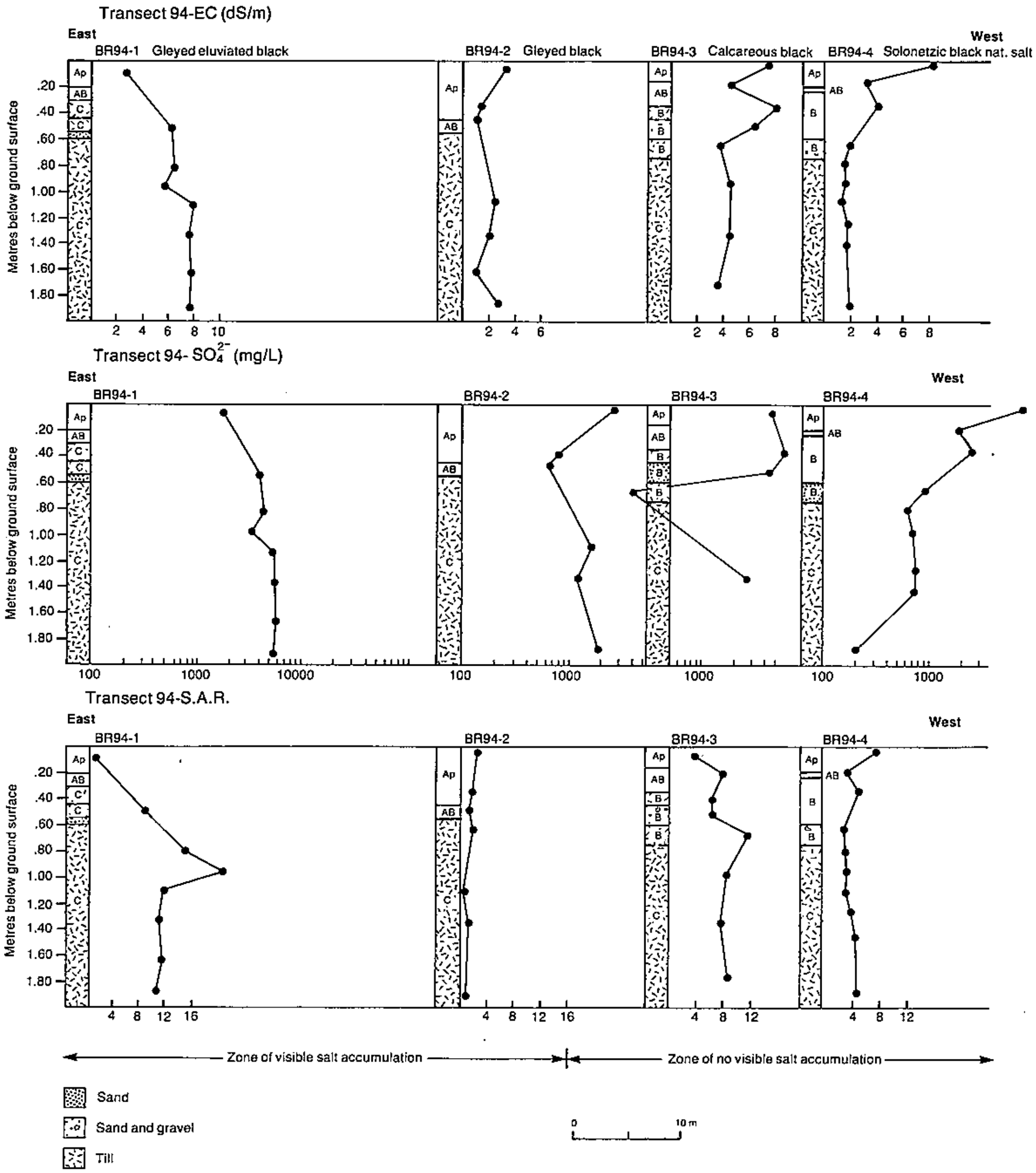

Figure 24. Vertical profiles of electrical conductance, sulfate, and sodium adsorption ratio in soil extracts, transect 94.

at 2 to 3 dS/m and 3 to 4 dS/m, respectively. The till at core 94-4 was the least saline material along the transect, at 1 to 2 dS/m.

The vertical distribution of sulfate concentration along transect 94 essentially parallels the EC distribution. Highest sulfate concentrations (3000 to 6000 mg/L) occurred at depths below 1.0 m in core 94-1 and at shallow depths (less than 0.6 m) in cores 94-3 and 94-4 (Figure 24). The lowest sulfate levels detected along this transect were approximately 200 mg/L.

SAR levels along transect 94 are generally low to moderate (less than 8; Figure 24). In three of the four cores (94-1 excepted) there was relatively little vertical variability in SAR values. In core 94-1 very low SAR levels (less than 1) were found in the topsoil, with high SAR values of 11 to 18 at depths greater than 0.8 m.

Coreholes along transect 95 were laid out in an analogous fashion to those along transect 94. That is, cores 95-1 and 95-2 were located within the fringe of visible salt accumulation, and cores 95-3 and 95-4 were in an area of no visible salt. Figure 25 shows the EC, SO_4^{2-}, and SAR profiles for transect 95. The two cores located within the salt fringe had very different profile characteristics (Figure 25). In core 95-1, EC, SO_4^{2-}, and SAR profiles all showed a bulge in the range of 0.5 to 0.9 m (B and C horizons), with significantly lower levels in the topsoil (Ap and Ab horizons). These parameters all showed a general decreasing trend in the till below 0.9 m depth, suggesting that accumulation of salts is occurring in the 0.5 to 0.9 m zone. In core 95-2, the overall trend in EC, SO_4^{2-}, and SAR levels was increasing with depth. The values of all parameters were low in the upper 0.6 m, but SO_4^{2-}, and SAR increased sharply at greater depths. SAR and SO_4^{2-} levels were high even in the sand layer at 1.5 to 2.0 m depth; this pattern may represent an upward-moving salinity front.

