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The geohydrology and hydrogeochemistry of the proposed Garrison Lignite Mine

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THE GEOHYDROLOGY AND HYDROGEOCHEMISTRY OF THE PROPOSED GARRISON LIGNITE MINE

by
Kevin Morin

Bachelor of Science, Edinboro State College, 1977

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota

December
1979

This Thesis submitted by Kevin Morin in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

(Chairman)

Walter L Moore

This Thesis meets the standards for appearance and conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

Dean of the Graduate School

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Title The Geohydrology And Hydrogeochemistry Of The Proposed Garrison Lignite Mine

Department Geology

Degree Master of Science

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Date

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This project was funded by the Nokota Company and the North Dakota Geological Survey.

ABSTRACT

A local groundwater study is a necessity before the opening of any lignite mine in North Dakota. The study becomes an important reference for the environmental impact during mining and after reclamation.

This report is a groundwater study of the Proposed Garrison Lignite Mine, McLean County, North Dakota. The mineable lignite is in the lower Sentinel Butte Formation (Paleocene). The remainder of the Paleocene material at the proposed mine site is mostly fluvial silty clay deposits with some sand beds. Pleistocene deposits, mostly pebble loam (till), cover the Sentinel Butte at the mine site.

Ninety piezometers in twenty-eight nests were installed at the Proposed Garrison Lignite Mine. Data from these piezometers show that the direction of groundwater flow in the pebble loam and silty clay is predominately downward into the lignite. Within the lignite, the water flows laterally toward the buried valleys at the west and south borders of the mine site. After flowing a short distance in the lignite, the water passes into the silty clay below the lignite or into Pleistocene sand and gravel above the lignite. The small amount of water that passes into the buried valleys probably remains in the valleys and flows generally toward the south.

Chemical analysis of the groundwater shows that the groundwater in the till is generally high in total dissolved solids with dominant concentrations of sodium, calcium, bicarbonate, and sulfate. By passing through silty clay into lignite, total dissolved solids decrease and there are dominant concentrations of sodium, bicarbonate, and sulfate. As the groundwater flows deeper into the Sentinel Butte Formation, total dissolved solids increase and the dominant ions become sodium and bicarbonate.

The information in this report shows that the physical and chemical groundwater systems at the proposed mine site resemble the groundwater systems at other mines in North Dakota.

Because the direction of groundwater flow is mostly downward, the removal of the lignite will probably have no major effect outside of the mine site. But mining plans must be made carefully so that the buried valleys at the proposed mine site are not dewatered.

I. INTRODUCTION

The Nokota Company and Utah International, Incorporated, plan to open a lignite strip mine near Garrison, North Dakota (Figure 1 and Plate I). The mine site, currently named the "Proposed Garrison Lignite Mine", encompasses about 44 square miles of farmland in Townships 149 and 150 North, Ranges 84 and 85 West.

The geomorphology of the Proposed Garrison Lignite Mine is largely the result of Pleistocene glacial activity and postglacial erosion. In the northeast quarter of the proposed mine site, the surface is hummocky, indicating the presence of dead-ice moraine. Most of the remainder of the surface is low relief sheet moraine (Bluemle, 1971). Two branches of Douglas Creek have cut valleys into the sheet moraine. The Middle Branch of Douglas Creek trends north-south near the western edge of the mine site. The East Branch trends north-south through the center of the mine site.

II. GEOLOGY

A. METHODS

The stratigraphy of the mine site (Figures 2 through 6) is based on 176 test holes drilled during 1977 and 1978 (Plate I). Density, natural gamma, and resistance logs were obtained for most of the test holes. Driller's logs were also made for most of the test holes.

B. STRATIGRAPHY

The Pleistocene deposits that cover most of the mine site consist largely of pebble loam (till), with some sand and gravel.

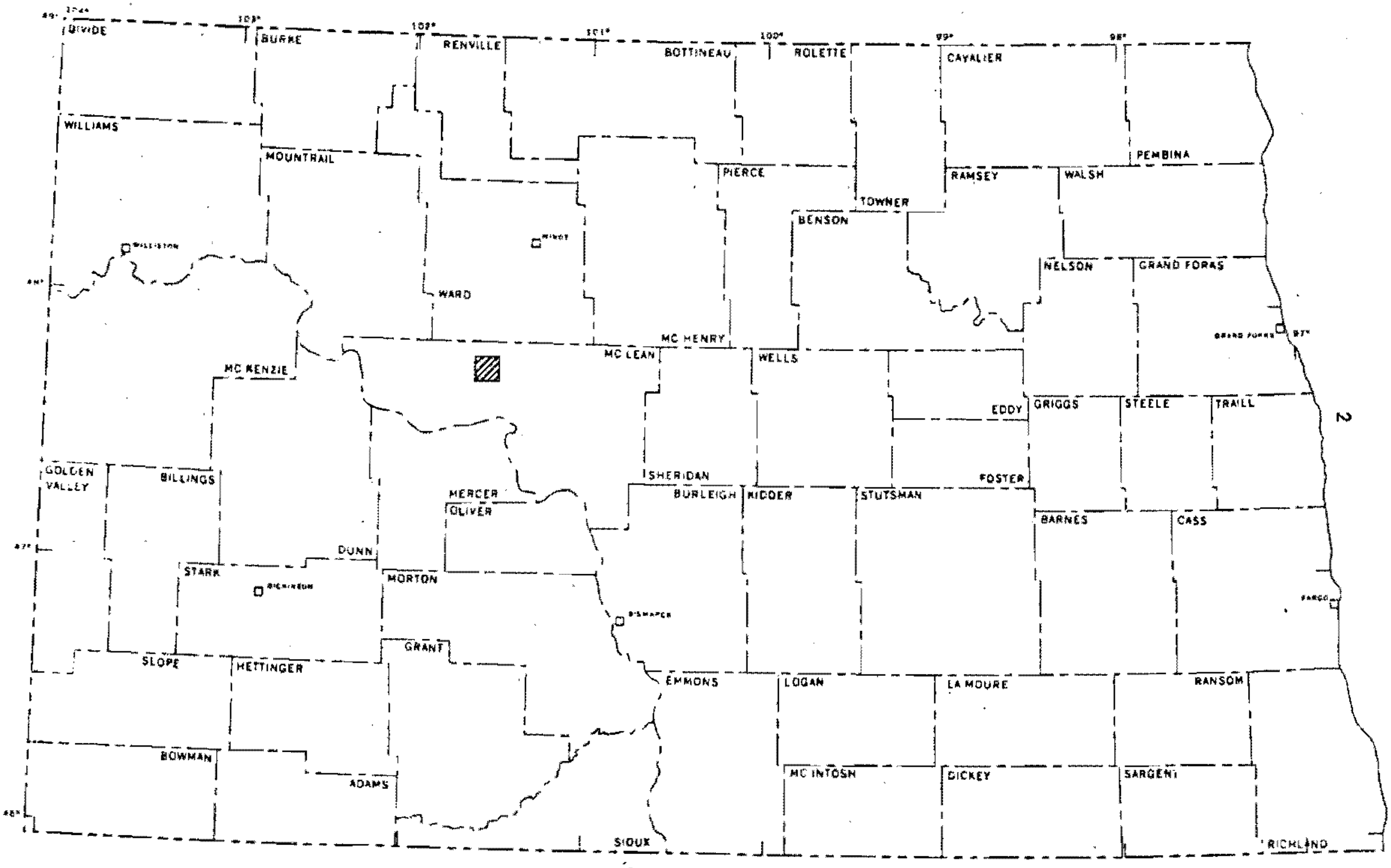


Figure 1. Location of the Proposed Garrison Lignite Mine, McLean County, North Dakota.

The Sentinel Butte Formation (Paleocene) is directly below the Pleistocene deposits. At the mine site, the Sentinel Butte contains mostly silty clay, lignite, and sand.

The contour map of the Pleistocene-Paleocene contact (Figure 2) shows that there has been post-Paleocene preglacial valley cutting. The valleys have been filled in with till (Figure 3), although there are some discontinuous sand and gravel beds in, or directly above, the buried valley bottoms (Figure 6).

The Sentinel Butte lignite at the mine site contains thin clay layers. In the eastern half of the area, the center clay layer in the shallow lignite bed, Seam AB, varies in thickness from 0 to 2 feet. In the western half, the center clay layer thickens from 2 to tens of feet, producing an upper lignite bed, Seam A, and a lower lignite bed, Seam B. The variations in lignite elevation (Figure 4) are possibly the result of differential settlement of deeper deposits. Thicknesses of the lignite seams are shown in Figure 5.

There are two major Sentinel Butte sand beds at the mine site (Figure 6). The first major sand bed is directly below the lignite. This bed is generally less than 10 feet thick and is usually found only in the southern one-third of the mine site. The second major sand bed is about 60 feet below the shallow lignite and is only a few feet thick. This second bed may exist throughout the mine site.

C. PALEOENVIRONMENTS

1. PALEOCENE ENVIRONMENT

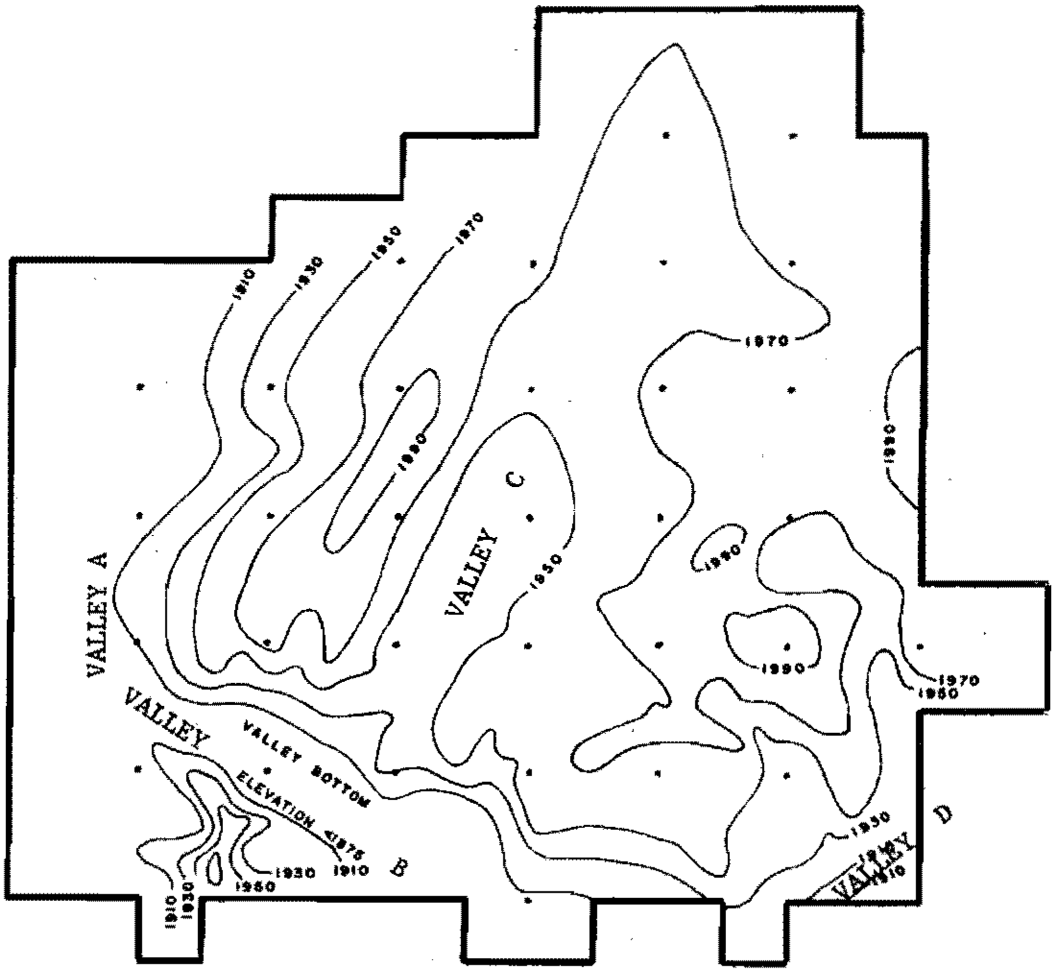


Figure 2. The Pleistocene-Paleocene Contact. Elevations are in feet above sea level. The dots are section corners. Buried valleys are labelled.

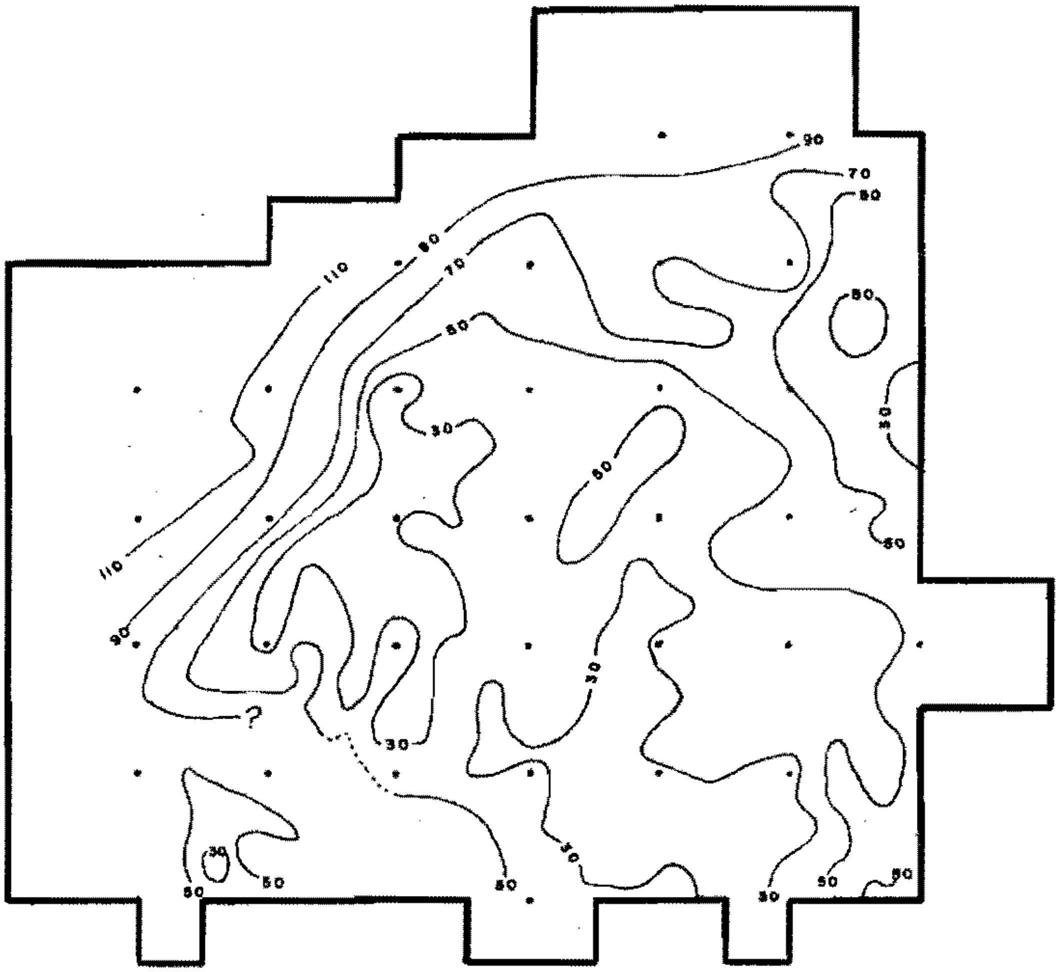
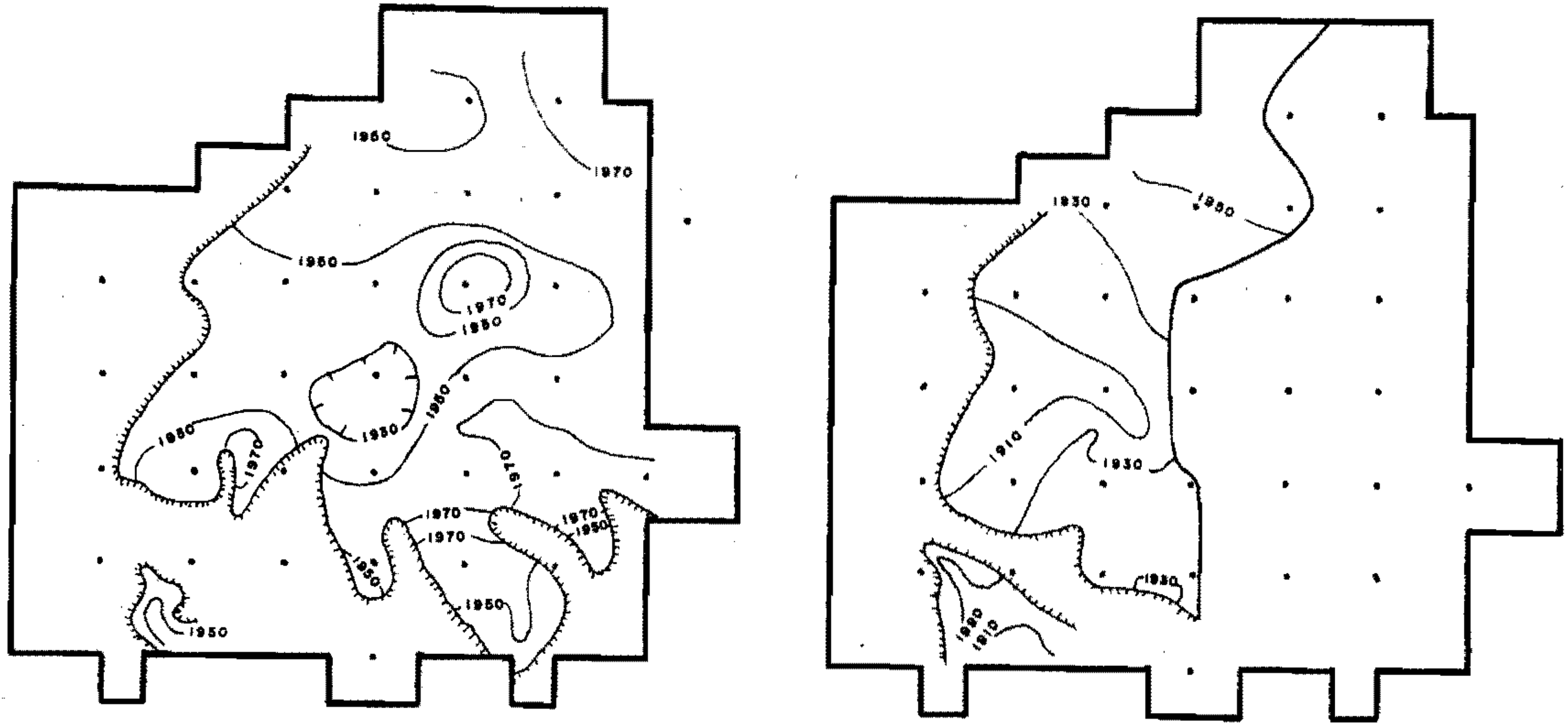


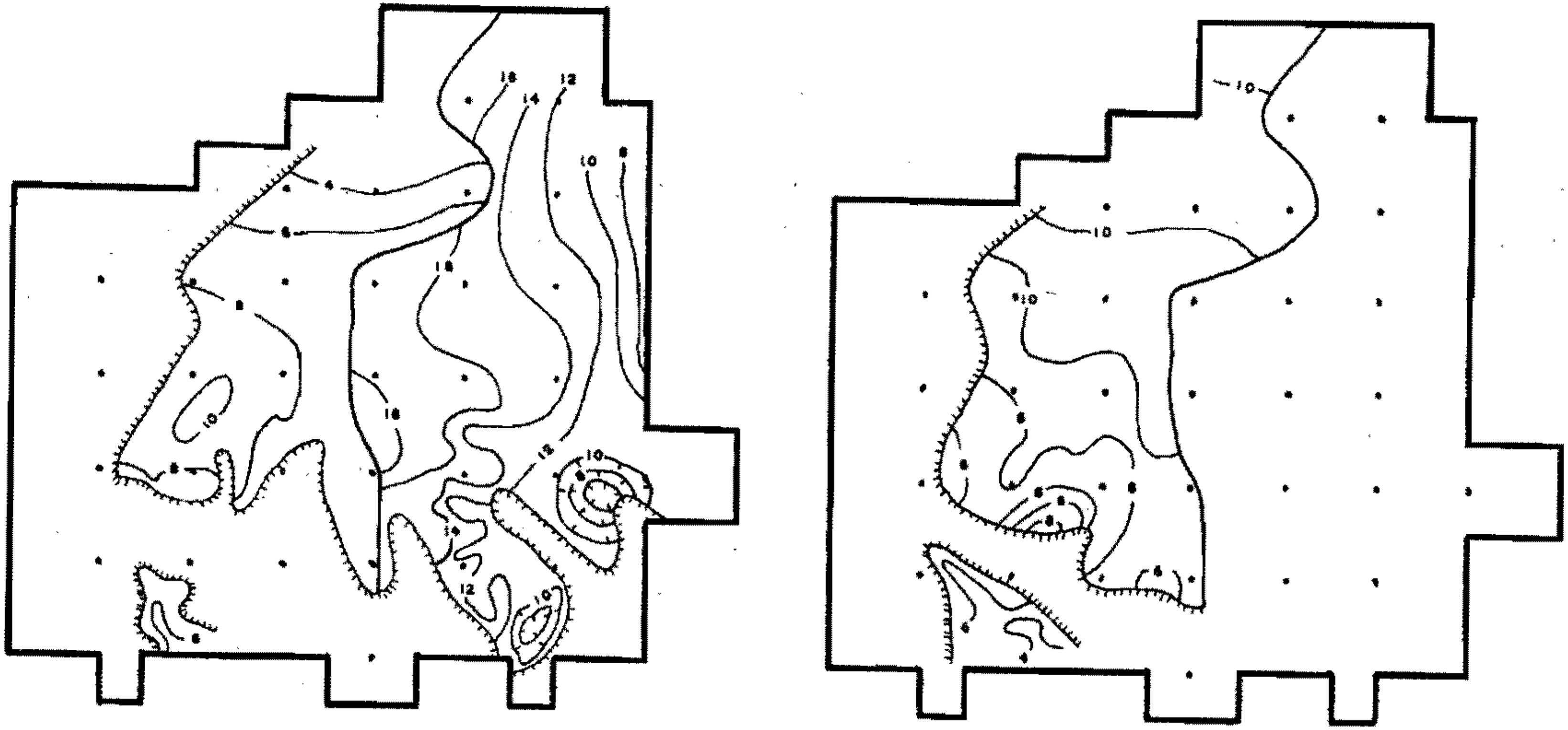
Figure 3. Depth Below Surface of the Pleistocene-Paleocene Contact. Depths are in feet.