Cores 95-3 and 95-4 had vertical profiles similar to 95-1; that is, most parameters showed a bulge at relatively shallow depth. In core 95-3, EC, and SO_4^{2-} levels were highest in the 0.5 to 0.9 m

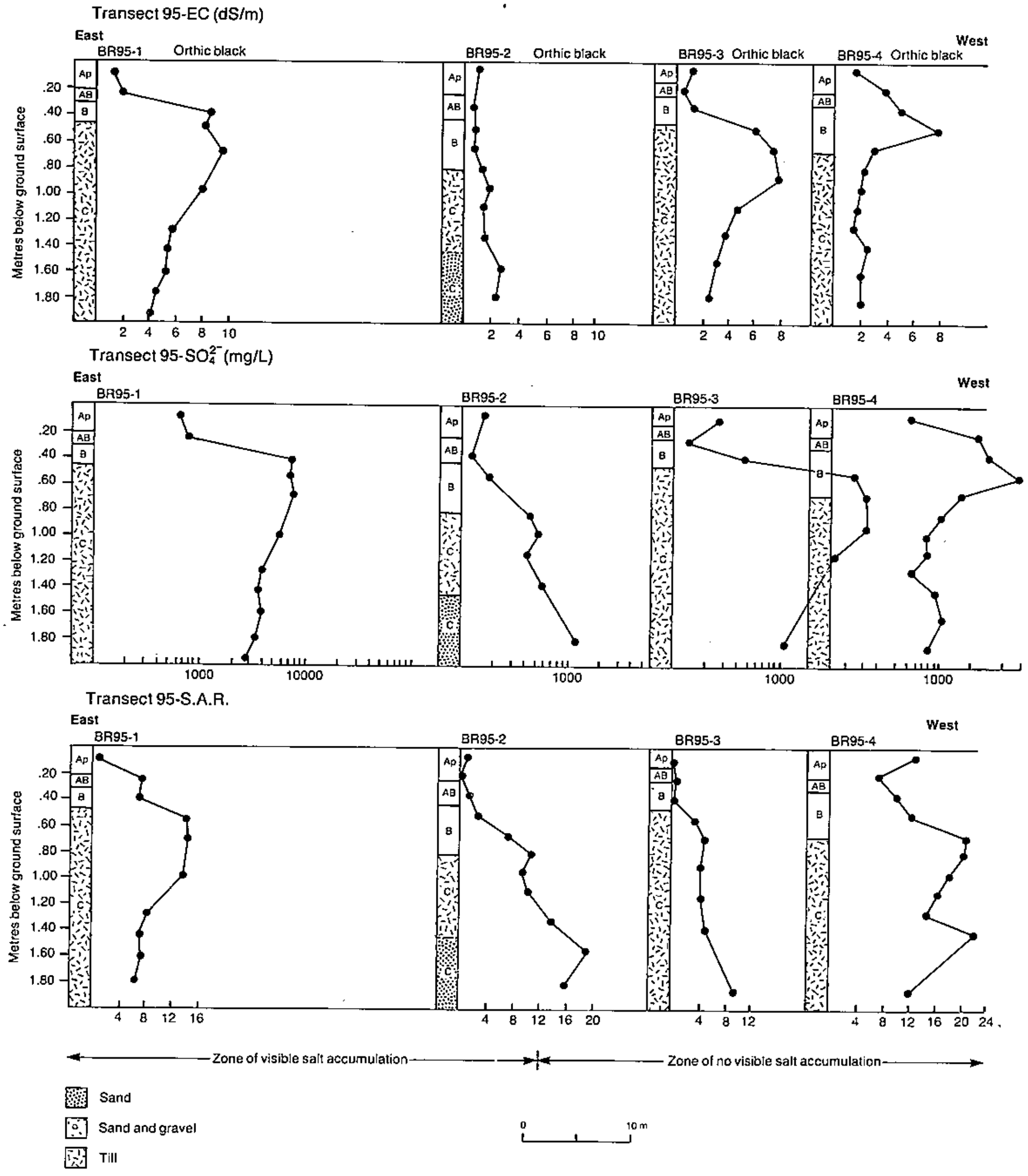

Figure 25. Vertical profiles of electrical conductance, sulfate, and sodium adsorption ratio in soil extracts, transect 95.

zone, and SAR showed a local maximum also in this zone, although SAR values peaked at 1.8 m depth. In core 95-4 maximum EC and SO_4^{2-} levels occurred in the 0.3 to 0.6 m zone. SAR values in this core were erratic but high, with values of 7 to 11 in the A and B horizons (0 to 0.6 m), and 12 to 24 in the lower part of the B horizon and underlying till (0.6 to 2.0 m).

The soil core profiles for transect 96 displayed a broad range of characteristics as shown in Figure 26. At the easternmost site (96-1) the salinity was low (less than 2 dS/m), sulfate was relatively low (less than 700 mg/L) and sodicity was moderate with SAR values in the topsoil less than 6, increasing to 8 in the subsoil and 10 in the till. EC and SO_4^{2-} levels were highest in the topsoil, decreasing with depth, whereas the maximum SAR value was at a depth of 0.95 m with lower values at both greater and shallower depths. In core 96-2 the topsoil salinity was relatively low, at less than 2 dS/m; but the salinity increased with depth through the subsoil and till to levels of approximately 7 dS/m at a depth of 1.5 m. SAR values also increased with depth in this core, from less than 4 in the topsoil to over 12 in the till at 1.4 m depth. Sulfate concentrations increased sharply with depth in this core to levels of more than 6000 mg/L at 1.4 m. Core 96-3 is characterized by very high levels of all parameters. EC values in the topsoil and in the till below 1.3 m depth are approximately 12 dS/m, the highest levels detected in this study. In the topsoil and till from 0.2 to 1.2 m depths, EC values were approximately 6 dS/m. The vertical distribution of sulfate followed a pattern identical to that for EC, with the topsoil and deeper till showing very high concentrations of approximately 8000 mg/L, and the shallow till and subsoil at somewhat lower concentrations of approximately 3000 mg/L. The SAR distribution for this core is essentially a mirror image of the EC and SO_4^{2-} profiles. High SAR values (40 to 42) correspond to the subsoil and shallow till, from 0.3 to 1.0 m; the deeper till (below 1.3 m) is somewhat less sodic, with SAR values of 30 to 33. In this