4a. Seams AB and A

4b. Seam B

Figure 4. Structure Contour Maps of the Lignite. Elevations are in feet above sea level. The closely spaced hachure lines are the lignite subcrops.



5a. Seams AB and A

5b. Seam B

Figure 5. Lignite Thicknesses. Thicknesses are in feet.

309	Test hole
306 P	Test hole and piezometer nest
←	Dominant direction of groundwater flow in the plane of the cross-section
⌒ -	Pleistocene-Paleocene contact (top of the Sentinel Butte Fm.)
▮	Location of a piezometer screen

Lithologies:

⁘	Gravel	Lithologies above the Pleistocene-Paleocene contact
⁙	Sand	
☒	Pebble loam (till)	
⁙	Sand	Lithologies below the Pleistocene-Paleocene contact
▯	Lignite	
□	Silty clay	

Figure 6a. Legend for the Stratigraphic Cross-sections

Figure 6. Stratigraphic Cross-sections. Numbered cross-sections are oriented East-West. Lettered cross-sections are oriented North-South.

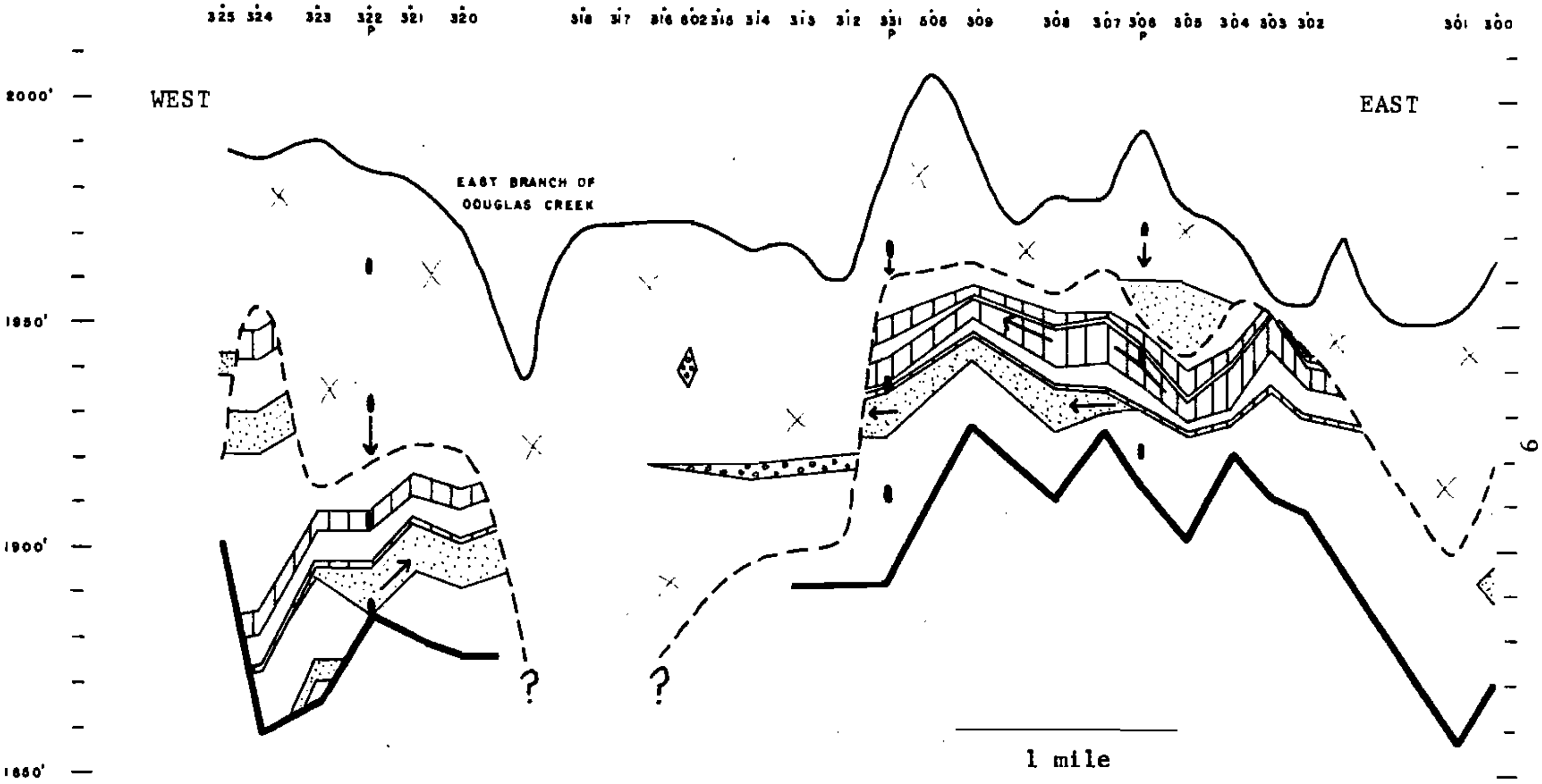


Figure 6b. Cross-section 1.

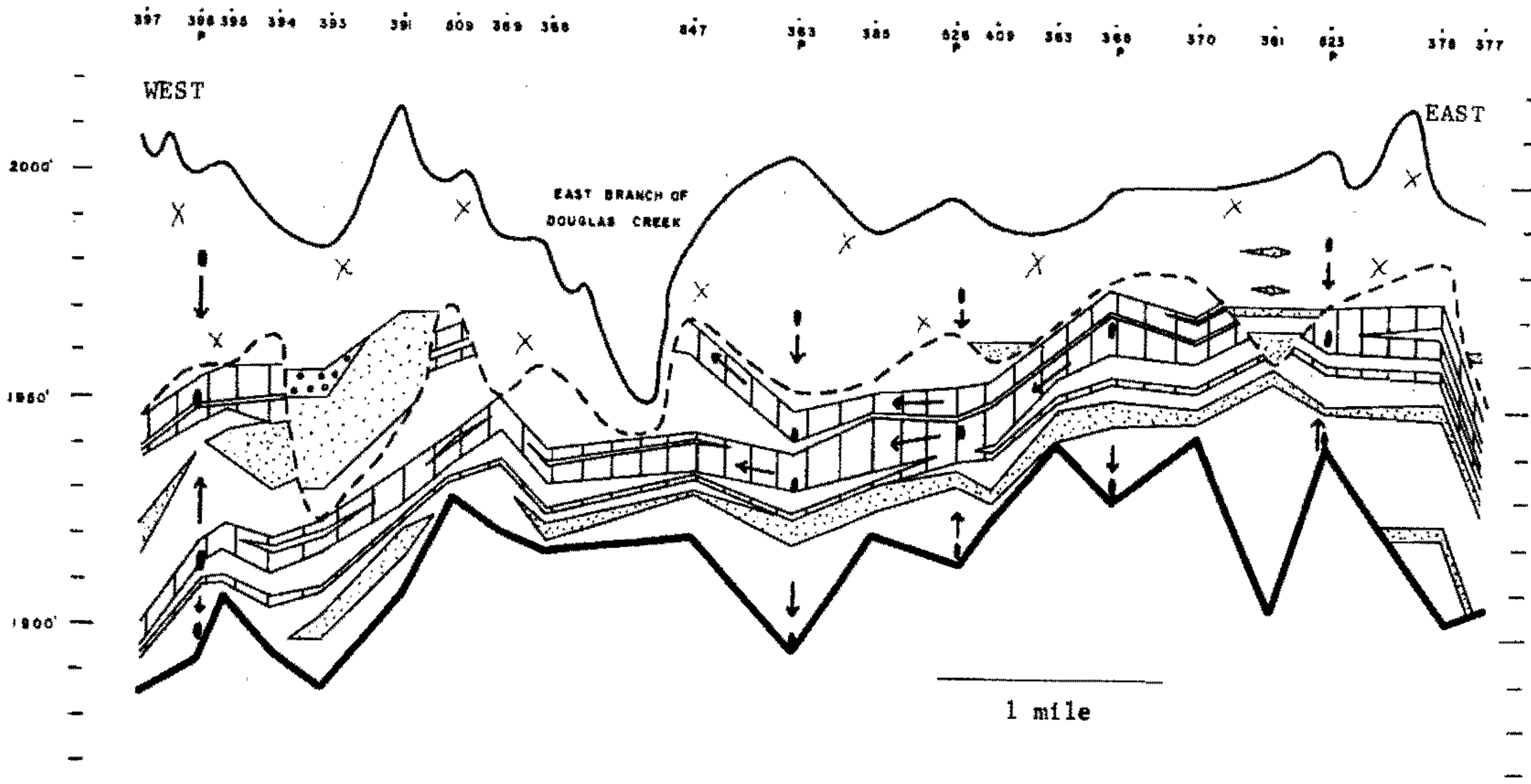


Figure 6c. Cross-section 2.

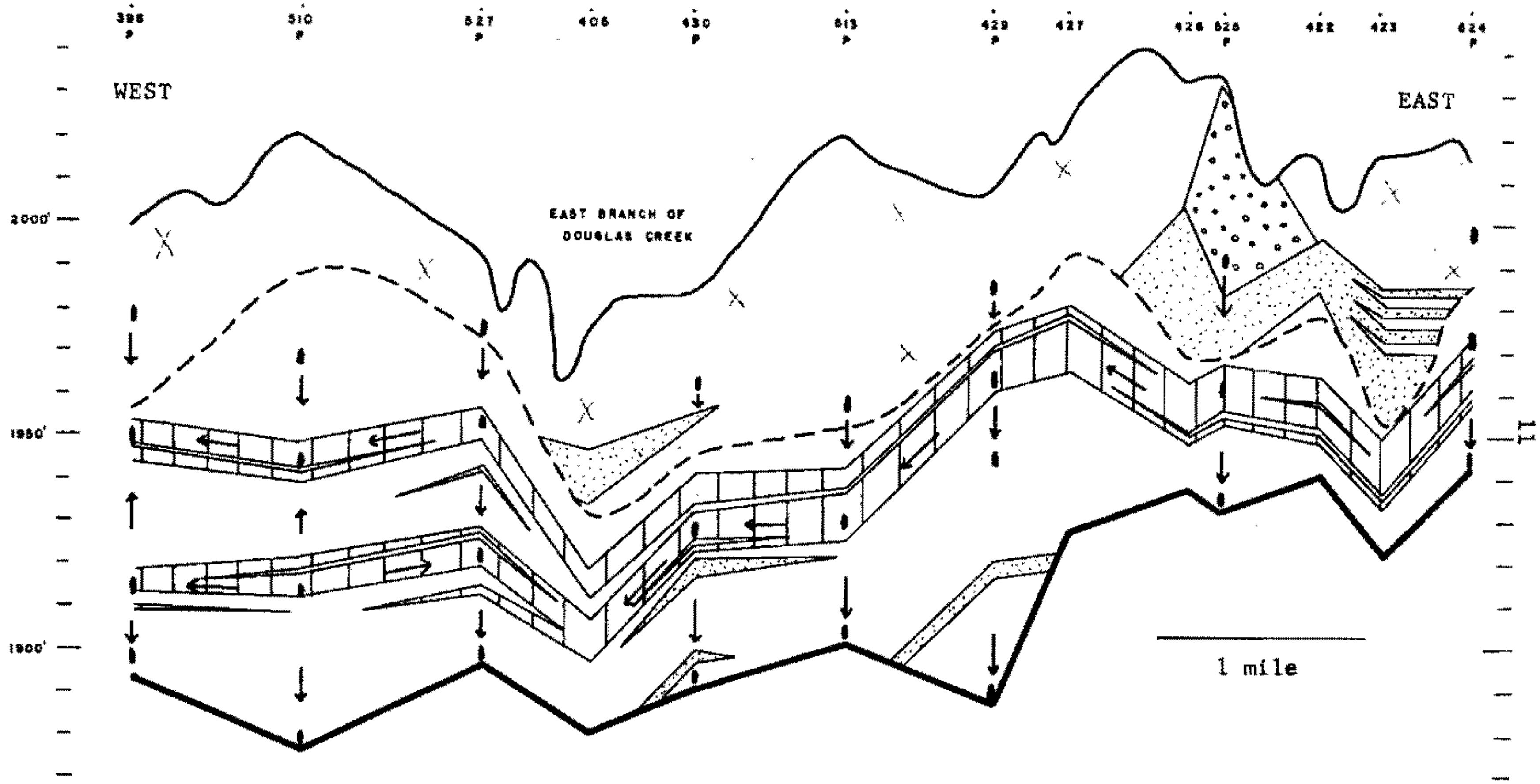


Figure 6d. Cross-section 3.

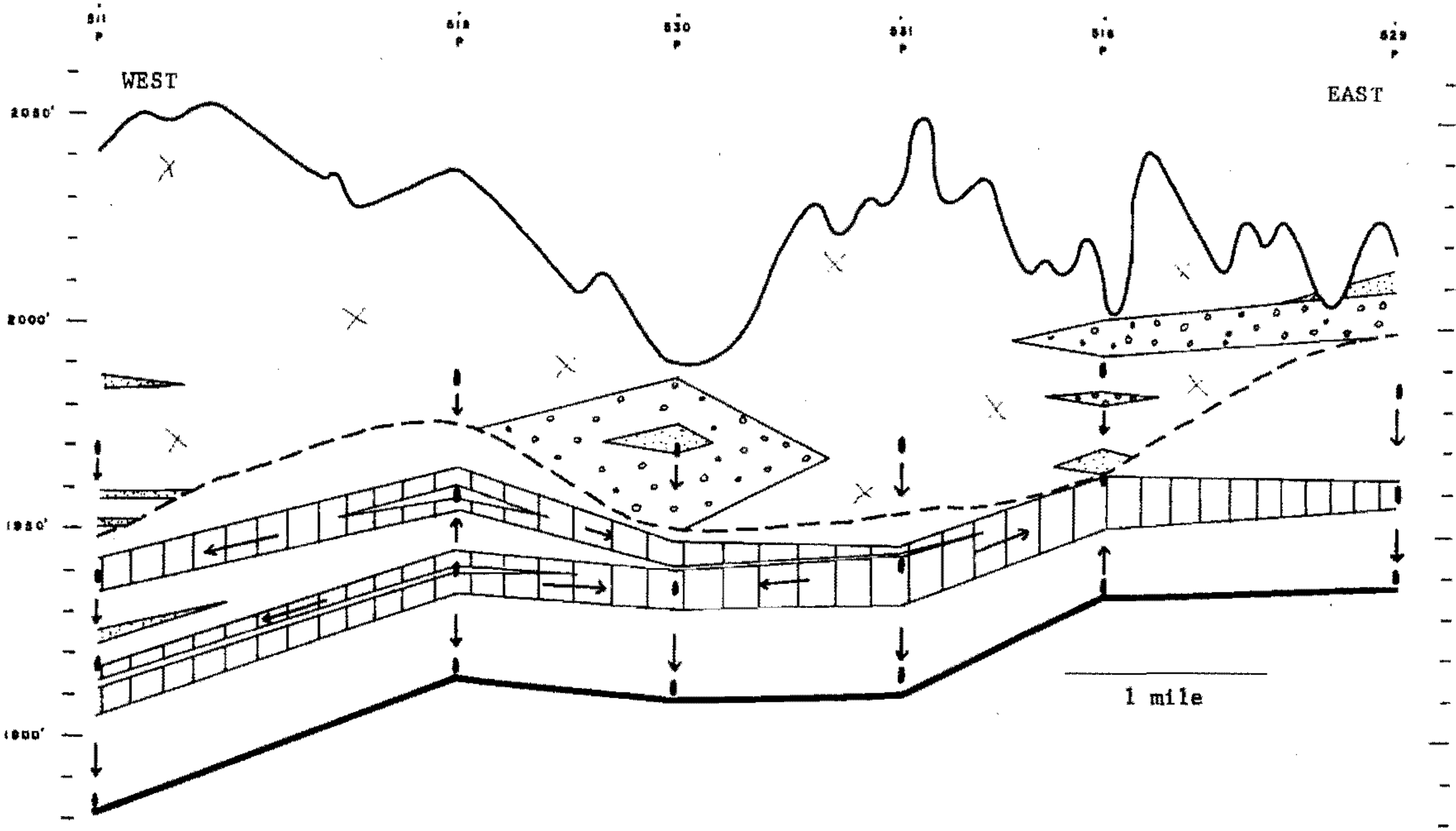


Figure 6e. Cross-section 4.

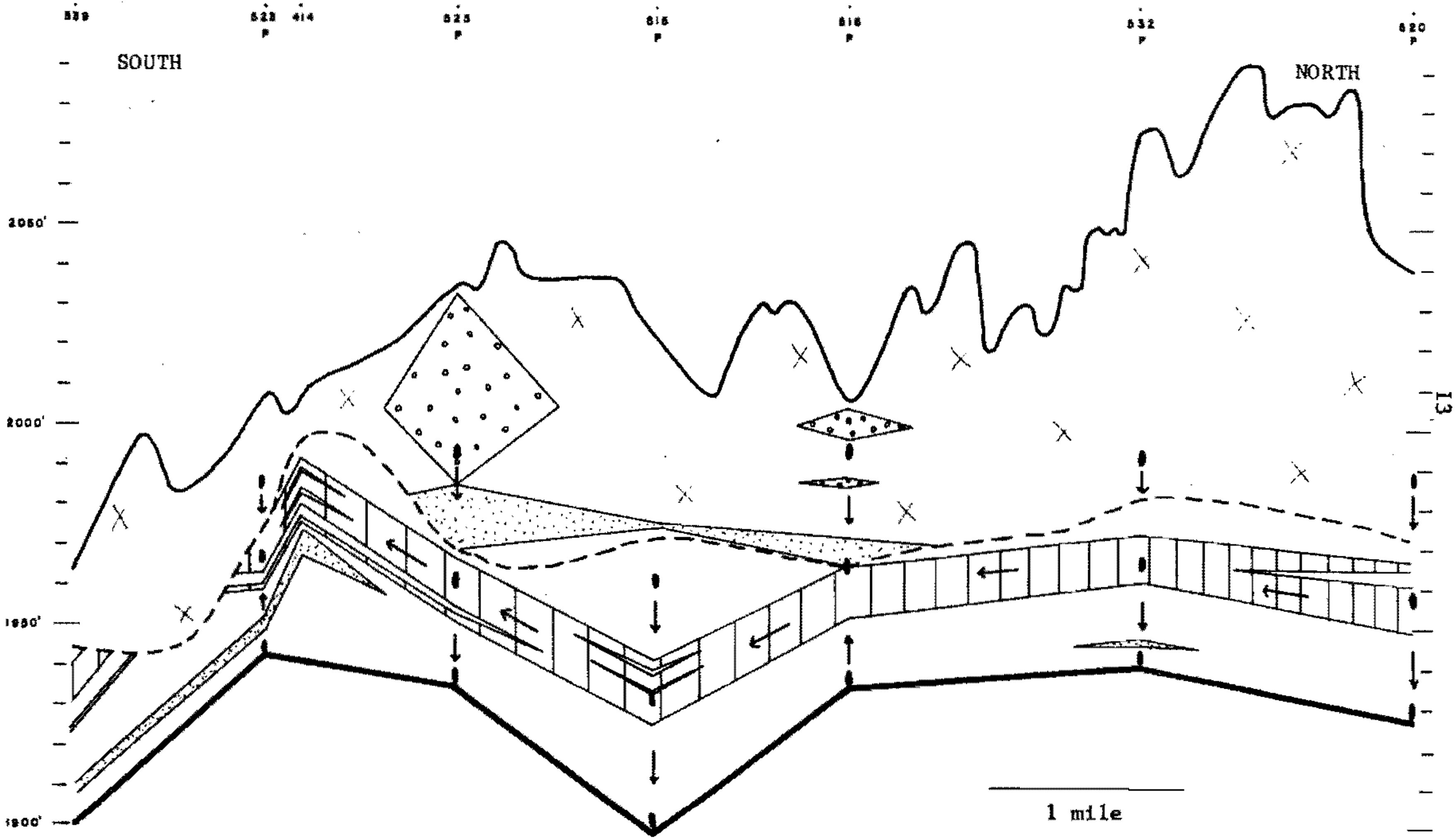


Figure 6f. Cross-section A.

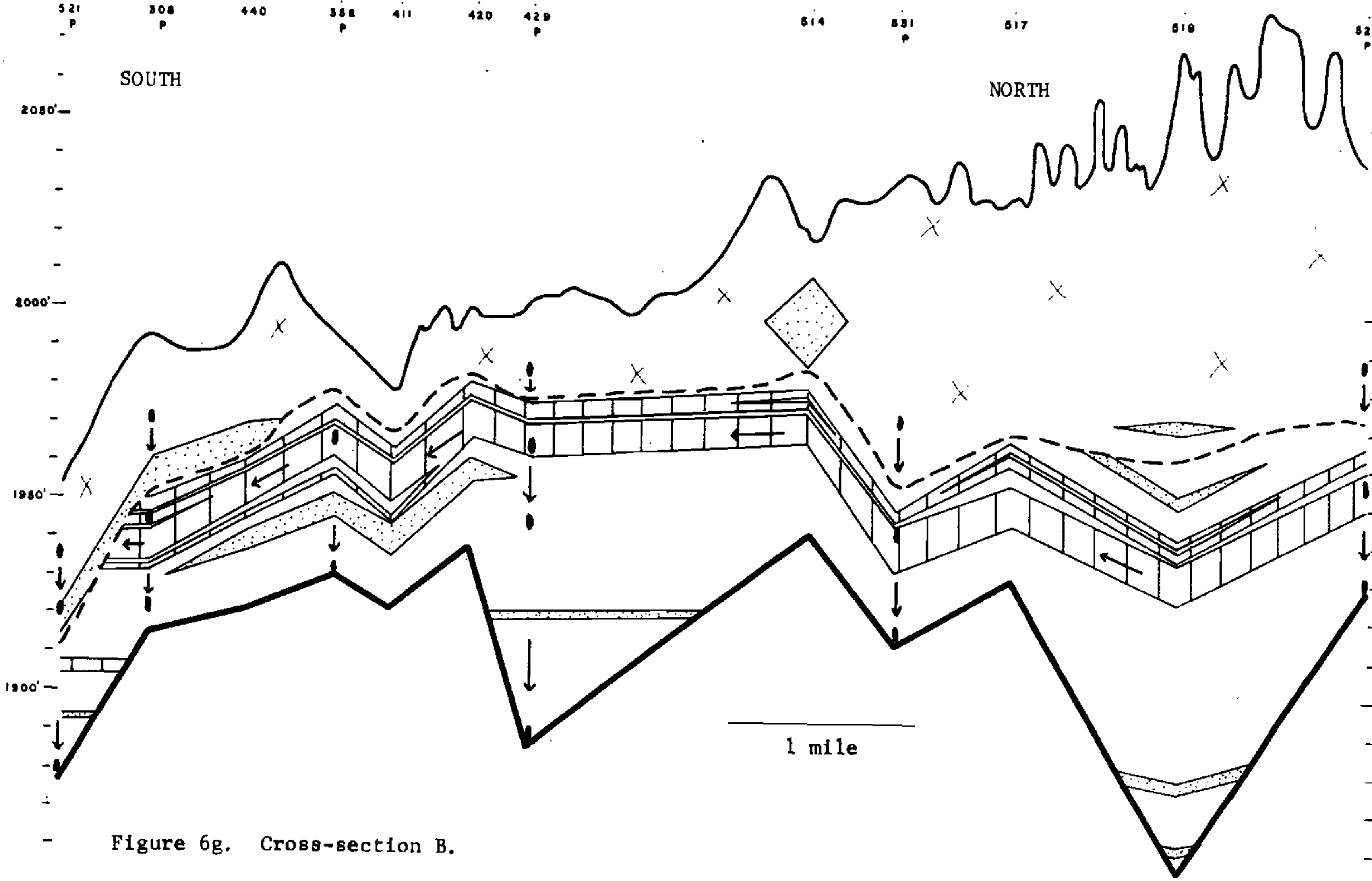


Figure 6g. Cross-section B.

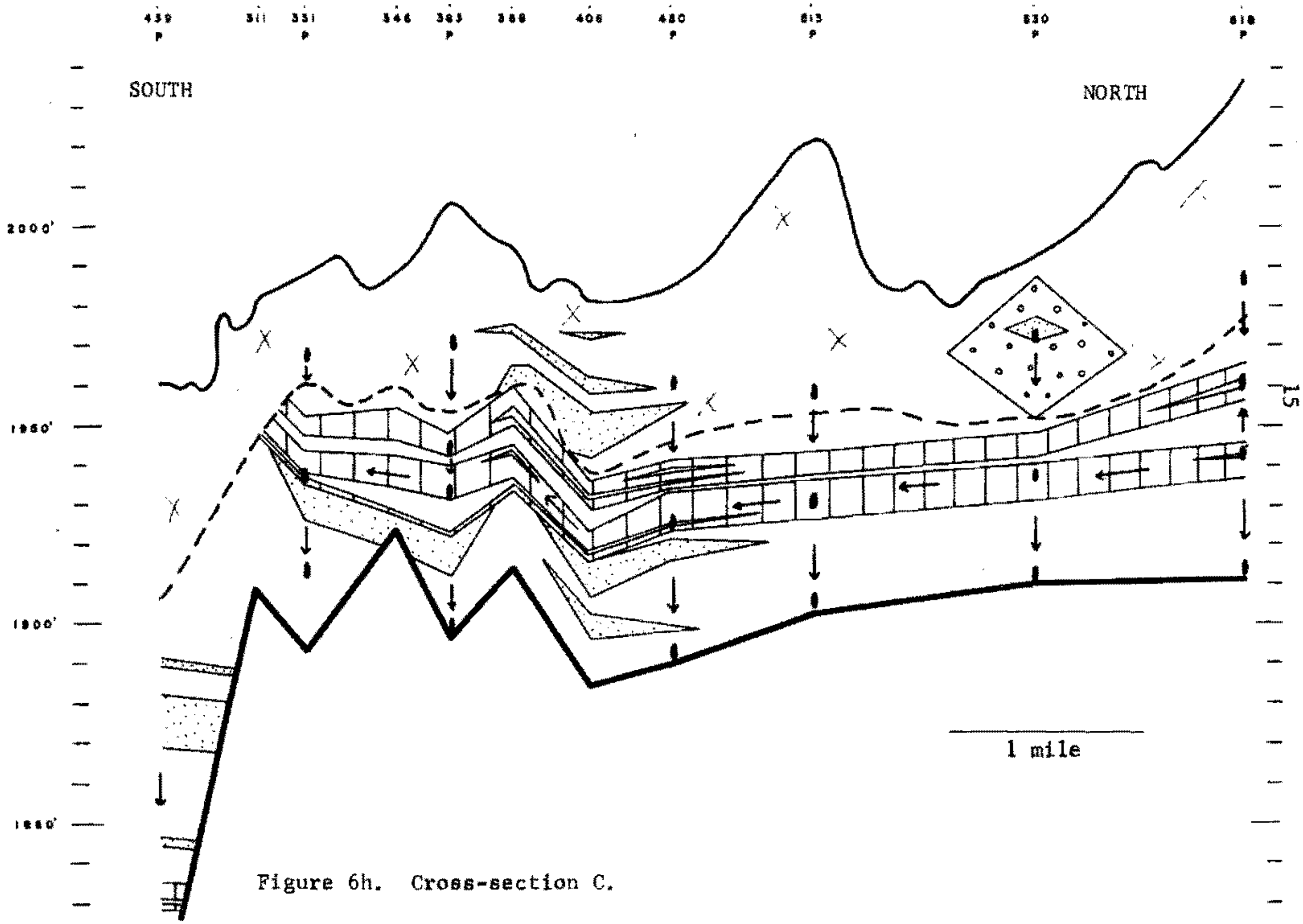


Figure 6h. Cross-section C.

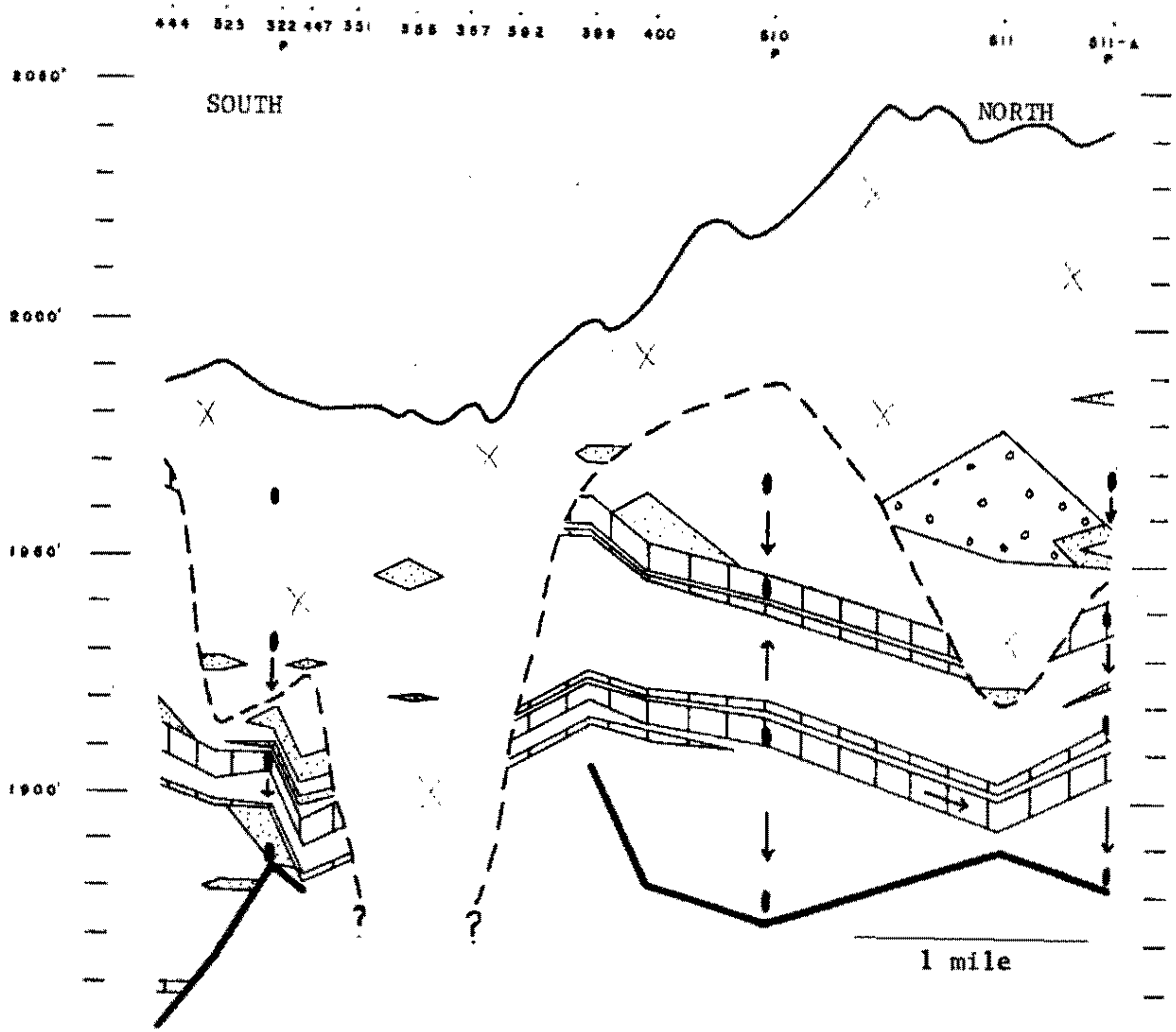


Figure 61. Cross-section D.

Jacob (1976) has interpreted the depositional environment of the Sentinel Butte and the underlying Bullion Creek Formations as an eastward prograding deltaic plain.

Most of the clayey sediment of the Sentinel Butte is overbank, swamp, and lacustrine deposits. Much of the clay is sodium montmorillonite (Moran and others, 1978b).

The Sentinel Butte lignite formed in fluvial floodbasins (Jacob, 1976). Flood waters from a channel spilt onto a low-lying floodplain, which became a swamp or, if the water was deep enough, a lake. If a swamp formed, vegetation grew quickly. If a lake formed, clay accumulated on the bottom until water depth was shallow enough for vegetation to grow. Eventually the layers of vegetation were covered by fluvial deposits. After millions of years of burial, the vegetal material was lignitized.

The Sentinel Butte sand beds are fluvial deposits (Jacob, 1976). Jacob found that the sand beds contain a large amount of volcanic-rock fragments, eroded from mountains to the west. These fragments eventually weather to sodium montmorillonite.

2. PLEISTOCENE ENVIRONMENT

The pebble loam (till) was deposited by Pleistocene continental glaciers that advanced from the north and may have been up to a few thousand feet thick in McLean County. The till covering most of the mine site was probably laid down beneath the glacier. The glacial deposits in the northeast quarter of the mine site were deposited at the stagnant edge of a glacier. The Pleistocene sand and gravel beds are probably outwash.

III. GEOHYDROLOGY

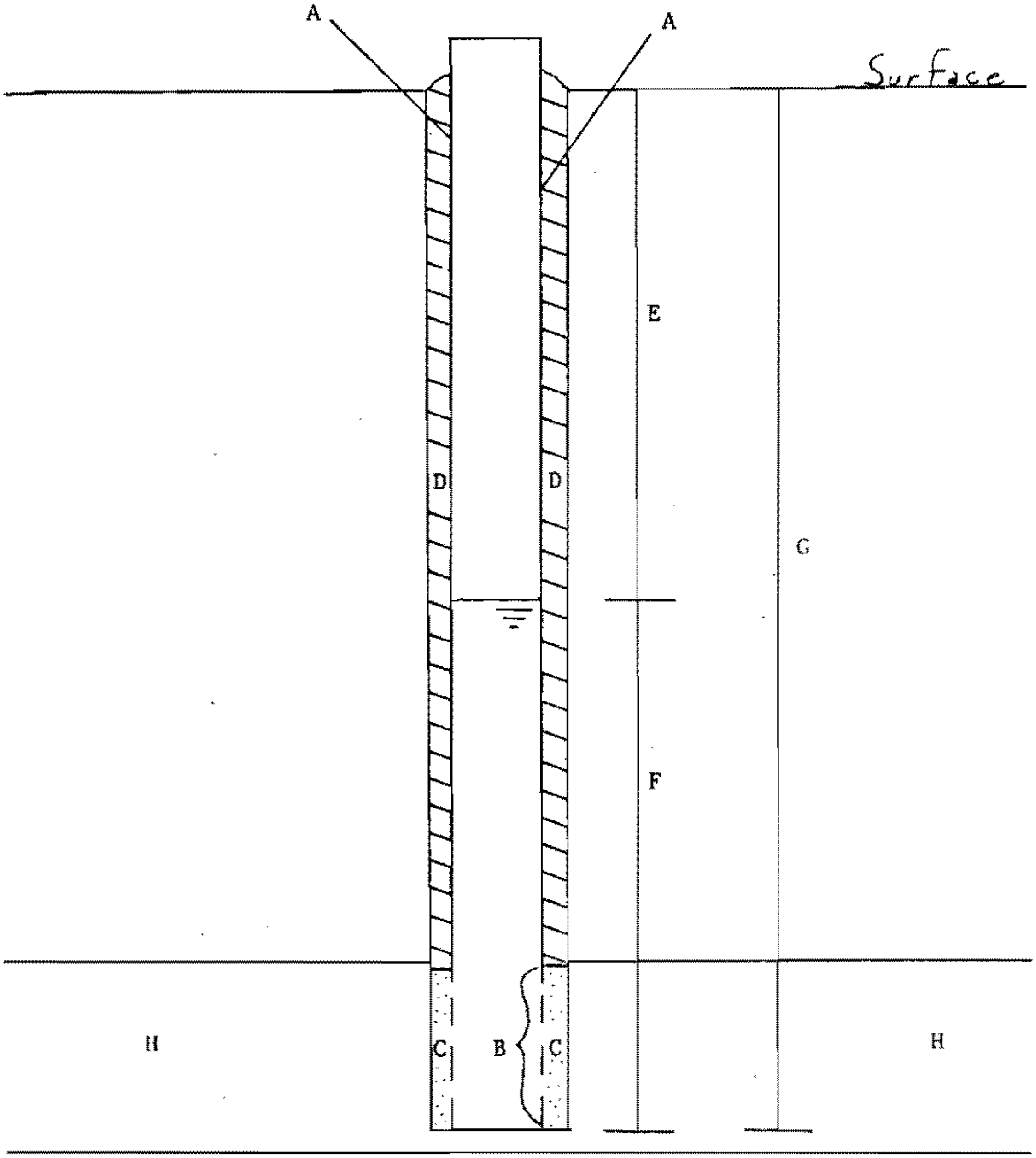
The main topic of this report is the groundwater and the lithologic properties that affect the groundwater at the Proposed Garrison Lignite Mine. With a background of mine-site stratigraphy, the groundwater can now be discussed in detail. This section contains the discussion of the physical characteristics of the groundwater and sediment. A following section contains the discussion of the chemical characteristics.

A. METHODS

Open-pipe piezometers were installed to obtain hydraulic head data at the mine site (Figure 7). Six-inch boreholes were drilled with a forward circulation rotary drill rig. Most of the holes were drilled with soap and water, the last 10 feet being drilled with high pressure air only. The completion of the borehole with air made the hole as clean as possible. In a few locations, the holes were drilled with bentonite mud to prevent caving.

After the holes were drilled, the piezometer pipe was installed. The 1977 piezometers were assembled and lowered into the hole by sections. The 1978 piezometers were assembled at the surface and lowered into the borehole as one continuous pipe.

All piezometer pipe was PVC (Schedule 40), 2 inches in diameter and in 20 foot sections. The sections were held together by larger diameter couplings and glue. All screens were pre-slotted with 0.020



A. Piezometer pipe	E. Depth to water
B. Screen	F. Water column height
C. Sand pack	G. Total depth
D. Cement	H. Monitored stratum

Figure 7. Piezometer Cross-section.

inch slots and were 5 feet in length.

After the pipe was installed, a 7-foot sand pack was shovelled into the hole. The sand pack thickness was measured by probing with a 1 inch diameter pipe. The 7 feet of sand produced a 2 foot overlap above the screen.

After the sand pack was completed, the remainder of the borehole was filled with cement. A small mound of cement was made around the pipe at the surface so that water would flow away from the area. The 2 feet of sand above the screen made a buffer zone for any cement seeping into the sand pack.

The water in each piezometer was removed at least twice after drilling with a hand-held bailer. This assured that drilling fluids were removed before water samples were taken. Many piezometers were bailed dry. Because of rapid recharge, some piezometers could not be bailed dry and so 1½ times the amount of water in the piezometers was removed.

Water levels in the piezometers were measured with an electric tape three times during the summer of 1978. Some water levels did not equilibrate until October, 1978. October water levels for all piezometers are listed in Appendix II.

Slug tests to determine the hydraulic conductivity of the monitored lithology were made during the summer of 1978. The specific method used to evaluate the slug tests is explained by Hvorslev (1951). The assumption that horizontal conductivity equals vertical conductivity was made, because of lack of data to indicate otherwise.

Although Hvorslev's method is relatively old, much research and testing indicates that it is still valid for measuring hydraulic conductivity (Hvorslev, personal communication, 1979).

B. PIEZOMETERS AT THE MINE SITE

At the mine site, ninety piezometers were installed in twenty-eight nests (Figure 8). At each nest in the eastern half of the area, one piezometer was installed about 20 feet above Seam AB; another, in Seam AB; and a third, about 20 feet below Seam AB. At each nest in the western half of the area, one piezometer was installed about 20 feet above Seam A; a second, in Seam A; another, in Seam B; and a fourth, about 20 feet below Seam B. Total depths and relationships to the lignite are listed in Appendix I for all piezometers.