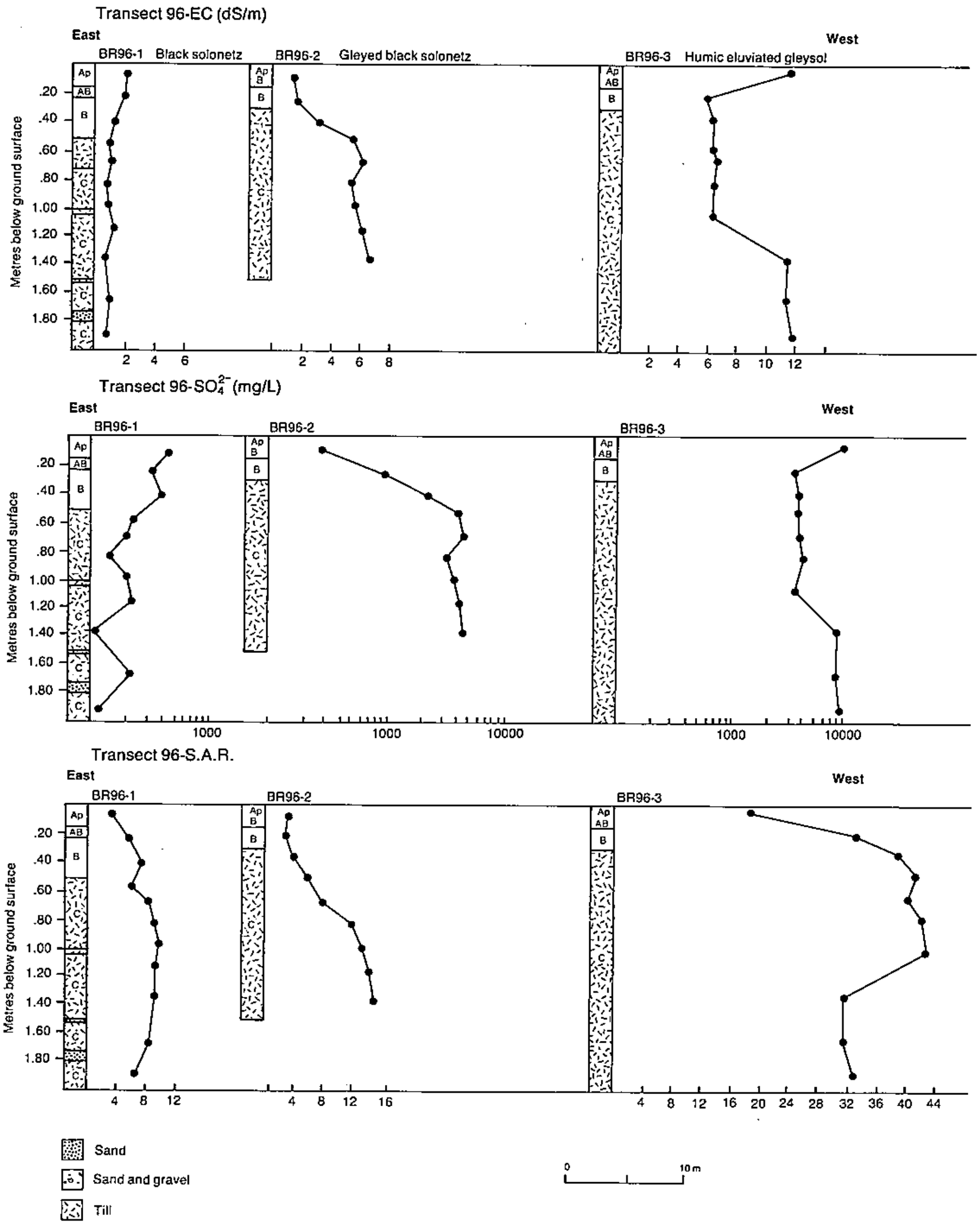

Figure 26. Vertical profiles of electrical conductance, sulfate, and sodium adsorption ratio in soil extracts, transect 96.

core, the lowest SAR values (approximately 18) are found in the topsoil layer (A horizon).

At sites 97, 98, and 99 (through the centre of section 23) natural soil conditions tend to be Solonetzic in nature. At site 97 the soil is a Solonetzic black, with salts observed at about 65 cm depth. At site 98, the soil is a Solonetzic black to eluviated black. No salts were evident down to 110 cm, however the B horizon had a fairly tough structure. The soils at site 99 are eluviated to orthic black, and show no evidence of salinity.

4.1.2 Interpretation of Soil Core Data

As described above, the soils at the north end of the study area, along transect BR93, are predominantly orthic and eluviated Chernozemic with no visual evidence of natural salinity. The soil core data from this transect further confirm this conclusion, there is no indication that salt is accumulating in this part of the study area. This conclusion is consistent with the original observations that no salt was visible in this part of the field.

At sites 94-1 and 94-2 the soil is imperfectly drained, and along with site 94-3 the soil is carbonated nearly to or to the surface. Site 94-4 is the only one of the four along this transect that has visible salts or structure leaning to that of Solonetzic or "Solonetz-like" soils. The change in elevation between sites 1 and 4 of this transect is about 30 cm. With the exception of site 94-4, which is Solonetzic in nature, the occurrence of carbonates and other salt at sites 94-1, 2, and 3 appears to be related to modern, anthropogenic processes. The poorly-drained conditions, together with evidence of salts at or near the surface, is consistent with the observed elevated water table and migration of spoil groundwater from Vesta Mine.

The soils along transect 95 are predominantly orthic blacks developed on till. Surface or Ap horizons are relatively thick and depth to $CaCO_3$ ranges from 30 to 70 cm. Nothing was observed along this transect to suggest that the soils are naturally affected by salinity. Consequently, the accumulations of salts in the B and C horizons at sites 95-1, 3, and 4 appear to be related to modern events. Again, the occurrence of elevated water-table conditions associated with reclaimed areas at Vesta Mine is consistent with the observed accumulations of salts along this transect.

Soil core analyses of samples from transect 96 at the southern edge of the study area are consistent with observations of surface salinity and profile characteristics. All the soils are Solonetzic and eluviated gleysols that are naturally saline. There is no indication that there is any secondary salinity related to the elevated water table that results from the plume of spoil groundwater along this transect.

Several conclusions can be drawn from these profiles. First, there appears to be no relationship between the observation of salt crusts on the soil surface and the overall salinity of the topsoil. In both transects across the observed salt fringe, the highest topsoil salinities were found in the cores located where no surface salt was observed. Second, the distribution of salts in the subsurface is highly variable, even over relatively short horizontal distances (e.g., 15 m) along one transect. The reason for this variability is uncertain, particularly in the deeper (1 to 2 m) parent material, which would be expected to display some degree of uniformity. The soils are naturally variable, as evidenced by transects 94 and 96, however at least some of the observed salt accumulations in the soil profiles along transects 94 and 95 are consistent with the observed elevated water-table conditions and migration of spoil groundwater from Vesta Mine.

4.2 SOIL SALINITY MAPPING

To augment the soil sampling program, electromagnetic induction (EM) profiling of the eastern 400 m of Sec 23, Tp 40, R 16, W 4 and the northeastern part of Sec 14, Tp 40, R 16, W 4 was conducted using two instruments, the Geonics EM38 and the EM31, each in vertical and horizontal orientations, for a total of four sets of readings. Measurements were taken on a 100 m grid, extending from Highway 855 (the eastern boundary of the above sections) approximately 400 m to the west. Three of the four sets of EM readings were calibrated against soil salinities measured from extracts of cores taken along the four sampling transects (93 to 96).

Each combination of instrument and orientation corresponds to a different depth of penetration. Consequently, the four maps produced from this work represent the apparent bulk EC of the subsurface materials over the following approximate depth ranges: 0 to 0.6 m (EM38 horizontal), 0 to 1.2 m (EM38 vertical), 0 to 3 m (EM31 horizontal), and 0 to 6 m (EM31 vertical). The soil core samples used for calibration of the EM instrument readings were from 0 to 2 m. As a result, correlation of the EM38, which had a depth of penetration of less than 2 m is considered to be excellent. The 2 m cores provided a good approximate calibration for the EM31 in a horizontal configuration (3 m depth of penetration) since the greatest influence on the instrument readings is from the upper 1 to 2 m. Because the 6 m depth of penetration of the vertically oriented EM31 far exceeded the 2 m depth range of the soil core samples, calibration of this set of measurements was not possible and the interpretation of EC is only approximate. The sequence of maps in Figure 27 represents increasing thickness of material measured, from 60 cm to 6 m.

The EM data show several areas where the profile is saline, that is, the conductivity is in excess of 4 dS/m (Figure 27). The first of these is an irregularly shaped area in the SE1/4 of the NE1/4 (LSD 9) of section 23 that is appreciably larger in the 1.2 and 3 m readings than in the 0.6 m reading (Figure 27). This area of high salinity overlies the maximum thickness of the intertill sand (Figure 9) and is also the area of highest salinity within the plume in the sand (Figures 16 and 17). The increase in size of this area of salinity with depth suggests that much of the salinity is associated with the brackish water in the sand and does not reflect