C. HYDRAULIC CONDUCTIVITIES

Hydraulic conductivity is a quantitative measure of the ability of a material to transmit a fluid. Hydraulic conductivities of the lithologies at the mine site are listed in Appendix II and mapped in Figure 9.

About 20 feet below the lignite, the hydraulic conductivity of the Sentinel Butte silty clay is around 10^{-8} to 10^{-7} feet/second. Near the edges of the buried valleys, it increases to over 10^{-6} feet/second. This may indicate increased fracturing caused by preglacial unloading during valley erosion.

Undisturbed lignite is very impermeable, probably less than 10^{-9}

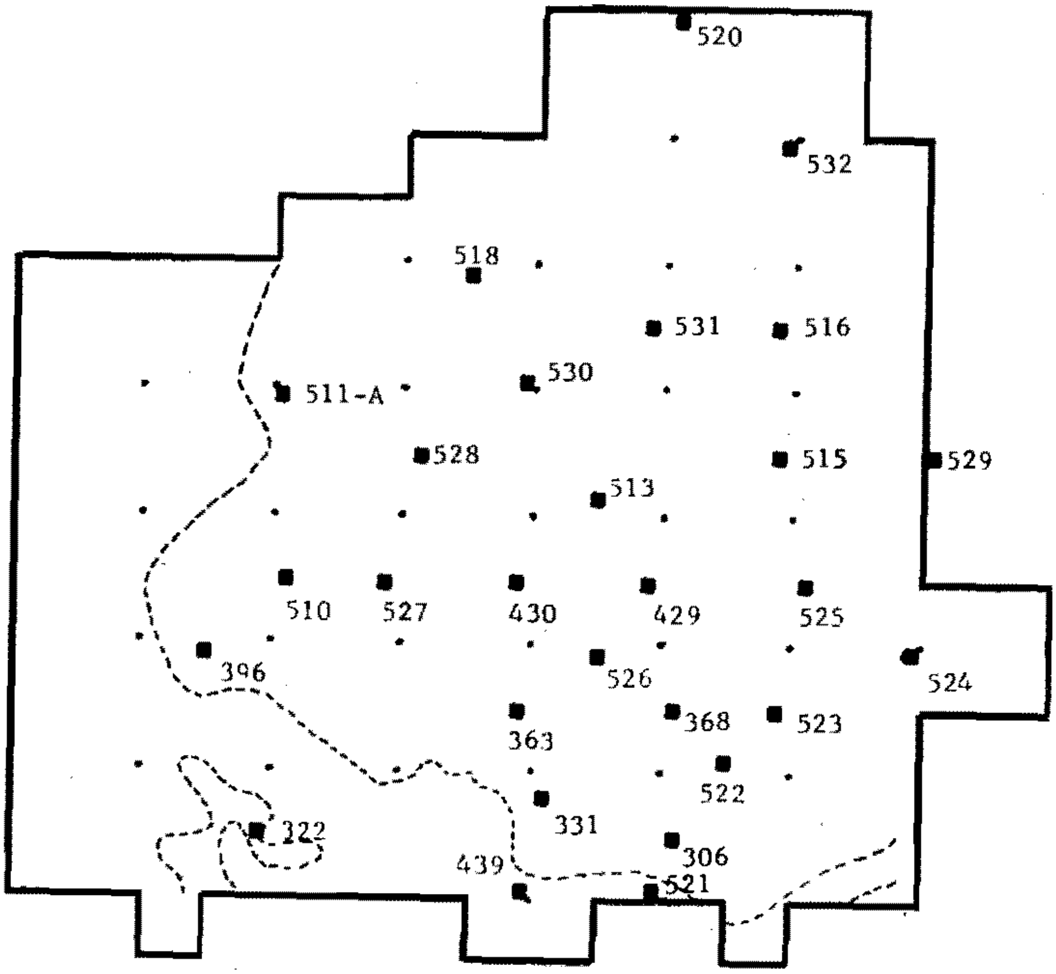
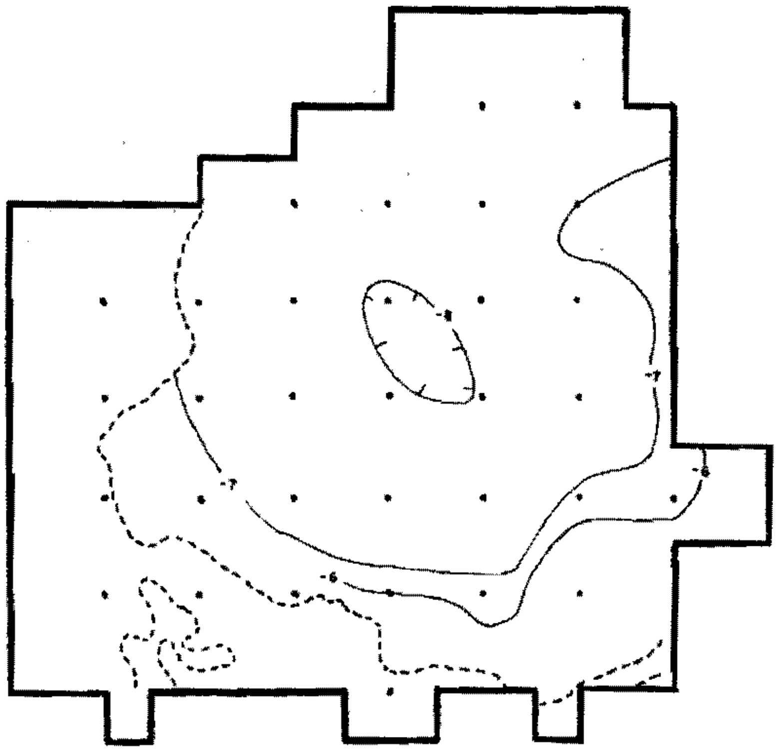


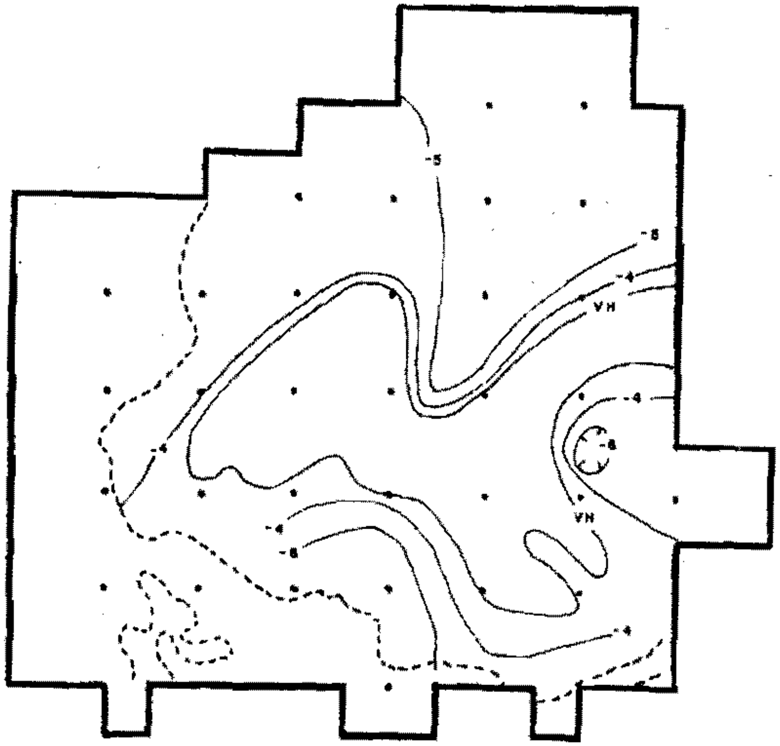
Figure 8. Location of Piezometer Nests at the Proposed Garrison Lignite Mine. The dashed line marks the 1920 foot elevation of the top of the Sentinel Butte Formation.



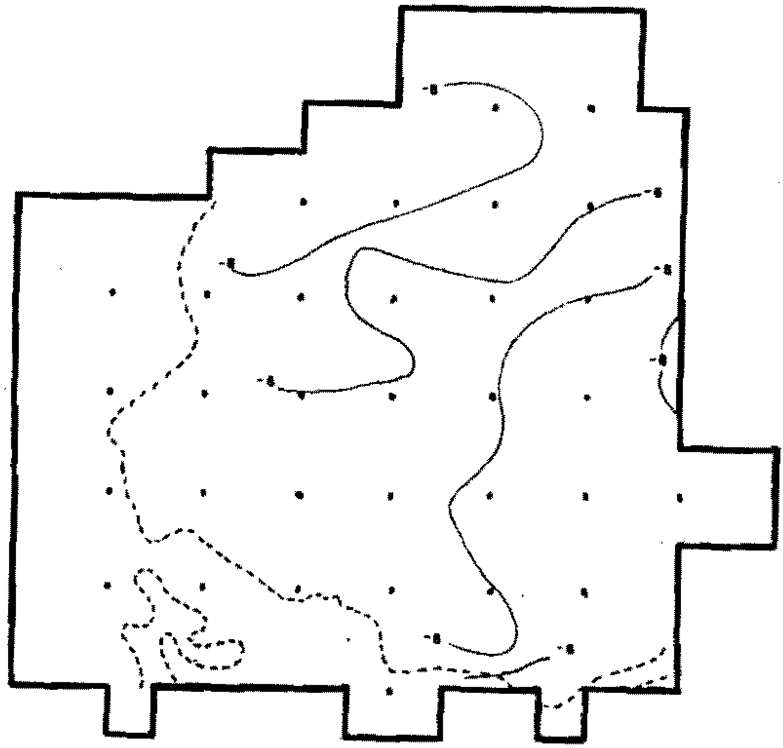
9a. Approximately 20 feet below lignite

9b. Seam B and AB

Figure 9. Hydraulic Conductivities at the Mine Site. Values are log (conductivity) in feet/second. VH = very high, greater than 10^{-3} feet/second.



9c. Seam A and AB



9d. Approximately 20 feet above lignite.

feet/second. But lignite is brittle and fractures easily. It is fracture permeability that makes some lignite an aquifer in western North Dakota.

At the mine site, Seams AB, A, and B have fracture permeability. These seams have areas where the hydraulic conductivity is greater than 10^{-3} feet/second (Figure 9).

Most of the piezometers that are about 20 feet above the lignite are in till. Although the till consists of grain sizes from clay to boulders, the majority of the grains fall into the clay and silt range. The dominance of clay and silt is reflected in the conductivities of 10^{-8} to 10^{-6} feet/second. The area where the conductivity is greater than 10^{-6} feet/second coincides with the area of high conductivity in the lignite. This suggests that the same process that fractured the lignite also fractured the till. If this is true, then the fracturing was probably caused by compaction during glacial advance and rebound during glacial retreat.

D. DIRECTIONS AND VOLUMES OF GROUNDWATER FLOW

The groundwater is recharged at the surface of the proposed mine site. The area around Garrison usually receives between 10 and 18 inches of precipitation a year (Klausing, 1974). In 1978, Garrison received about 15 inches of precipitation (National Weather Service, personal communication, 1979).

Calculations (see below) give the quantity of groundwater flow into the lignite at the mine site during one second. When expanded to the length of one year, the quantity of flow is only about 15 percent of the total precipitation. Thus, about 85 percent of the precipitation at the mine site is removed by evapotranspiration and runoff. In the dead-ice moraine, the runoff is held in the depressions, apparently producing a major recharge area.

The 15 percent of precipitation that passes through the unsaturated zone reaches the top of the unconfined saturated zone, the water table (Figure 10). The shape of the water table shows that there is a small horizontal component of flow oriented from the dead-ice moraine to the buried valleys. Hydraulic heads in the piezometers near the water table show that the major direction of groundwater flow is downward.

Figure 10 is based on water levels in the shallow piezometers and gradients between the shallow and the lignite piezometers. Because of the wide spacing between piezometer nests, Figure 10 shows only the general trend of the water table. The local flow systems in the dead-ice moraine are not shown. Throughout the year, the water table fluctuates above and below the October levels of Figure 10.

Volume rate of flow of the groundwater can be calculated from Darcy's Law:

$$Q = KiA$$

where Q is the volume rate of flow in cubic feet/second
K is the hydraulic conductivity in feet/second
i is the hydraulic gradient in feet/feet
A is the cross-sectional area of flow in feet^2

The groundwater flow in the pebble loam and silty clay is essentially vertical into the lignite below with an average gradient

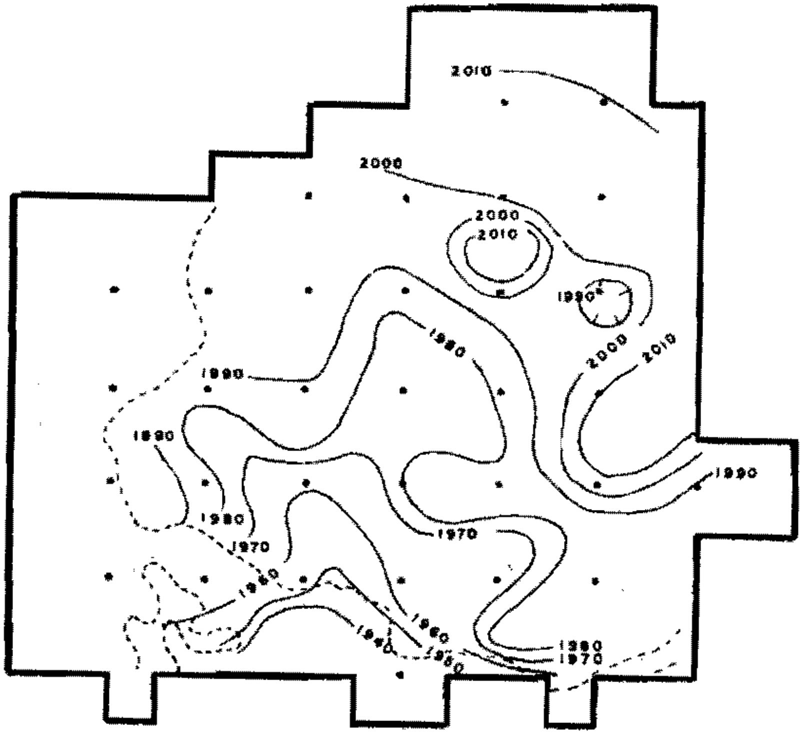
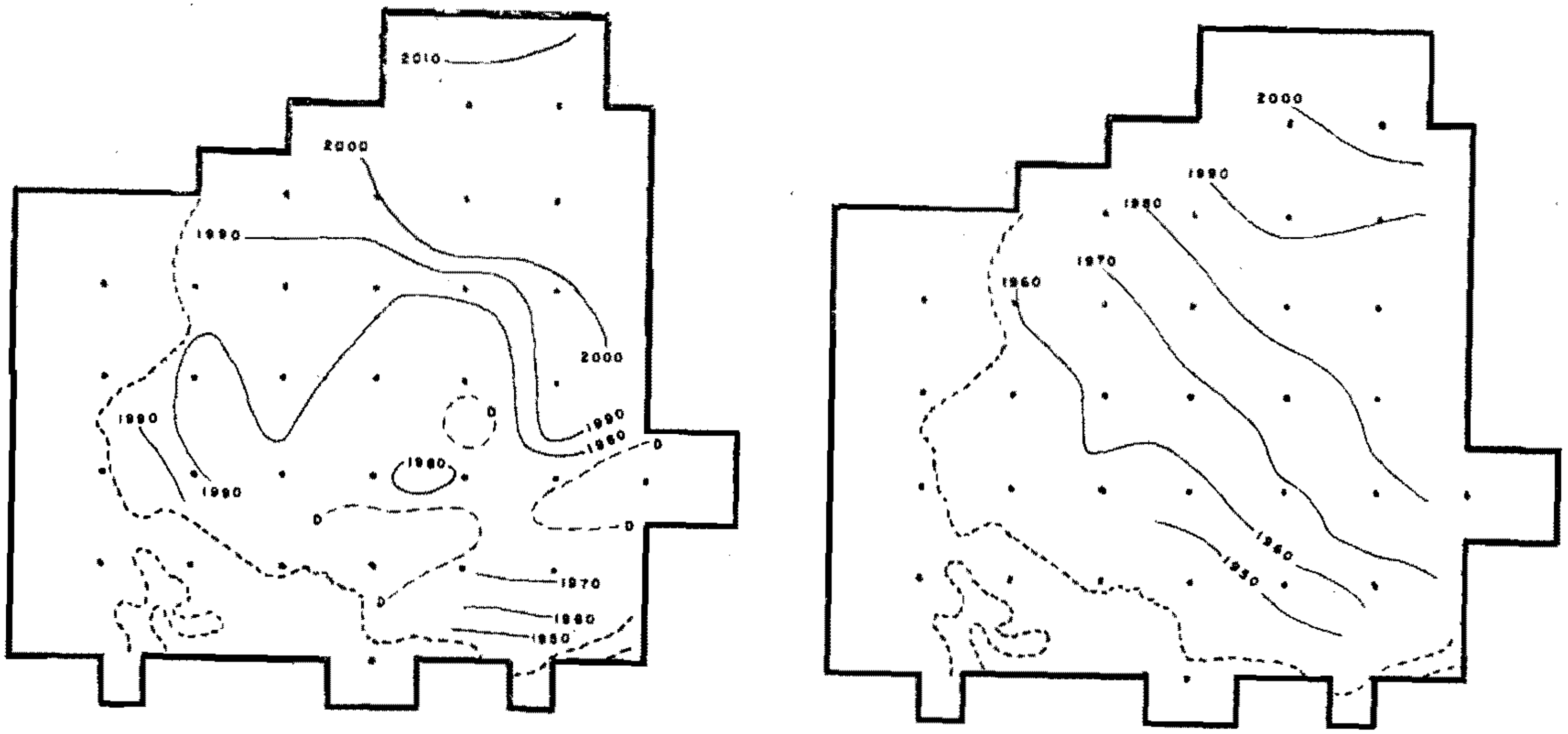


Figure 10. Water Table at the Mine Site. Elevations are in feet above sea level.

of about 0.60 (Appendix II). This gradient is based on water levels at thirteen piezometer nests, where little sand and gravel lies between the screen in the till and the screen in the lignite. Most of the till at the mine site is unfractured or slightly fractured, yielding a small average hydraulic conductivity of about 10^{-8} feet/second, calculated from eleven slug tests. From the above values, the volume rate of flow into the lignite of Seam AB and A is about 6×10^{-9} cubic feet/second/square foot. Because the surface area of Seam AB and A is about 25 square miles at the mine site, total discharge into these seams is about 4.2 cubic feet/second.