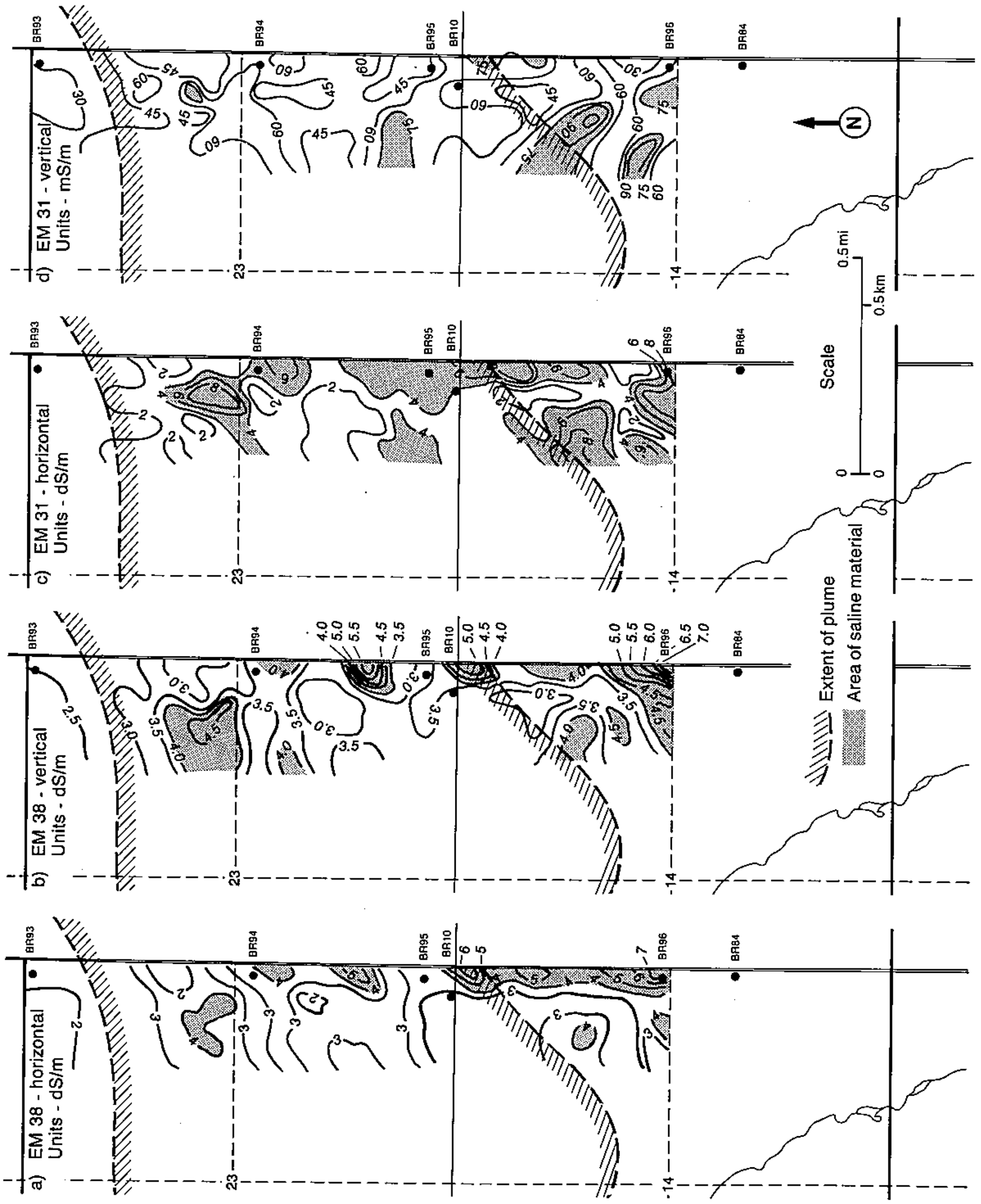

Figure 27. Map showing distribution of soil salinity as identified by EM38 and EM31 mapping, (a) 0.0 to 0.6 m, (b) 0.0 to 1.2 m, (c) 0.0 to 3.0 m, and (d) 0.0 to 6.0 m.

soil salinity. Whether the near-surface saline patch will increase in size or severity over time is not known.

The second area of salinity is along Highway 855 just south of site BR94 in the NE1/4 of the SE1/4 (LSD 8) of section 23 (Figure 27). This area of salinity, which is one of the sites where white saline crusts were observed on the surface during 1984, also overlies an area of thick intertill sand, which appears to be connected to the spoil to the east (Figure 9).

The third area of salinity is located along Highway 855 in the SE1/4 of the SE1/4 (LSD 1) of section 23 between sites BR94 and 95 (Figure 27). This site, which is also a site where white saline crusts were observed on the surface during 1984, is immediately west of the area in the spoil that has the highest hydraulic head, and, therefore, presumably produces a strong component of lateral flow out of the spoil in the intertill sand (Figure 11).

The fourth area of salinity is an irregular series of patches that borders Highway 855 and extends along the entire eastern edge of the NE1/4 of section 14 (Figure 27). At the 1.2, 3.0, and 6.0 m depths, the area of salinity expands westward. This area of salinity is believed to reflect naturally saline, thin till overlying bedrock rather than salinity induced by the plume of spoil-derived groundwater. The total thickness of drift and thickness of the intertill sand are both at a minimum in this area (Figures 3 and 9). Salinity profiles along transect BR96 (Figure 26) show high levels of salinity that, as was discussed above, appear to be of historical rather than of recent origin.

5. DISCUSSION

As shown in the preceding sections, chemical and isotopic composition of groundwater in both the drift and the Battle River Bed west of Vesta Mine strongly suggest the presence of plumes of brackish water migrating outward from mine spoil at Vesta Mine. This interpretation is further supported by calculations of flow rates in the drift plume.

Much of the portion of the Vesta Mine indicated as the source of the spoil groundwater plume was mined during the period from 1965 to 1975 (Figure 28). Consequently, the oldest portion of the plume could conceivably be as much as 15 years old (given approximately two to five years for the spoil to resaturate). The presence of numerous deep ponds in this area of the mine combined with the height of the spoil terrain above the adjacent unmined area is likely responsible for relatively rapid resaturation of the 1965-75 spoil, as well as for relatively high hydraulic heads in the reclaimed landscape. This could account for the rapid initial flushing of the spoil that gave rise to the very high salinity plume that presently occupies the drift adjacent to Slough Creek.

In order for the interpretation that the low quality water is a plume of spoil water to be realistic, it should be shown that it is feasible for groundwater to move from the Vesta Mine spoil to the present location of the centroid of the plume near Slough Creek in the period of time since mining occurred.

If the centroid of the plume corresponds approximately to an area near site BR87, then the plume has migrated a distance of approximately 1200 m. The horizontal hydraulic gradient (i) between site BR80 in the spoil at Vesta Mine and site BR87 is approximately 0.004. The mean hydraulic conductivity (K) of the sheet sand, based on single-well response tests of four piezometers, is 3.5×10^{-6} m/s. Given these conditions, and assuming an effective porosity (n) of the sand of 0.10, then, according to Darcy's Law, which can be expressed as $v = Ki/n$, the calculated velocity (v) of the groundwater in the plume is 4.4 m/a. At this velocity, it would take the plume