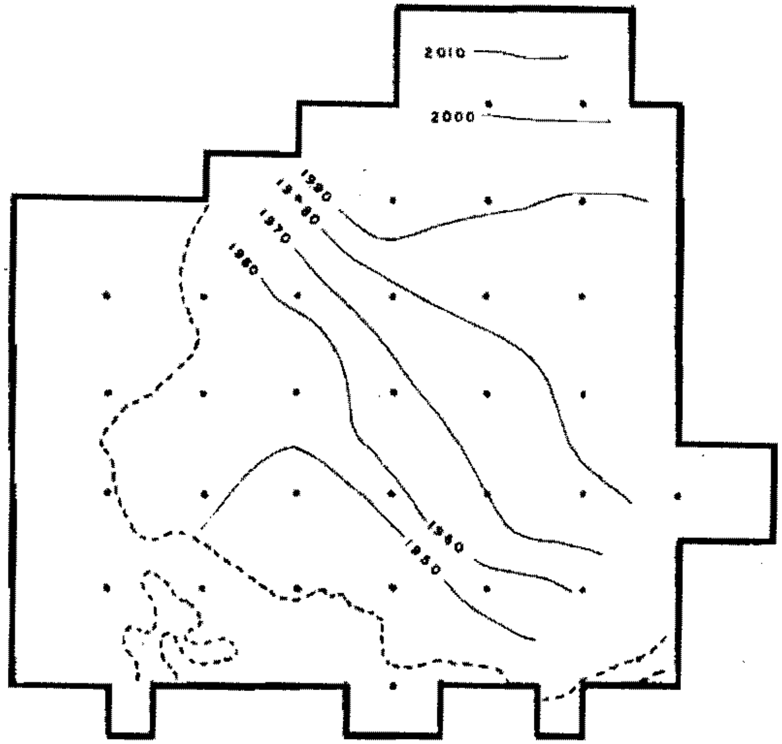
The lignite has a higher hydraulic conductivity than the silty clay. As water passes into the lignite, the direction of flow undergoes a refraction and the water flows in a more horizontal direction. This lateral flow is oriented from the recharge area in the northeast to buried valleys in the west ans south (Figures 6 and 11). The quantity of water discharged laterally from the lignite subcrop into the buried valleys is calculated with an average lateral gradient of 0.004 (Figure 11) and an average hydraulic conductivity of 10^{-4} feet/second (Figure 9). The subcrop of the lignite is about 15 miles long and average thickness at the subcrop is 12 feet, giving a total discharge into the buried valleys of about 0.4 cubic feet/second, or about 10 percent of the water that enters the lignite from above. Apparently, most of the groundwater flows only a short distance within the lignite, perhaps about a thousand feet, before discharging into the silty clay below



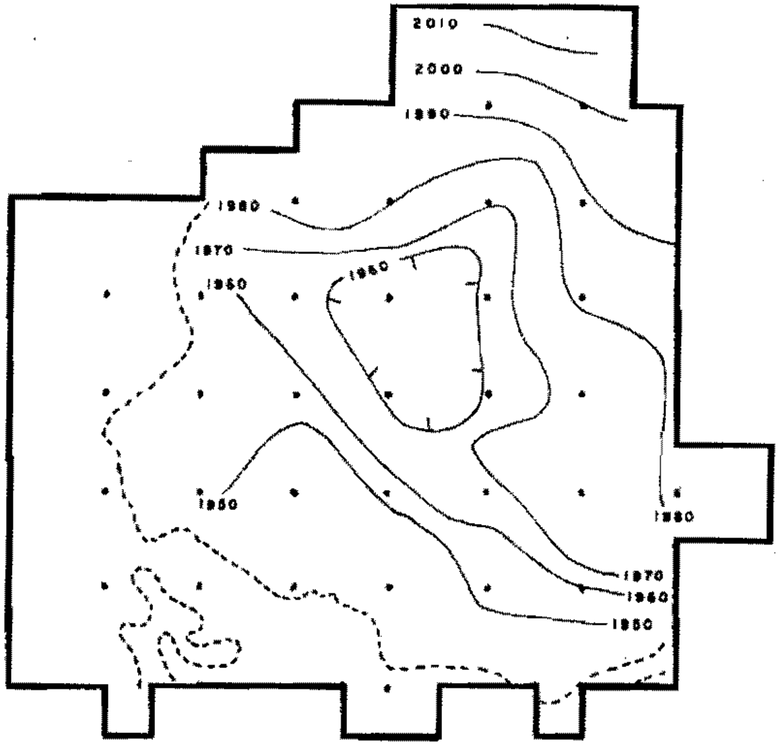
11a. 20 feet above lignite.

11b. Seam A and AB.

Figure 11. Head Distributions. Head values are in feet above sea level.



11c. Seam B and AB.



11d. 20 feet below lignite.

the lignite or into Pleistocene sand and gravel above the lignite. The average downward gradient from twenty-one nests, 0.20, and the average hydraulic conductivity from nineteen slug tests, 2×10^{-8} feet/second, in the silty clay below the lignite indicate that at least 65 percent of the water in the lignite flows into the silty clay below.

There are some complexities and unknowns in the flow system. First, in some places, Seam A recharges Seam B, whereas the reverse is true in other locations at the mine site (Figure 6). The reason for this cannot be confirmed, but it may reflect local variations of hydraulic conductivities and gradients within the seams. Second, in some places the lignite is recharged by the deeper silty clay (Figure 6), however, the quantity of water rising from the deeper flow system is negligible. Third, the movement of groundwater in the Sentinel Butte sand beds is unknown, because of the scarcity of piezometers in the beds. Based on a few piezometers and data from other North Dakota sites, the flow pattern in the sand beds appears to be similar to the flow in the lignite. Fourth, there is probably some groundwater discharging from the lignite into higher Pleistocene sand and gravel beds. The water in the Pleistocene aquifers probably follows the regional gradient and flows toward the buried valleys. Because these aquifers are discontinuous across the mine site, the water must eventually discharge onto the surface or flow back into the lignite. The scarcity of surface water at the mine site indicates that the flow is predominately into the lignite.

Fifth, there has been no detailed study of groundwater flow in the materials in the buried valleys. Because large amounts of water are available within the permeable valley-fill material to the south of the proposed mine site, water probably flows into the valleys along their lengths and then flows generally south toward Lake Sakakawea.

IV. HYDROGEOCHEMISTRY

A. METHODS

Groundwater samples were removed from piezometers with a hand-held bailer during the fall of 1978. The samples were forced through 0.45 micrometer filter paper by a peristalic pump, then bottled and chilled. The trace metal samples were acidified with nitric acid. Within 24 hours after sampling, the water samples were shipped to the Chemistry Department of North Dakota State University for chemical analysis. The results of the analyses are in Appendix III.

B. CONCLUSIONS

Extensive research on hydrogeochemistry has been done in North Dakota by Moran and others (1978a), Moran and others (1978b), and Groenewold and others (1979). This section is based on the findings of these reports.

The root zone at the proposed mine site has not been monitored in this study. The general chemical processes in the root zones in western North Dakota have been discussed by Moran and others (1978b)

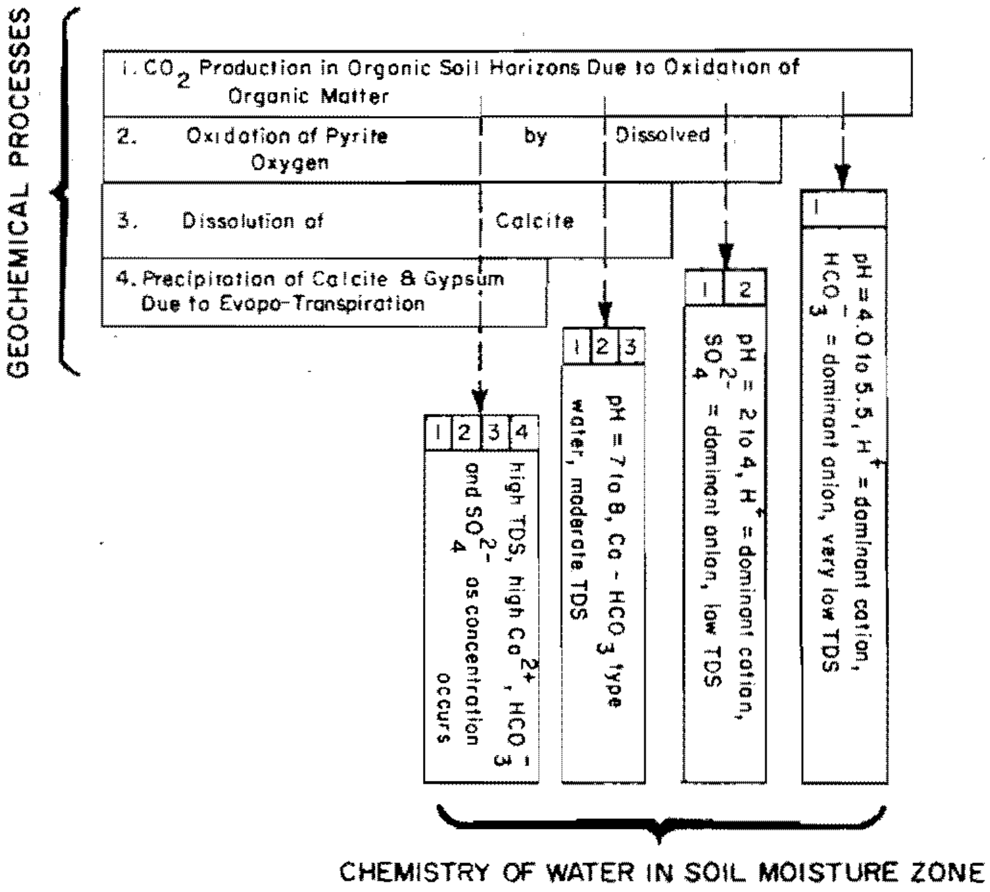


Figure 12. Geochemical Reactions in the Water in the Root Zone. This water is removed by evapotranspiration. From Moran and others (1978b).

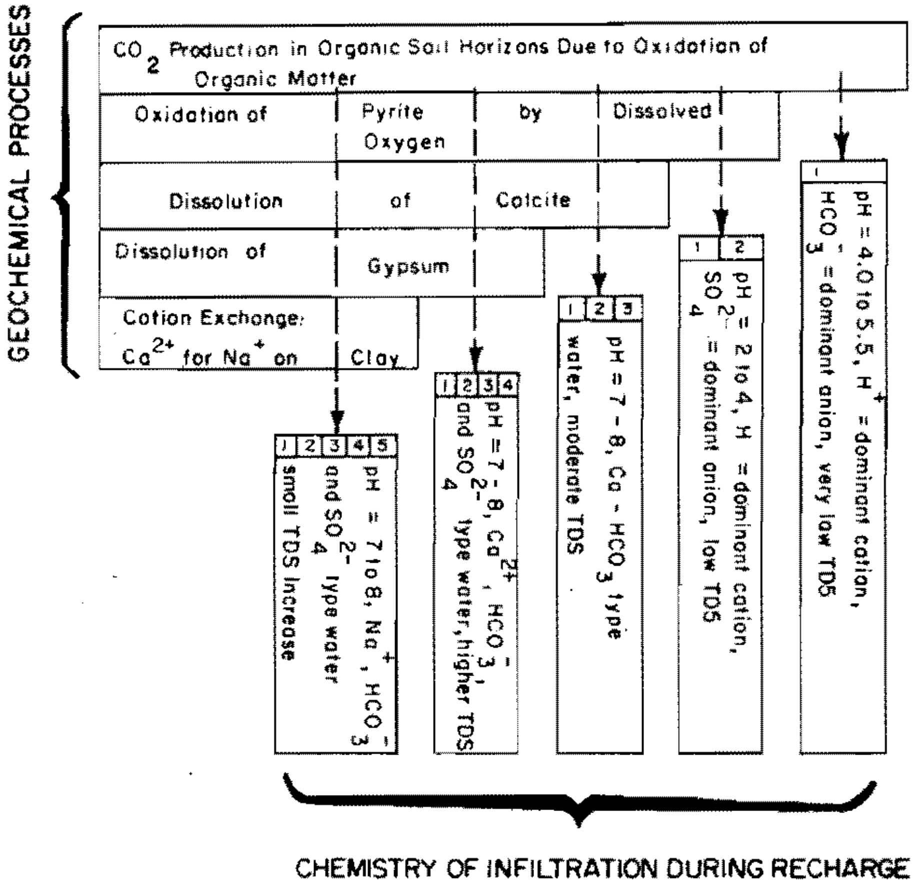


Figure 13. Geochemical Reactions in the Water That Reaches the Water Table. From Moran and others (1978b).

1/

CO_2 production in organic horizons of the soil

$$CH_2O + O_2 \longrightarrow CO_2 + H_2O$$

2/

Oxidation of pyrite

$$4FeS_2 + 15O_2 + 14H_2O \longrightarrow 4Fe(OH)_3 + 16H^+ + 8SO_4^{2-}$$

3/

Dissolution of calcite and dolomite

$$CaCO_3 + H^+ \longrightarrow Ca^{2+} + HCO_3^-$$

$$CaMg(CO_3)_2 + 2H^+ \longrightarrow Ca^{2+} + Mg^{2+} + 2HCO_3^-$$

4/

Precipitation and dissolution of gypsum

$$Ca^{2+} + SO_4^{2-} + 2H_2O \longrightarrow CaSO_4 - 2H_2O$$

5/

Cation exchange

$$Ca^{2+} + 2Na\ (\text{adsorbed}) \longrightarrow 2Na^+ + Ca\ (\text{adsorbed})$$

Figure 14. Chemical Equations for the Reactions of Figure 13. From Groenewold and others (1979).

and are summarized in Figure 12. The four processes in Figure 12 take place in the water that is removed from the soil by evapotranspiration. During times of much infiltration, some water is able to pass below the root zone and reach the water table. This water goes through the chemical processes listed in Figures 13 and 14 as it flows downward toward the water table. Chemical data from piezometers about 20 feet above the lignite indicate the extent to which these processes are occurring at the mine site. The data show that much dissolution of calcite and gypsum occurs. As indicated by analysis with the WATEQ computer program (Truesdell and Jones, 1974), most of the groundwater in the till is supersaturated or near saturated with respect to calcite and gypsum (Appendix IV). At some time in the past, oxidation of pyrite was probably a widespread reaction in the till, producing most of the sulfate in the gypsum now at the mine site. Cation exchange of calcium for sodium probably accounts for large concentrations of sodium (Figure 19) in the groundwater in the till. The clay on which the exchange occurs is sodium montmorillonite, eroded from nearby bedrock as the Pleistocene glaciers advanced from the north.

The groundwater within the lignite has lower concentrations of many ions than within the till, as shown by lower total dissolved solids (Figure 21). The reason for this decrease is not known, but there are two obvious explanations. First, the decrease is from mixing (dilution) of the water from the till with low total-dissolved-solids groundwater already in the lignite. The problem with this explanation is the source of the low total-dissolved-solids water. Because groundwater flows only several hundred feet within the lignite, the dilute water initially came from the till a short distance up-gradient. So the problem again appears of the cause of decreasing ion concentrations from the till to the lignite. Also, if this mixing was taking place on a large scale, there should be a trend within the lignite of increasing concentrations from the northeast quarter of the proposed mine site to the buried valleys. This trend does not appear in Figures 15 through 23.

The second explanation for the decreased ion concentrations is the differing geochemistries of the Pleistocene and Sentinel Butte sediments. As the generally high total-dissolved-solids groundwater passes from the till into the Sentinel Butte, it undergoes certain chemical reactions. For instance, precipitation of gypsum, calcite, and dolomite possibly occurs (Reaction 4 and the reverse of reaction 3 in Figure 14). The precipitation of these minerals would account for the decrease in concentrations of calcium (Figure 20), sulfate (Figure 17), bicarbonate (Figure 16), and magnesium (Figure 20). The chemical reactions that could cause lower concentrations of the other major ions (sodium, potassium, and chloride) are not yet known. The iron content in the water in the lignite is highly variable (Figure 21), but the water is generally closer to siderite saturation than it is in the till (Appendix IV). This is apparently the result of dissolution of iron minerals that are common in the Sentinel Butte (Moran and others, 1978b).

From the lignite, the groundwater passes into the silty clay below. Water analyses from about 20 feet below the lignite shows that the total dissolved solids (Figure 21) have increased. Bicarbonate concentrations increase with calcite dissolution (Figure 16), and the water begins to approach saturation with respect to calcite (Appendix IV). Calcium concentrations decrease and sodium concentrations increase because of cation exchange on the sodium montmorillonite. The water becomes slightly less saturated with respect to gypsum (Appendix IV). This is primarily the result of decreasing sulfate concentrations (Figure 17), possibly caused by microbial sulfate reduction. Hydrogen sulfide gas, a product of sulfate reduction, has been detected in a few of the deeper piezometers at the mine site. The water approaches saturation with respect to siderite as iron minerals in the Sentinel Butte continue to dissolve.

In summary, the initial water chemistry is made in the root zone and is controlled by the mineralogy in the till. The mineralogical and textural heterogeneity of the till allows the water to obtain high levels of total dissolved solids. Many minerals are at levels of supersaturation or near saturation in the water in the till. After passing into the Sentinel Butte sediments, the water undergoes a significant decrease in total dissolved solids due to precipitation and other reactions. Concentrations of many ions increase with depth in the Sentinel Butte Formation. Major exceptions are calcium and sulfate, which decrease in concentration because of cation exchange and sulfate reduction, respectively.

Within the lignite seams, some ions increase in concentration near the buried valleys. This may be from increasing till thickness above the lignite, allowing the water to obtain a higher level of total dissolved solids before and after passing into the Sentinel Butte. Or the cause of high concentrations near the buried valleys may be the result of mixing of groundwater from the buried valleys, typically high in ion concentrations, with groundwater in the lignite.

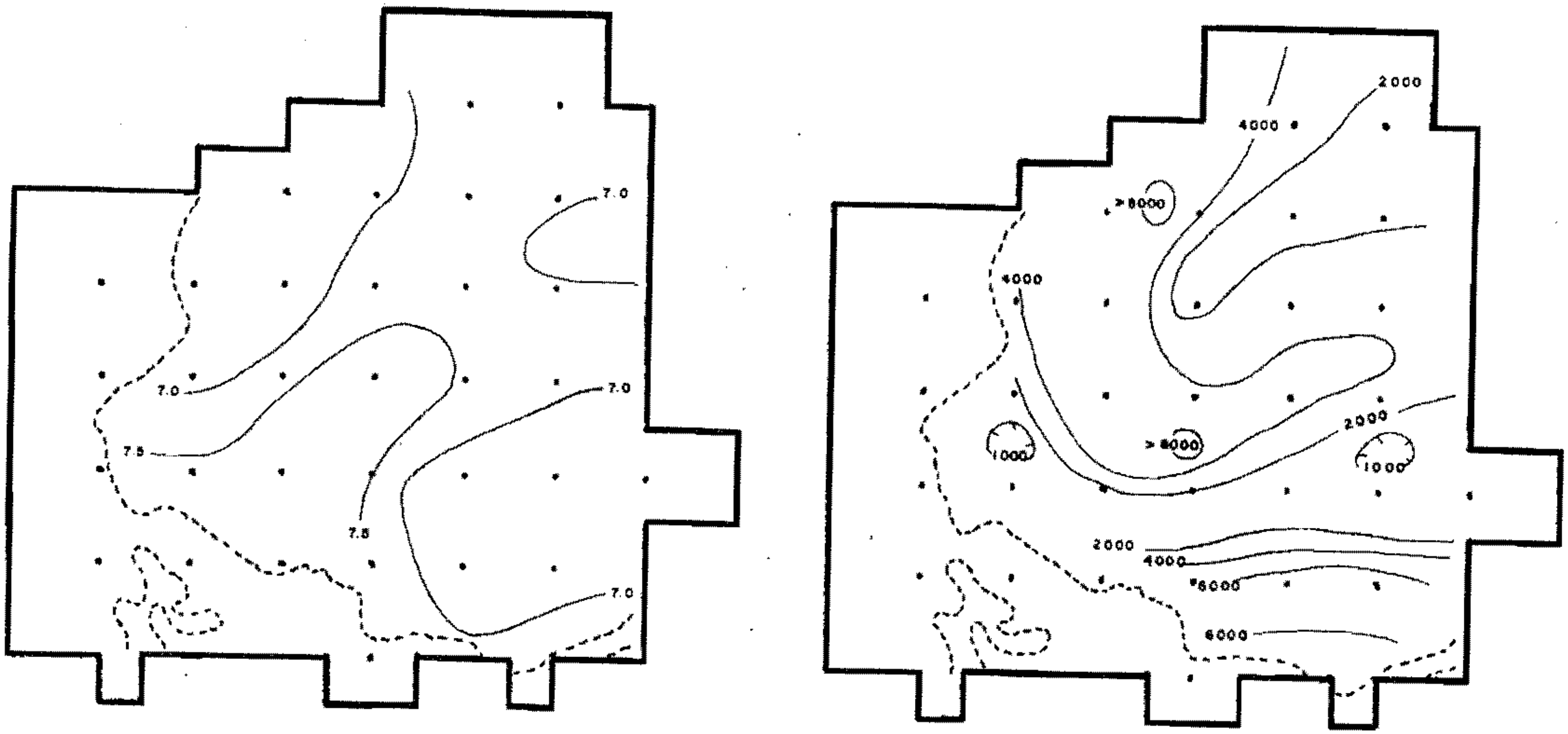
C. WATER SUITABILITY

The Environmental Protection Agency has set maximum concentration limits on ions in water for human consumption. Of the ions studied in this report, six have maximum limits based mainly on taste characteristics:

Total dissolved solids	500 milligrams/liter
Chloride	250
Sulfate	250
Iron	0.3
Manganese	0.05
Copper	1.0

Total dissolved solids (Figure 21), sulfate (Figure 17), and manganese (Figure 22) are almost always above the recommended limits in the groundwater at the mine site. Chloride (Figure 18) exceeds the limit only in groundwater in the till. Iron concentrations (Figure 21) exceed 0.3 milligrams/liter only in the southeast quarter of the mine site. Copper (Figure 22) does not exceed the recommended limit.

Of the ions studied in this report, three have maximum limits

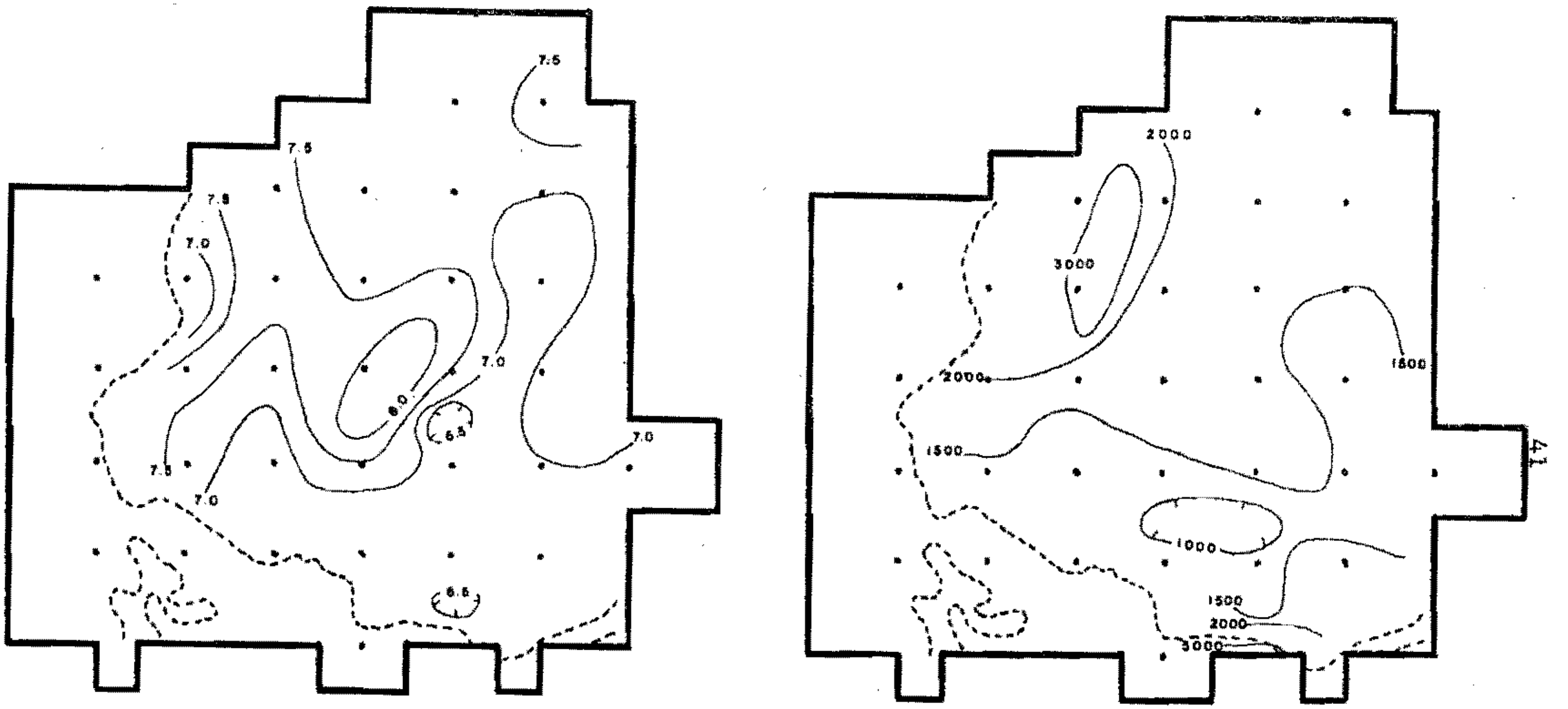


pH

Specific Conductance in micromhos/cm

15a. About 20 feet above Seam AB and A

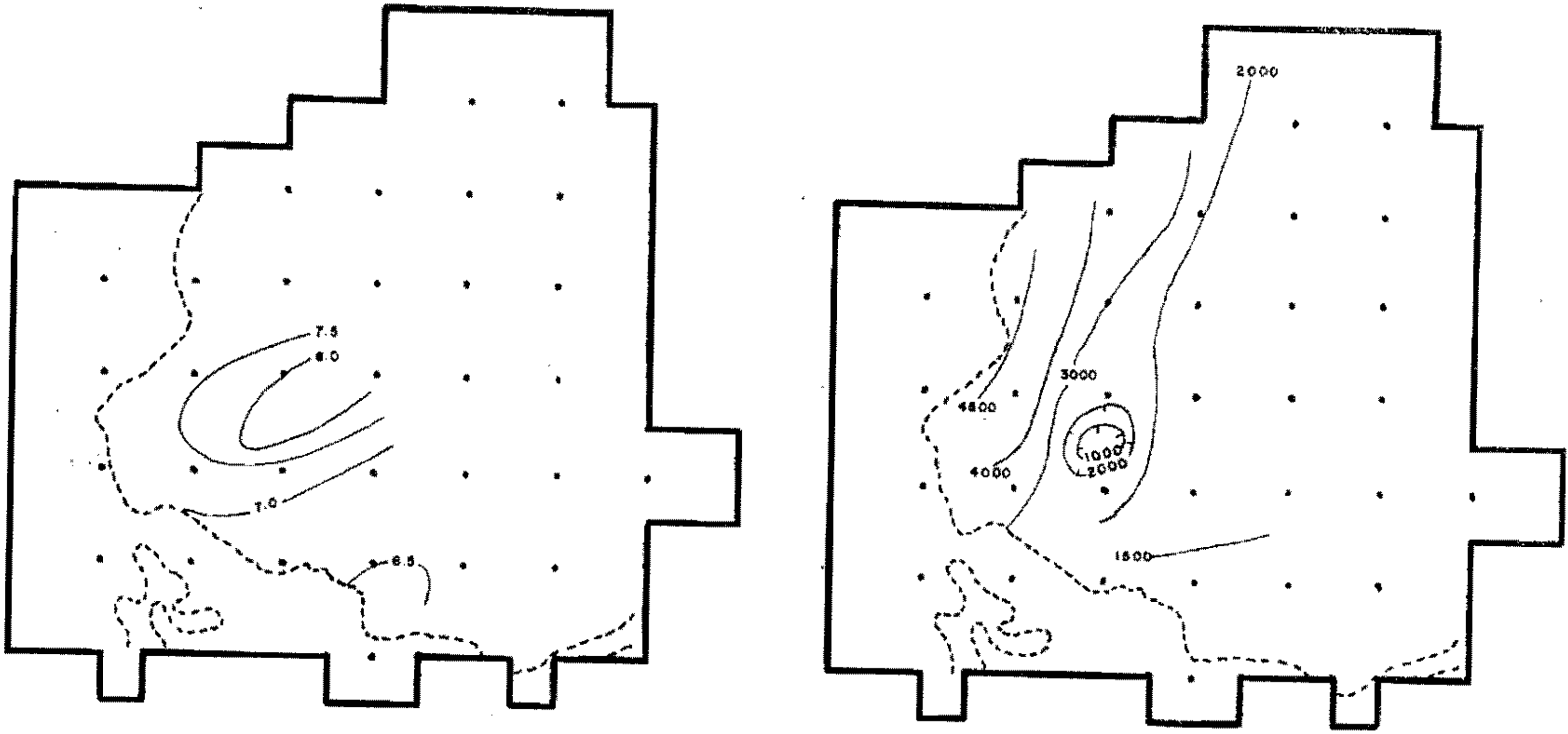
Figure 15. pH and Specific Conductance.



pH

Specific Conductance in micromhos/cm

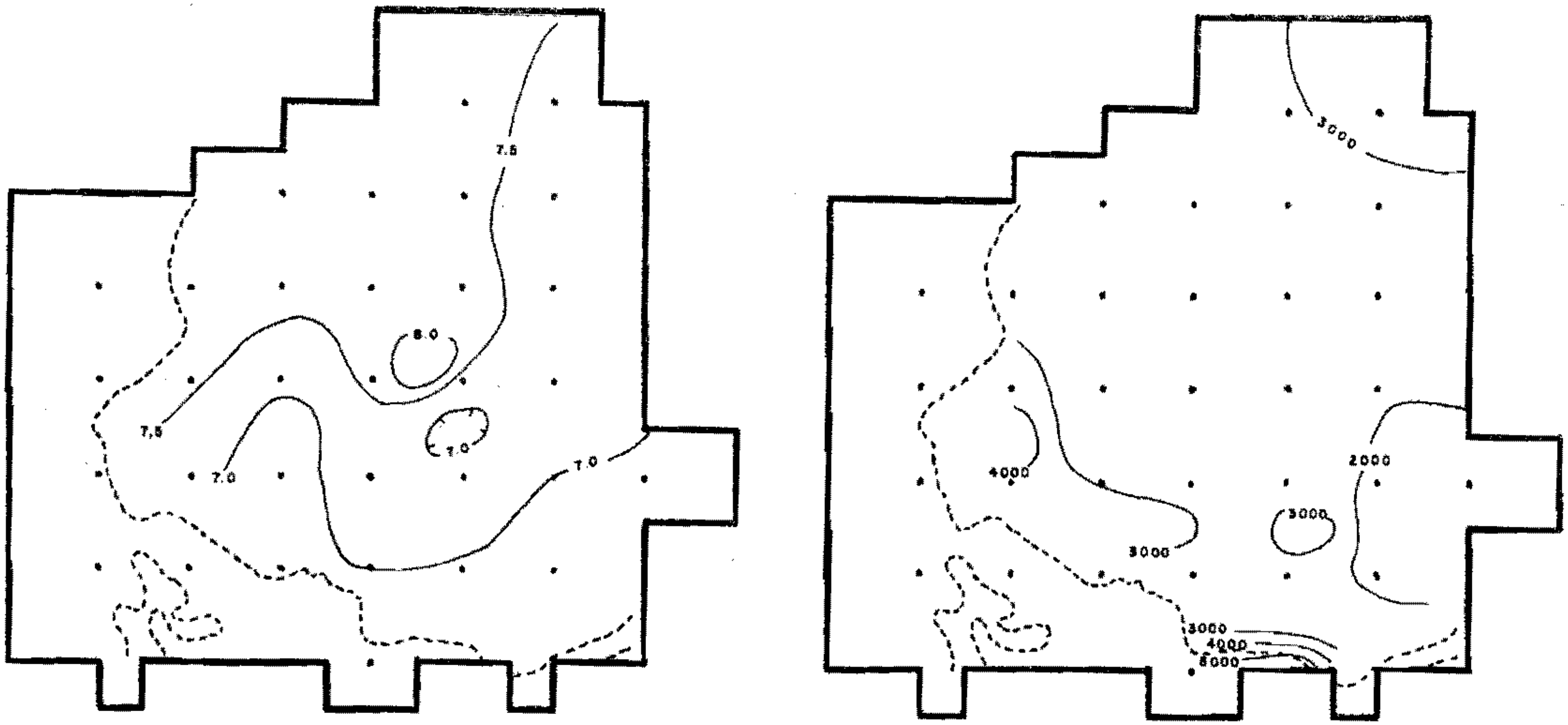
15b. Seam AB and A



pH

Specific Conductance in micromhos/cm

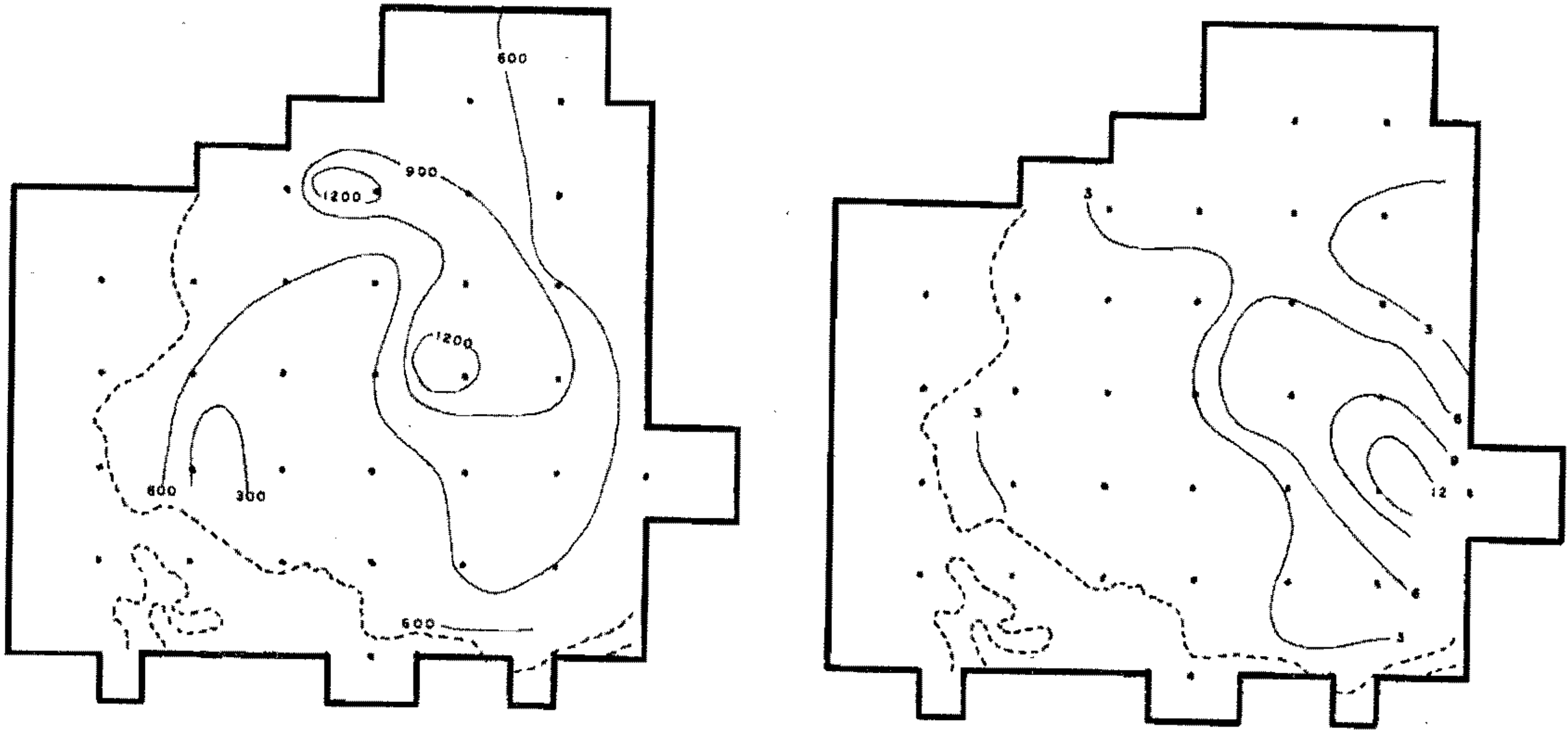
15c, Seam B



pH

Specific Conductance in micromhos/cm

15d. About 20 feet below Seam B and AB

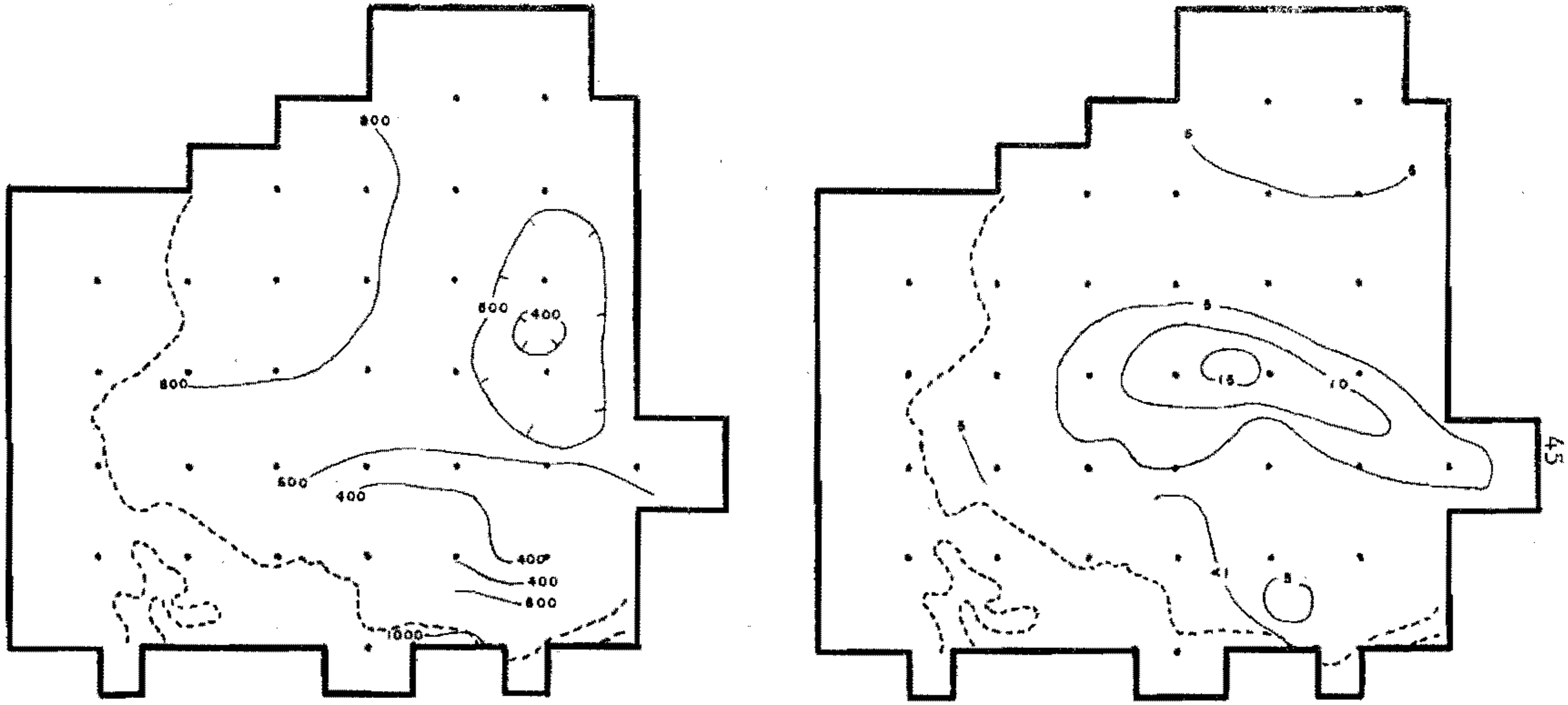


HCO_3^- in milligrams/liter

$CO_3^=$ in milligrams/liter

16a. About 20 feet above Seam A and AB

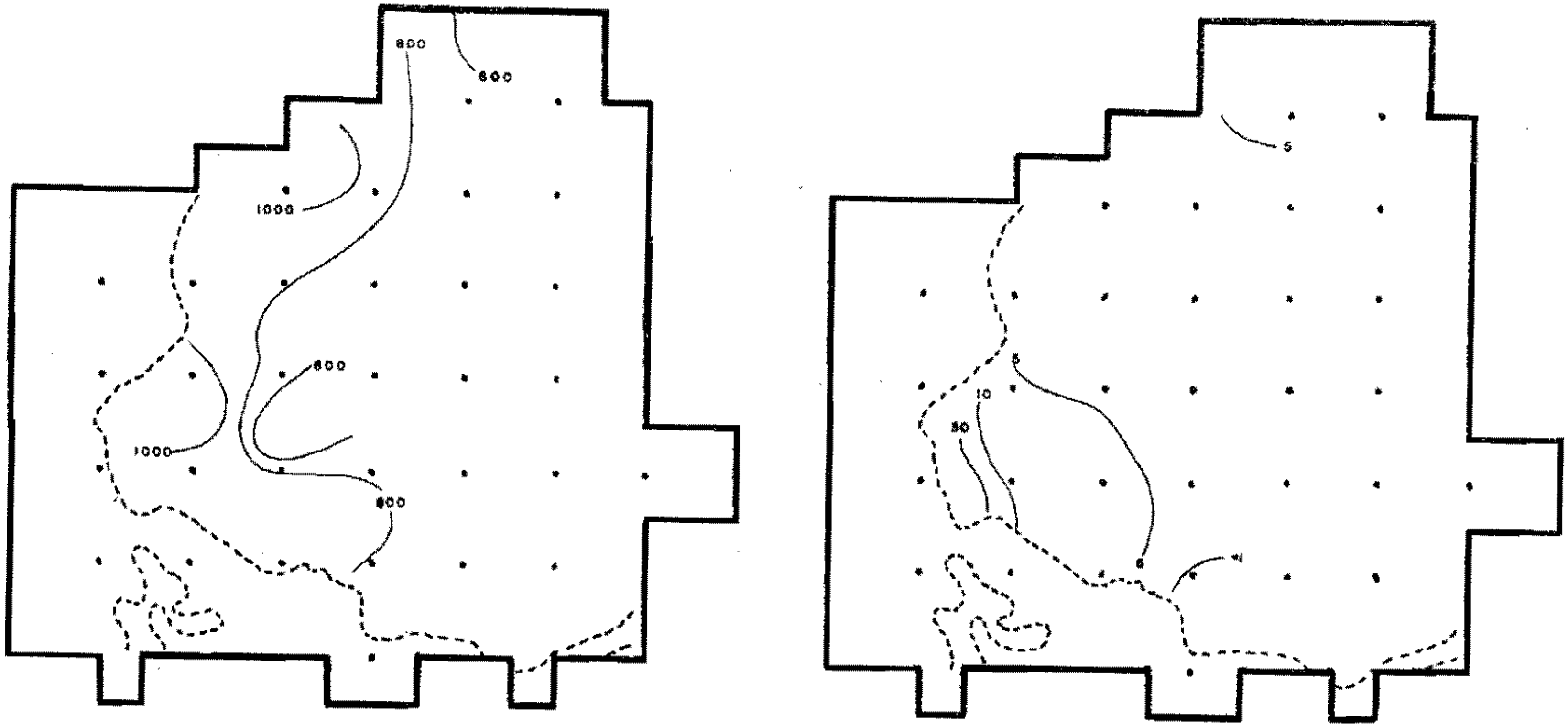
Figure 16. HCO_3^- and $CO_3^=$.