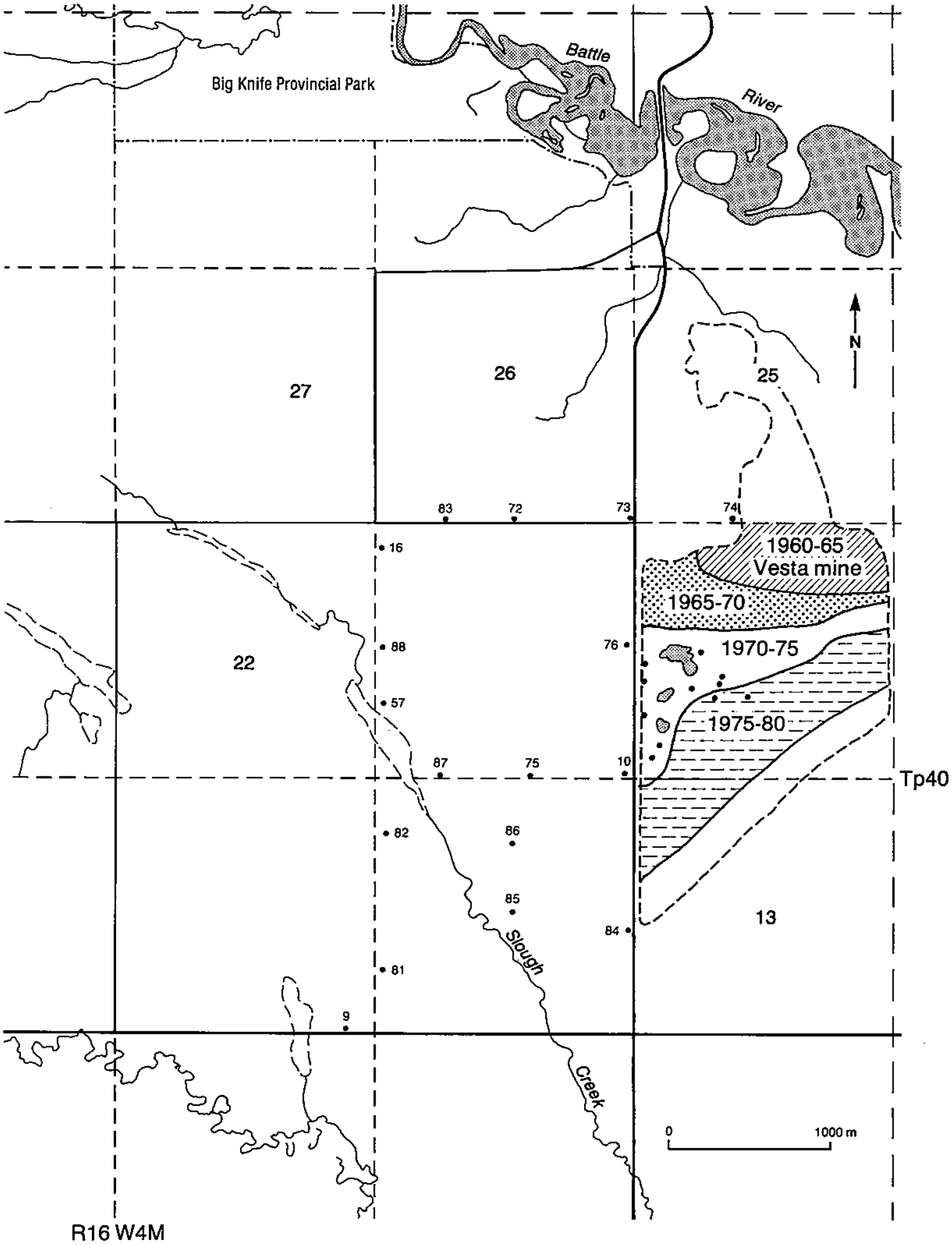

Figure 28. Mining progress at Vesta Mine, 1960 to 1980.

271 years to travel the observed distance (1200 m). However, if the velocity is calculated using the maximum K value from the four single-well response tests ($K_{max} = 3.5 \times 10^{-5}$ m/s) the calculated velocity is 44.2 m/a, and the plume would migrate the observed distance in approximately 27 years. Although this is approximately twice the actual time available for migration, if movement is taking place preferentially within the most permeable zones of the sheet-like sand, it is possible that the observed migration could have taken place in approximately 10 to 15 years. In addition, if resaturation of the spoil at Vesta Mine occurred over a relatively short period of time (i.e., a few years), then the initial hydraulic gradient between the spoil and the unmined drift might have been significantly higher than the present day, presumably steady-state, gradient. This mechanism also might be at least partly responsible for the difference between the observed and calculated groundwater velocity.

One of the obvious implications of the presence of plumes of water with degraded chemical quality in aquifers adjacent to mined areas is deterioration of water supply potential. In the area west of Vesta Mine such loss of groundwater resource is not a significant factor because of the thinness and shallowness of the drift sand, which render its water supply potential low. In addition, there are no wells in the area of the plume in the Battle River Bed. In other places, such plumes might have a significant negative effect on a local scale.

A less obvious, but potentially more significant consequence of the presence of plumes of degraded water in unmined aquifers adjacent to reclaimed areas, is soil salinization. Two areas are potential sites for such salt accumulation. The first is immediately adjacent to the mine where the water table is close to the surface (Figure 29). The second is where the permeable bed crops out and the plume groundwater is discharged to the surface (Figure 29).