HCO$_3^-$ in milligrams/liter

CO$_3^=$ in milligrams/liter

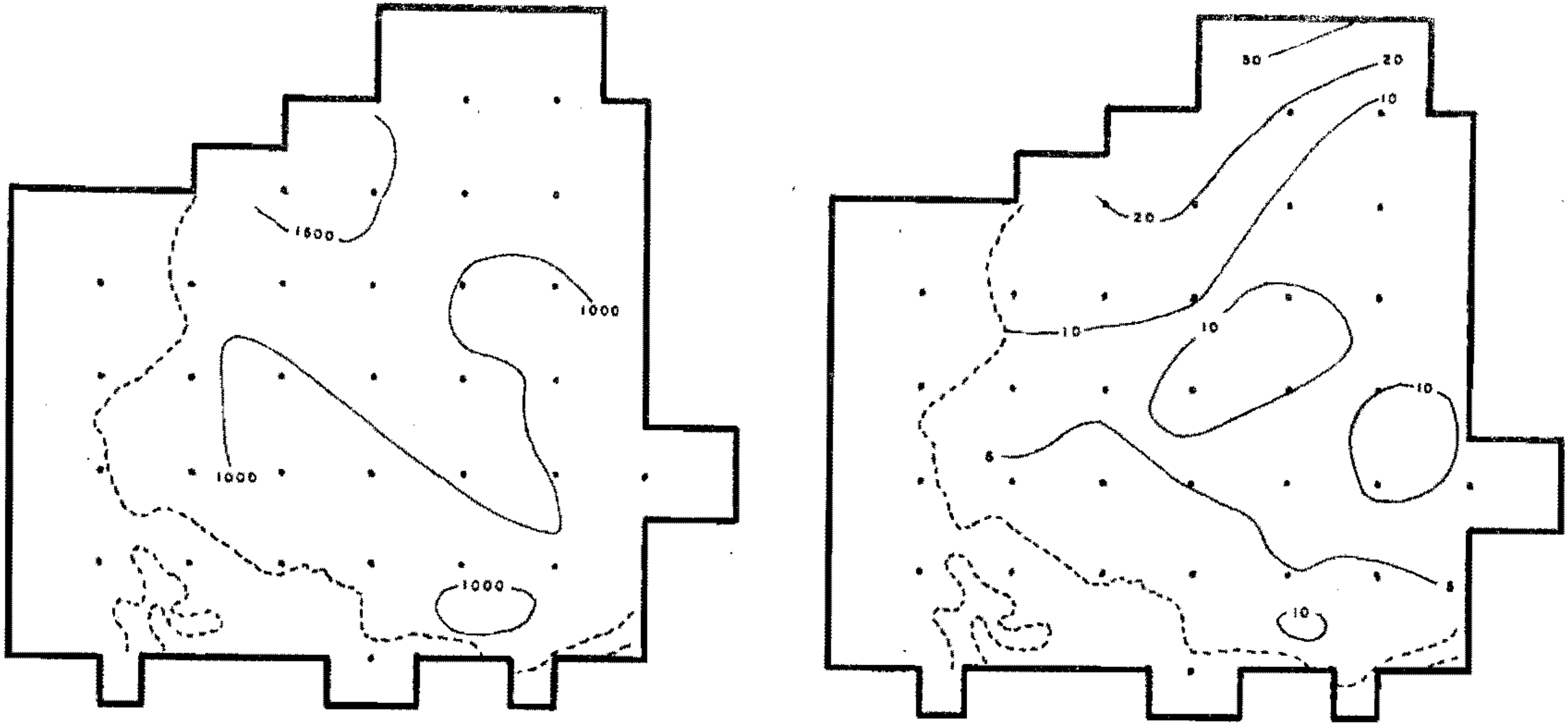
16b. Seam A and AB



HCO_3^- in milligrams/liter

$CO_3^=$ in milligrams/liter

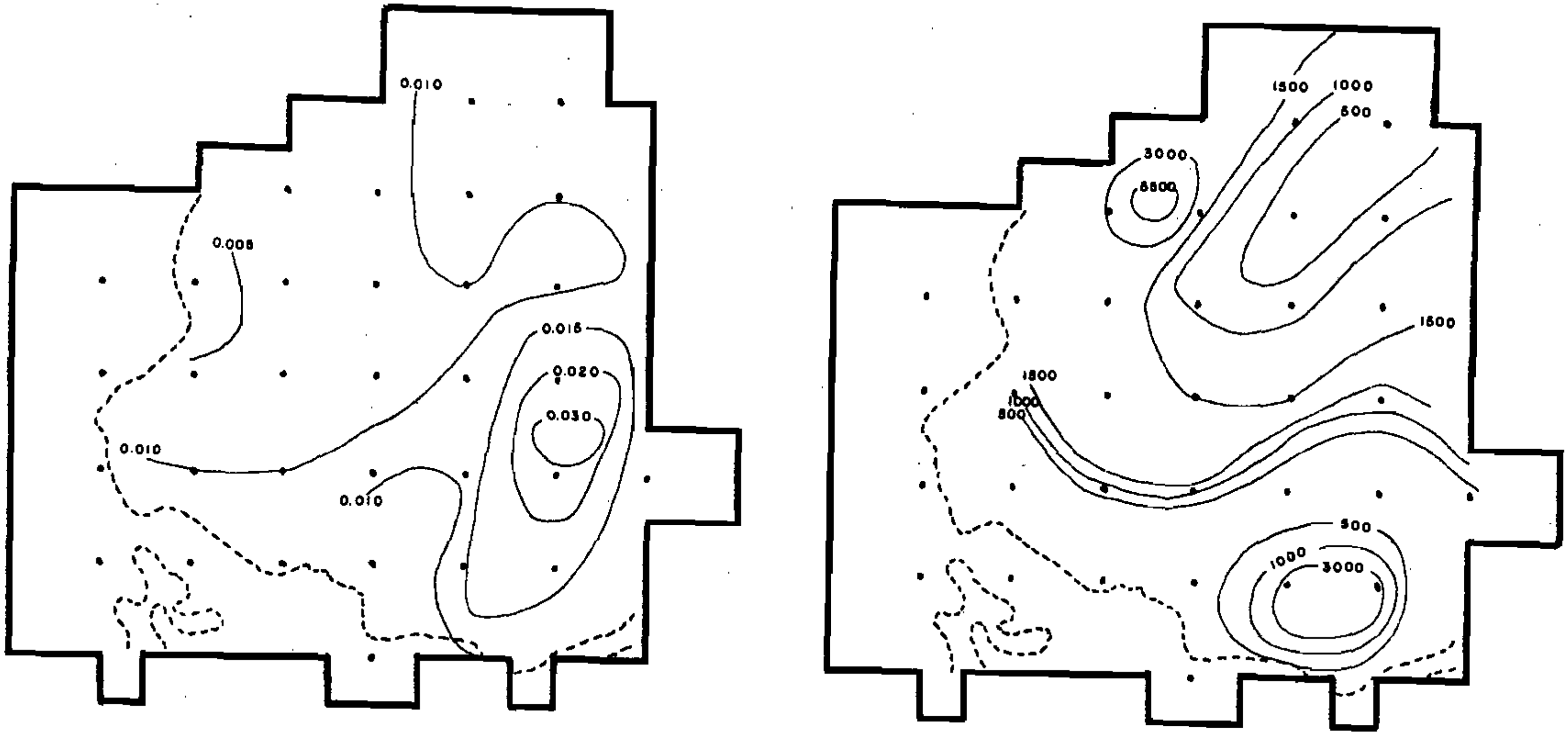
16c. Seam B



HCO_3^- in milligrams/liter

$CO_3^=$ in milligrams/liter

16d. About 20 feet below Seam B and AB

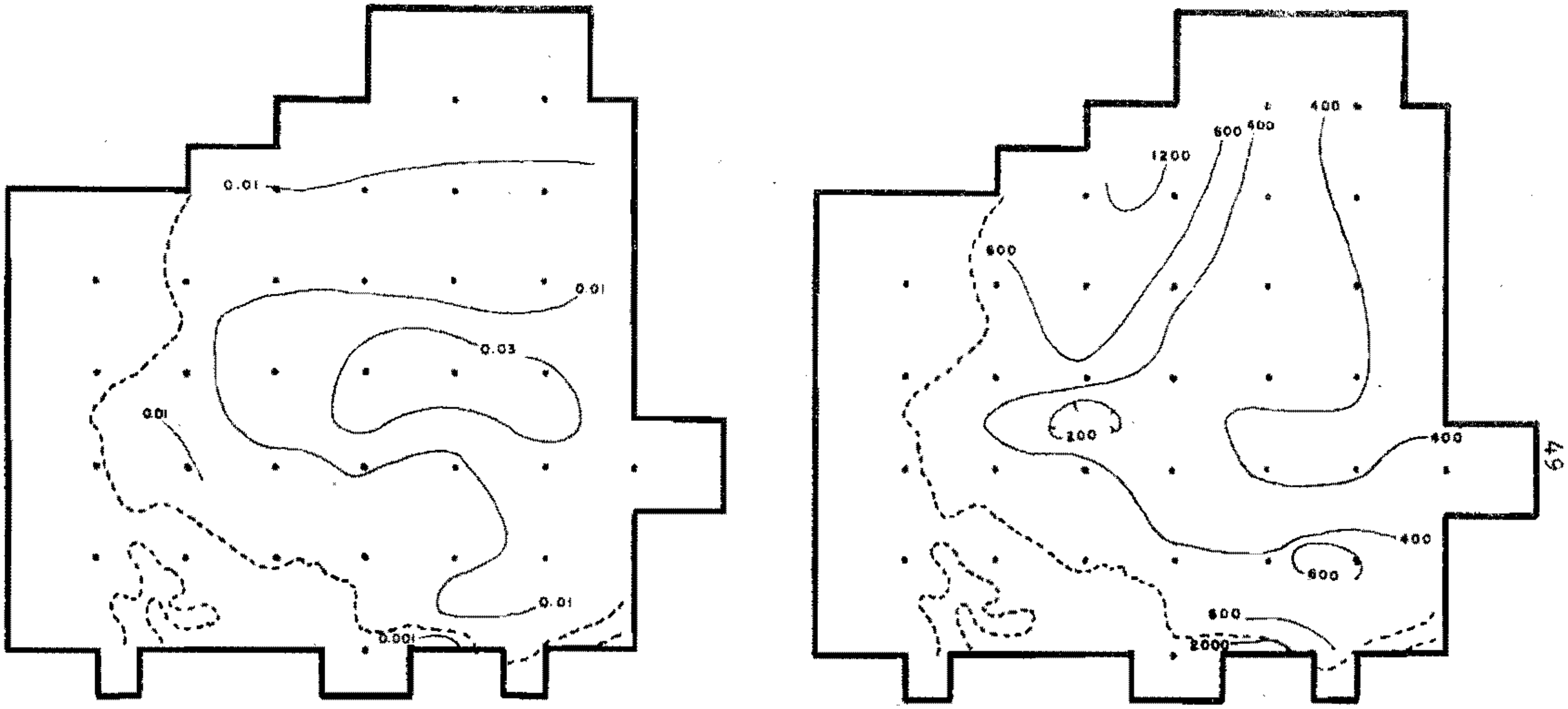


OH$^-$ in milligrams/liter

SO$_4^=$ in milligrams/liter

17a. About 20 feet above Seam A and AB

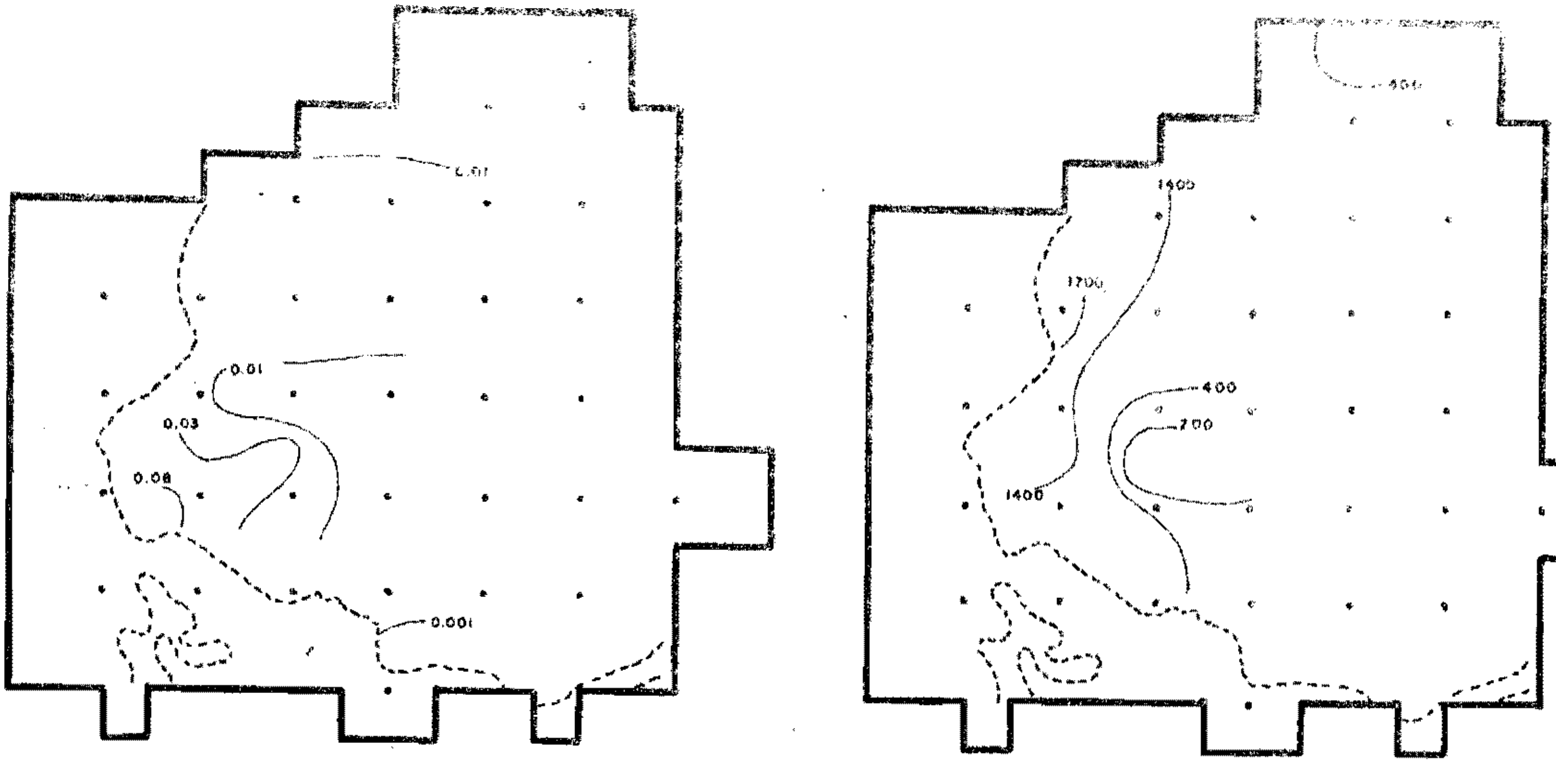
Figure 17. OH$^-$ and SO$_4^=$.