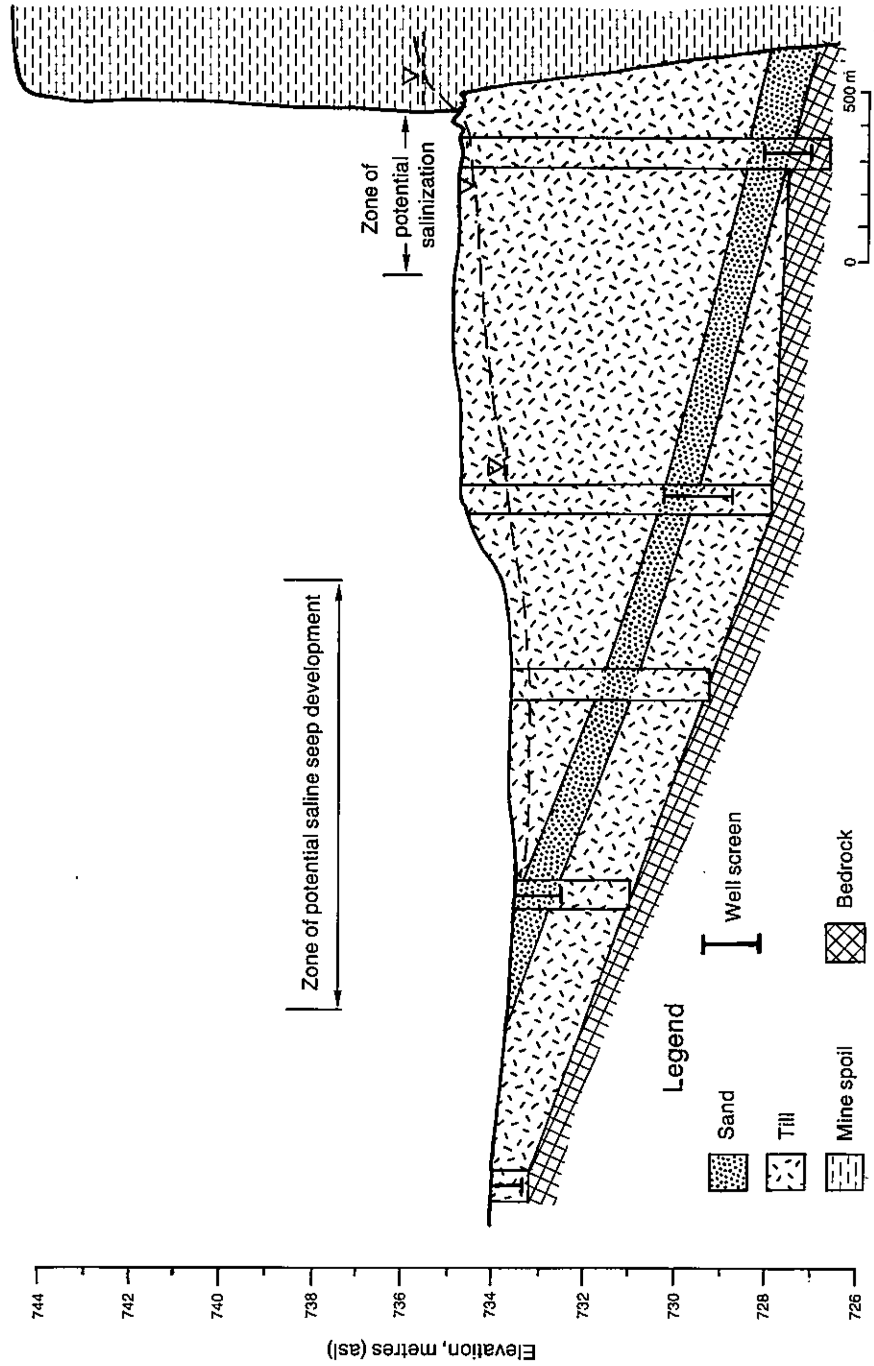

Figure 29. Hypothetical cross section showing potential zones of soil salinization.

The mechanism of salinization in the area adjacent to Vesta Mine appears to be the upward capillary transport of salt and water from the shallow water table accompanied by evaporation of the water. The salt in the groundwater of the plume itself may be less important than salts dissolved from the subsoil by upward migrating water. Surface salinity and vegetation stress indicative of incipient salinization has been observed in the field immediately west of Vesta Mine. Furthermore, the apparently recent buildup of salts in the naturally nonsaline orthic black soils west of Vesta Mine may be due to shallow water-table conditions produced by the high water table in reclaimed lands at Vesta Mine. The depth to water table in most of the study area is generally between 1.5 and 2.0 m, as shown in Figure 30, however the water table is less than 1 m deep in the area immediately west of Vesta Mine where salt accumulations have been observed.

The second type of salinity does not appear to be a problem west of Vesta Mine because of the stratigraphy of the site. Rather than discharging to the surface as is required to produce salinization, the salty water of the plume enters a thick, permeable fill of sand that lies beneath Slough Creek (Figures 5, 6, and 8) and is transmitted as groundwater to the southeast. Where the stratigraphy of a site is less favourable, as is shown in the hypothetical cross section of Figure 29, the salty water of the plume could be discharged at the surface to generate saline seeps.

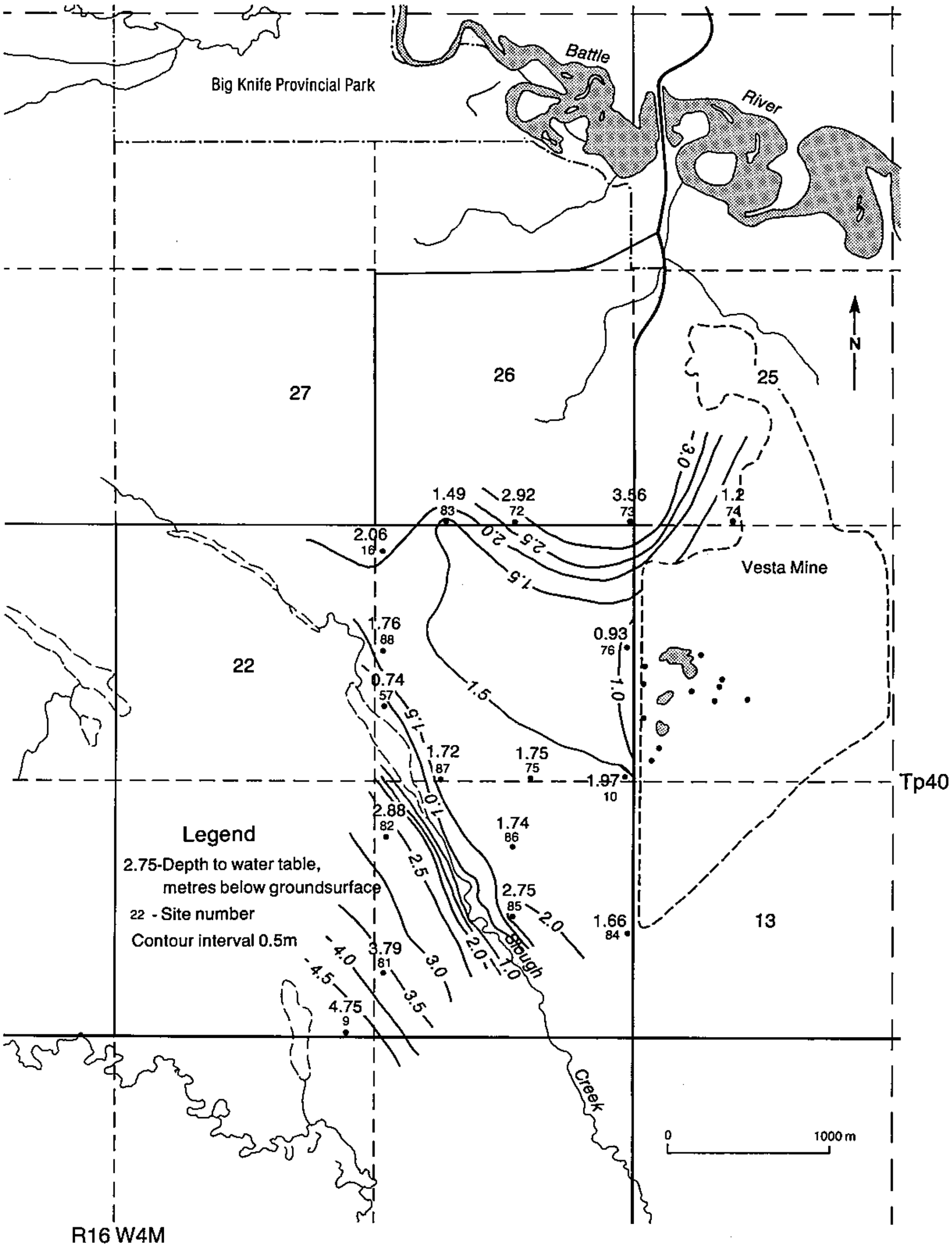

Figure 30. Map showing the depth to water table in the study area.

6. CONCLUSIONS

Spoil groundwater from Vesta Mine is migrating to the west and southwest into unmined drift and coal aquifers. In the Battle River Bed adjacent to Vesta Mine, spoil-derived groundwater has been detected at two sites, indicating that a plume is migrating to the southwest from the mine. The direction of migration is controlled by the anisotropy of horizontal hydraulic conductivity associated with the orientation of fractures in the coal seam. The southwesterly direction of migration for the plume is opposite to the natural (premining) flow direction in the coal, but is related to the cone of depression around the mine pit. In the drift west of Vesta Mine a plume of high salinity sodium-calcium-sulfate water has migrated through a permeable sheet-like sand body as far as 1.7 km, to a discharge area along Slough Creek. The TDS concentrations in this plume are as high as 14 000 to 15 000 mg/L, representing an initial flushing of saline groundwater from the spoil. The velocity of groundwater required to accommodate this rate of migration indicates that flow is occurring mainly through high permeability lenses within the sand body. Salinity levels as high as 6 to 8 dS/m in soils that are naturally nonsaline appear to be related to the elevated water-table conditions associated with the migration of spoil groundwater from Vesta Mine.

In both cases, high hydraulic heads in the spoil at Vesta Mine are related to topographically elevated areas in the reclaimed landscape, and in the case of the Battle River Bed plume, to high heads at the base of the spoil associated with deep ponds in the reclaimed setting.

In general, then, the potential for migration of spoil groundwater into unmined aquifers exists wherever hydraulic head in the spoil is greater than in the surrounding area. Migration of spoil groundwater into bedrock aquifers is most likely to occur where the reclaimed landscape includes deep ponds that recharge the base of the spoil and result in relatively high hydraulic head at depth. The potential for spoil groundwater migration into shallow surficial aquifers will be greatest in settings where the elevation of the reclaimed landscape is significantly higher than the surrounding area, particularly if there are ponds located in topographically high areas of the reclaimed spoil.

The direction of spoil-groundwater migration is influenced not only by the distribution of hydraulic head, but also by the horizontal anisotropy of hydraulic conductivity. In coal aquifers such anisotropy, which is related to fracture orientation, is probably the hydraulic parameter controlling the direction of plume migration. The rate of plume movement appears to be controlled, particularly in unconsolidated sand aquifers, by zones or lenses of higher than average permeability.

7. REFERENCES

Brown, R.M. 1970. Distribution of hydrogen isotope in Canadian waters. Isotope Hydrology 1970. Proceedings of a Symposium. International Atomic Energy Agency. March 9-13, 1970; Vienna, Austria. pp. 3-22.

Egboka, B.C.E., J.A. Cherry, R.N. Farvolden, and E.O. Frind. 1983. Migration of contaminants in groundwater at a landfill: a case study, 3. Tritium as an indicator of dispersion and recharge. Journal of Hydrology 63(1/2). pp. 51-80.

Freeze, A. and J.A. Cherry. 1979. Groundwater. Englewood Cliffs, N.J.: Prentice-Hall Inc. 604 pp.

Maslowski Schutze, A., R. Li, M.M. Fenton, and S.R. Moran. 1986. Geology of the Battle River study site: Plains Hydrology and Reclamation Project. Alberta Land Conservation and Reclamation Council Report #RRTAC 86-4. 70 pp.

Trudell, M.R., R.L. Faught, and S.R. Moran. 1988. Chemistry of groundwater in mine spoil, Central Alberta. In: Trudell, M.R. (compiler). 1988. Plains Hydrology and Reclamation Project: spoil groundwater chemistry and its impacts on surface water. Alberta Land Conservation and Reclamation Council Report #RRTAC 88-2. 135 pp.

Trudell, M.R., R.L. Faught, and S.R. Moran. 1987. Hydrogeology and groundwater chemistry of the Battle River mining area. Alberta Land Conservation and Reclamation Council Report #RRTAC 87-9. 97 pp.

Vogwill, R.I.J. 1976. Hydrogeological investigations of a coal seam near Halkirk, Alberta. Alberta Research Council Report.