OH$^-$ in milligrams/liter

SO$_4^=$ in milligrams/liter

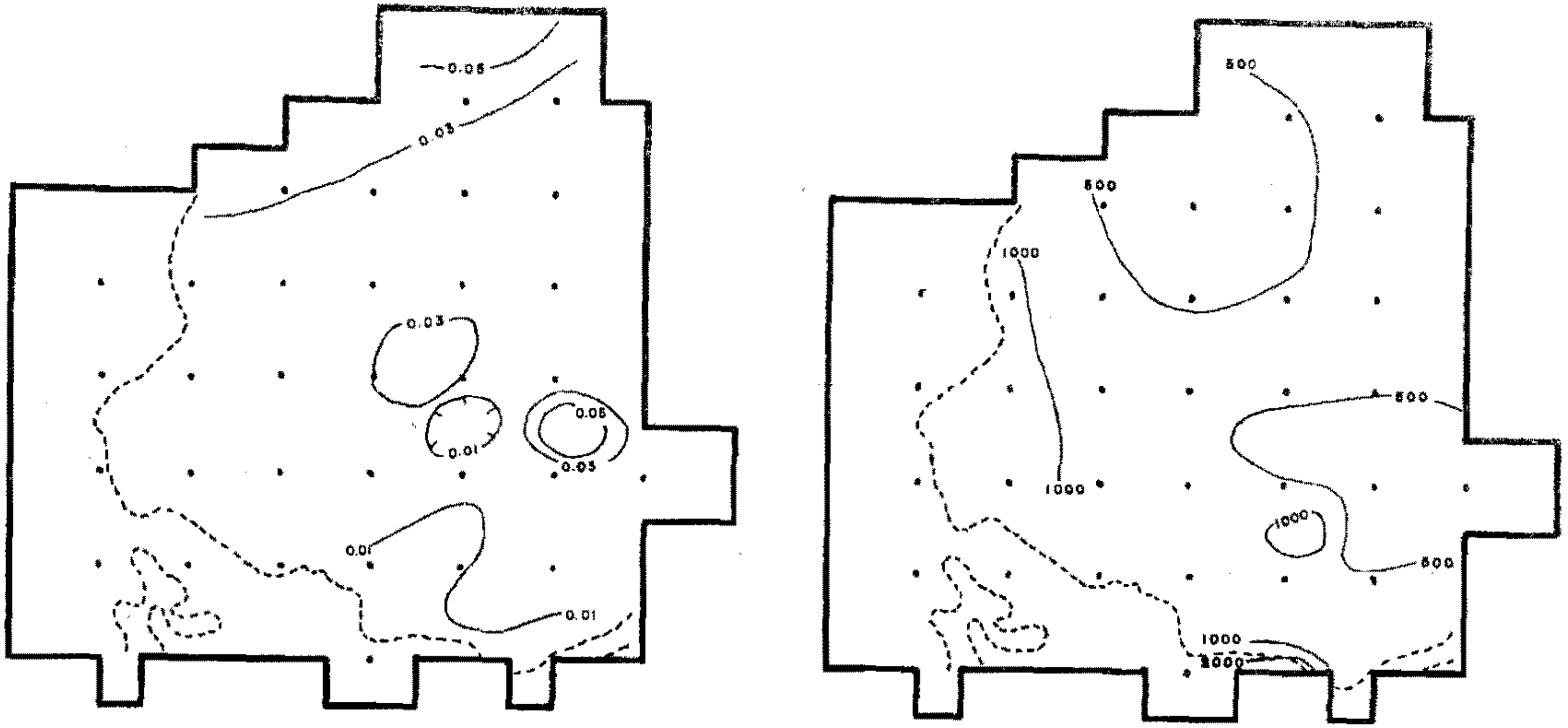
17b. Seam A and AB



OH^- in milligrams/liter

$SO_4^=$ in milligrams/liter

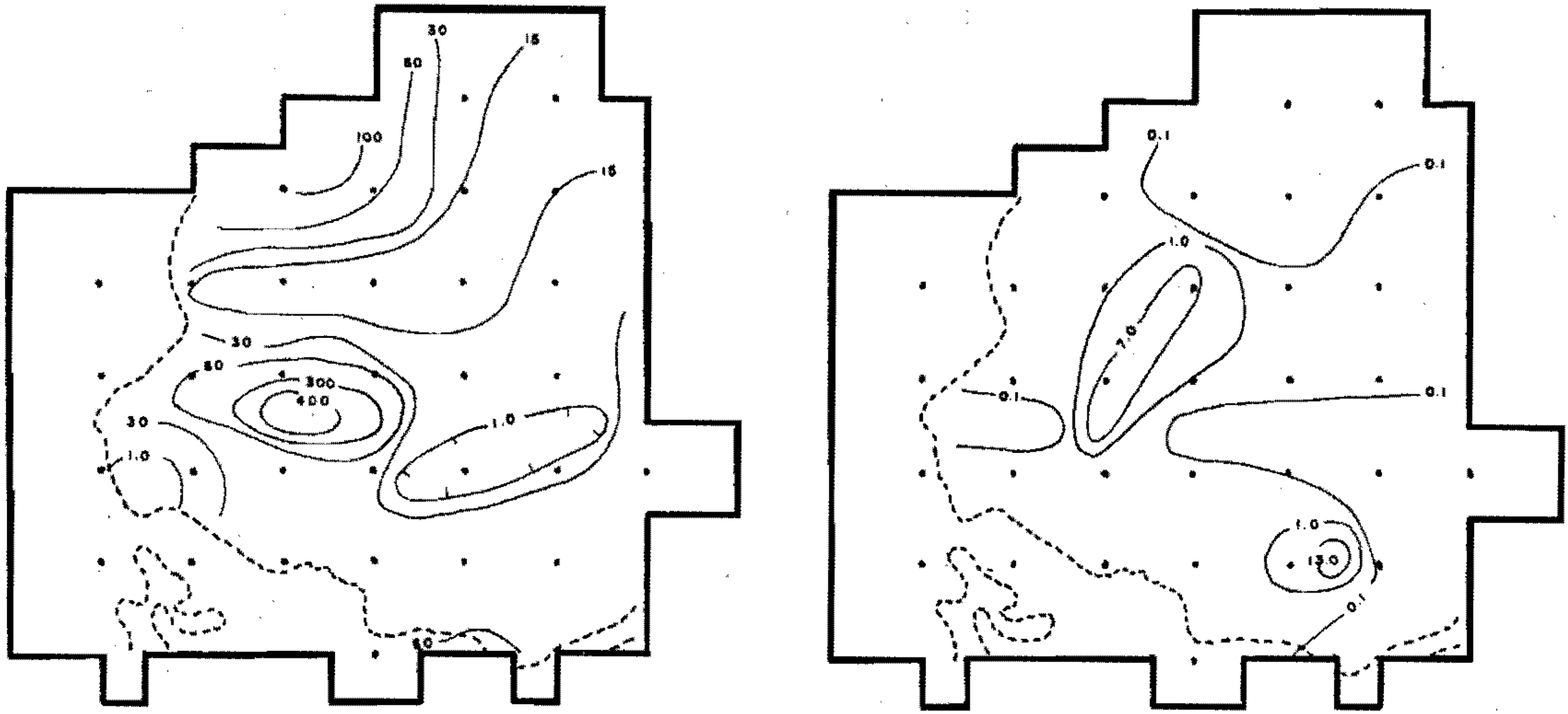
17c. Seam B



OH^- in milligrams/liter

$SO_4^=$ in milligrams/liter

17d. About 20 feet below Seam B and AB

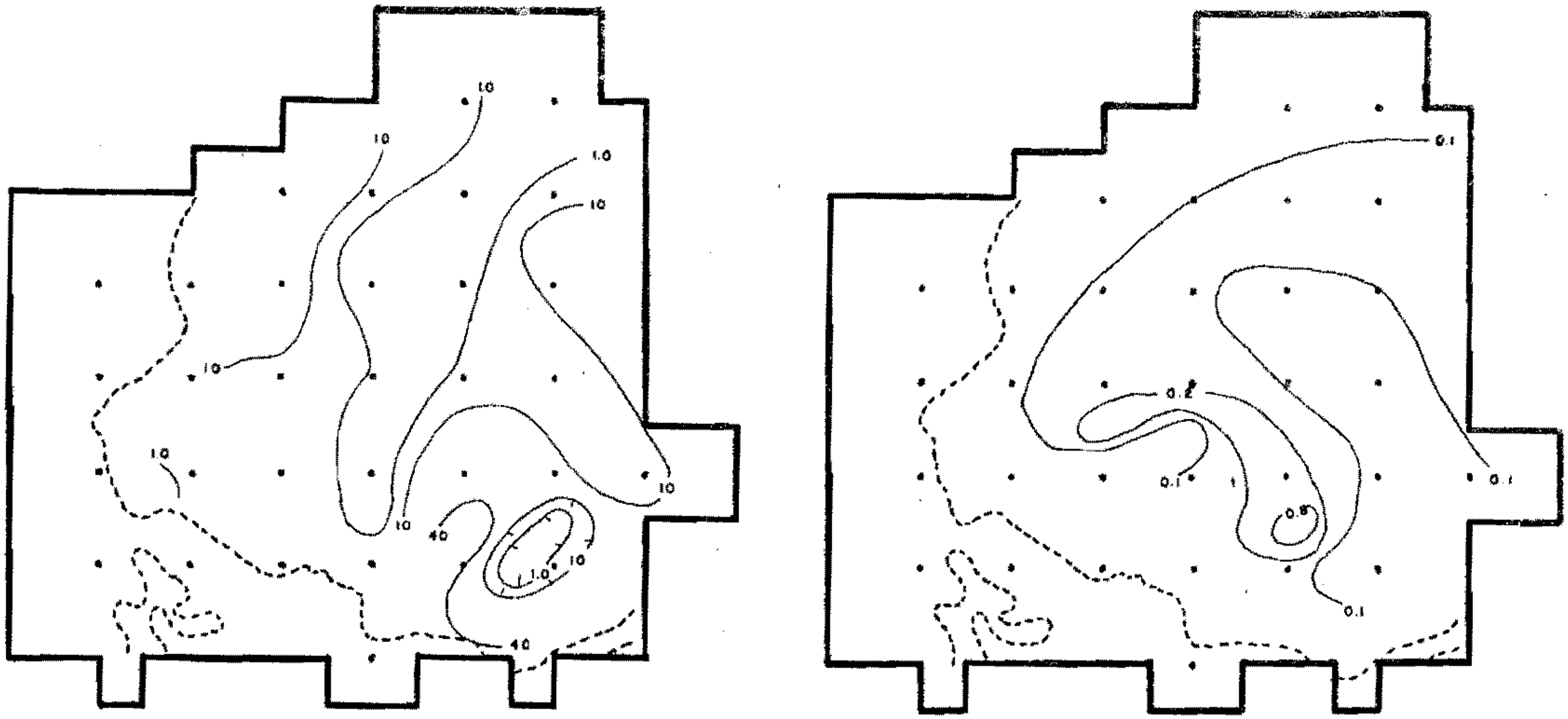


Cl$^-$ in milligrams/liter

NO$_3^-$ in milligrams/liter

18a. About 20 feet above Seam A and AB

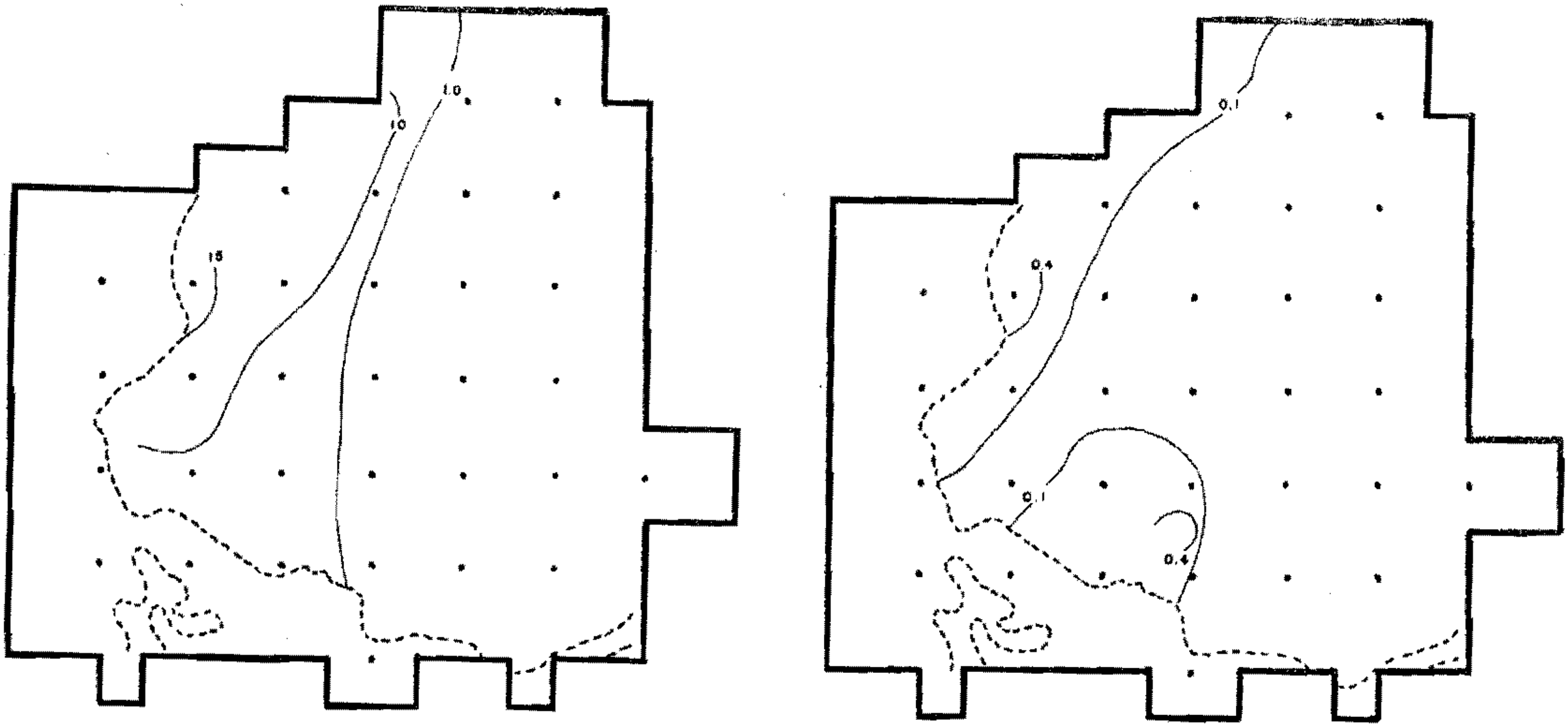
Figure 18. Cl$^-$ and NO$_3^-$.



Cl$^-$ in milligrams/liter

NO$_3^-$ in milligrams/liter

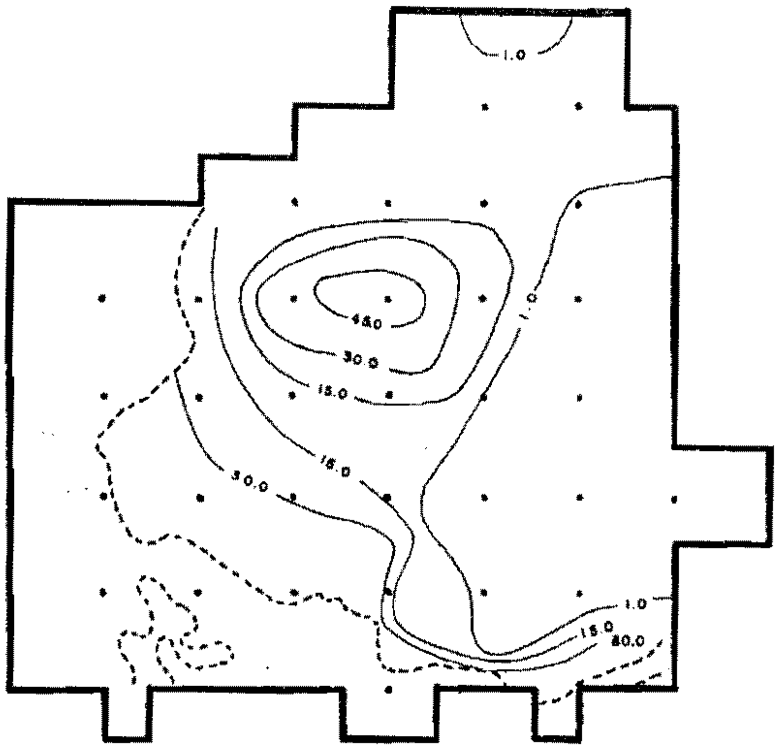
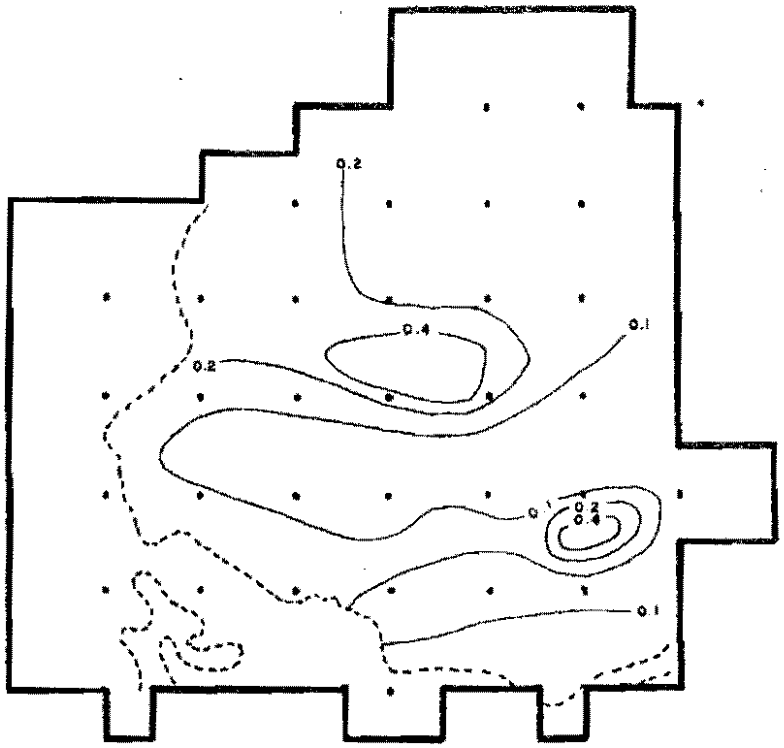
18b. Seam A and AB



Cl$^-$ in milligrams/liter

NO$_3^-$ in milligrams/liter

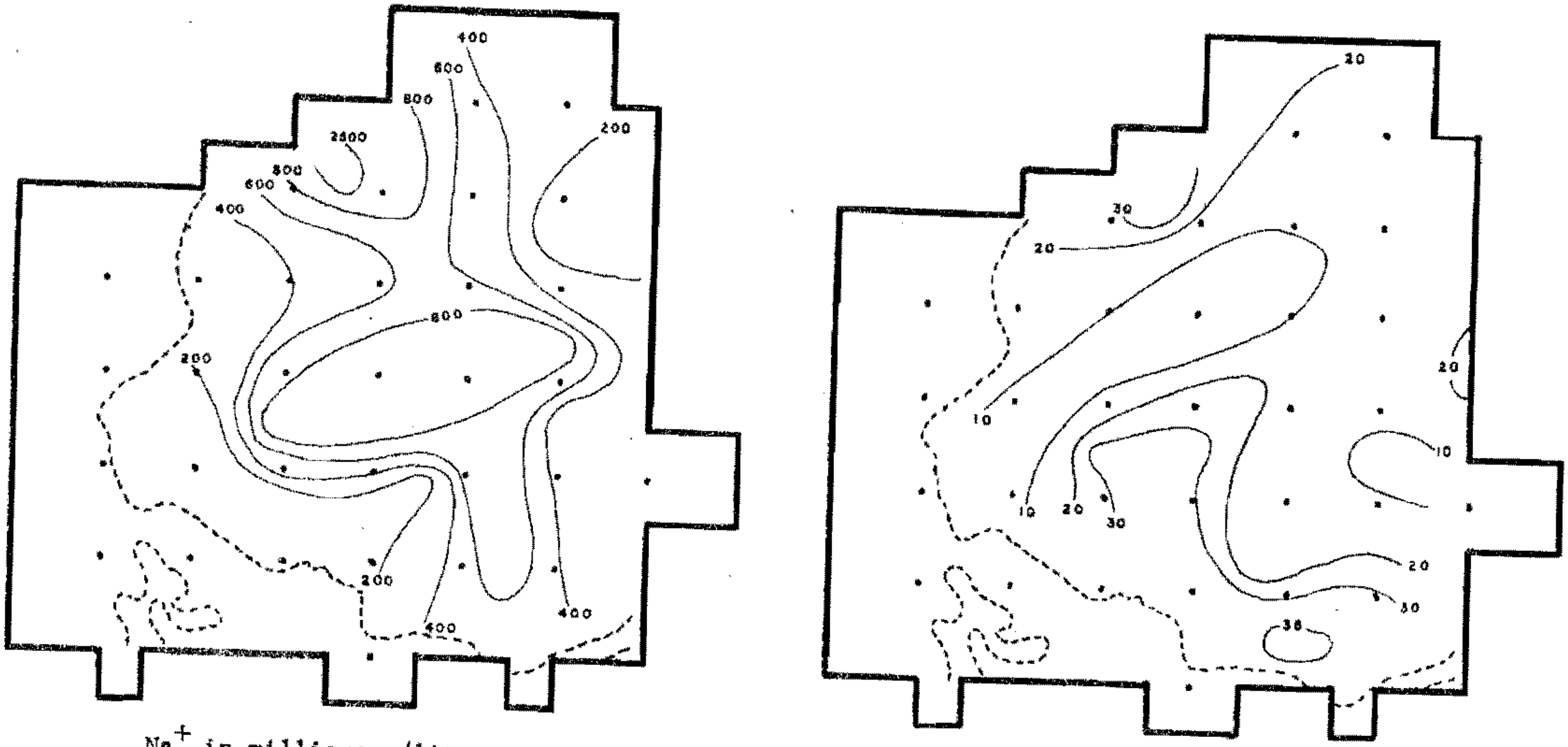
18c. Seam B



Cl$^-$ in milligrams/liter

NO$_3^-$ in milligrams/liter

18d. About 20 feet below Seam B and AB

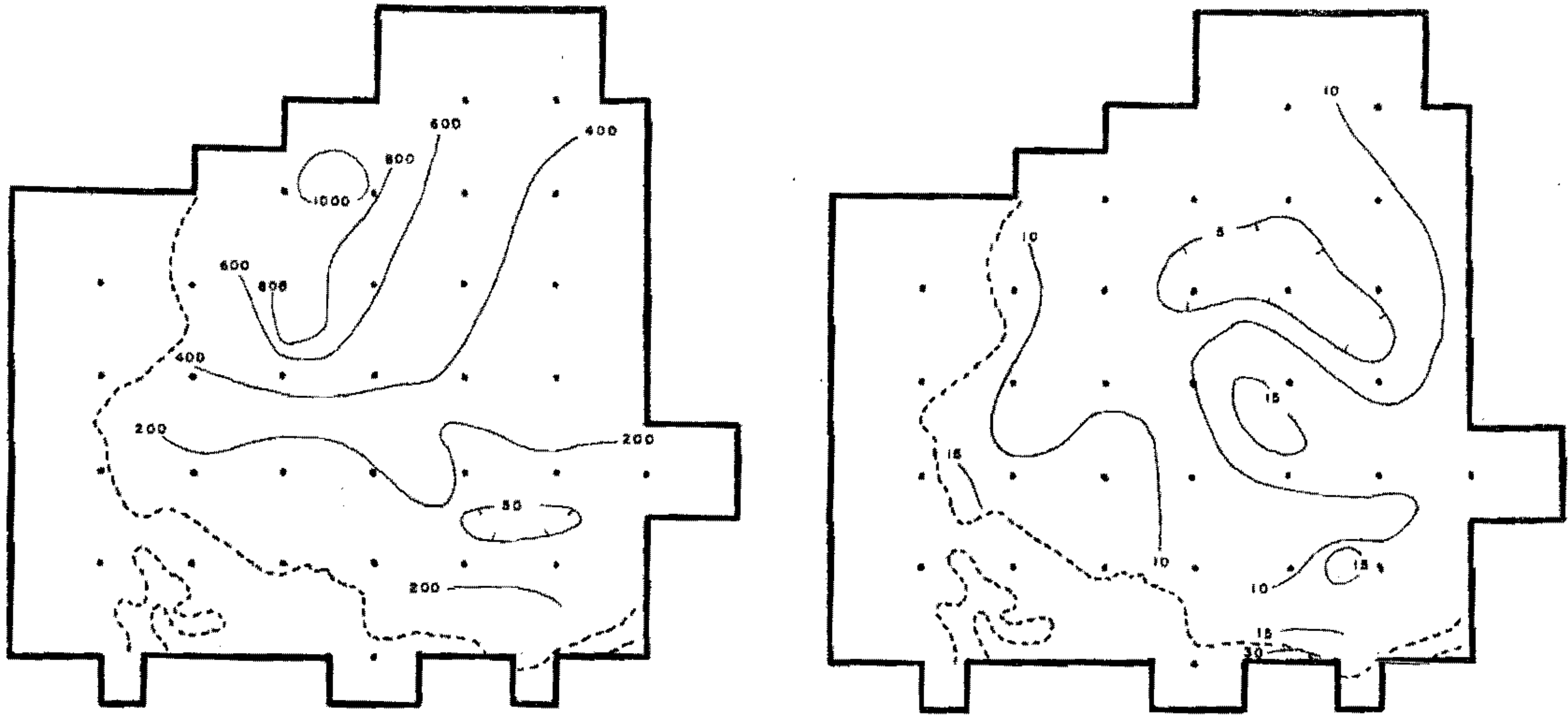


Na$^+$ in milligrams/liter

K$^+$ in milligrams/liter

19a. About 20 feet above Seam A and AB

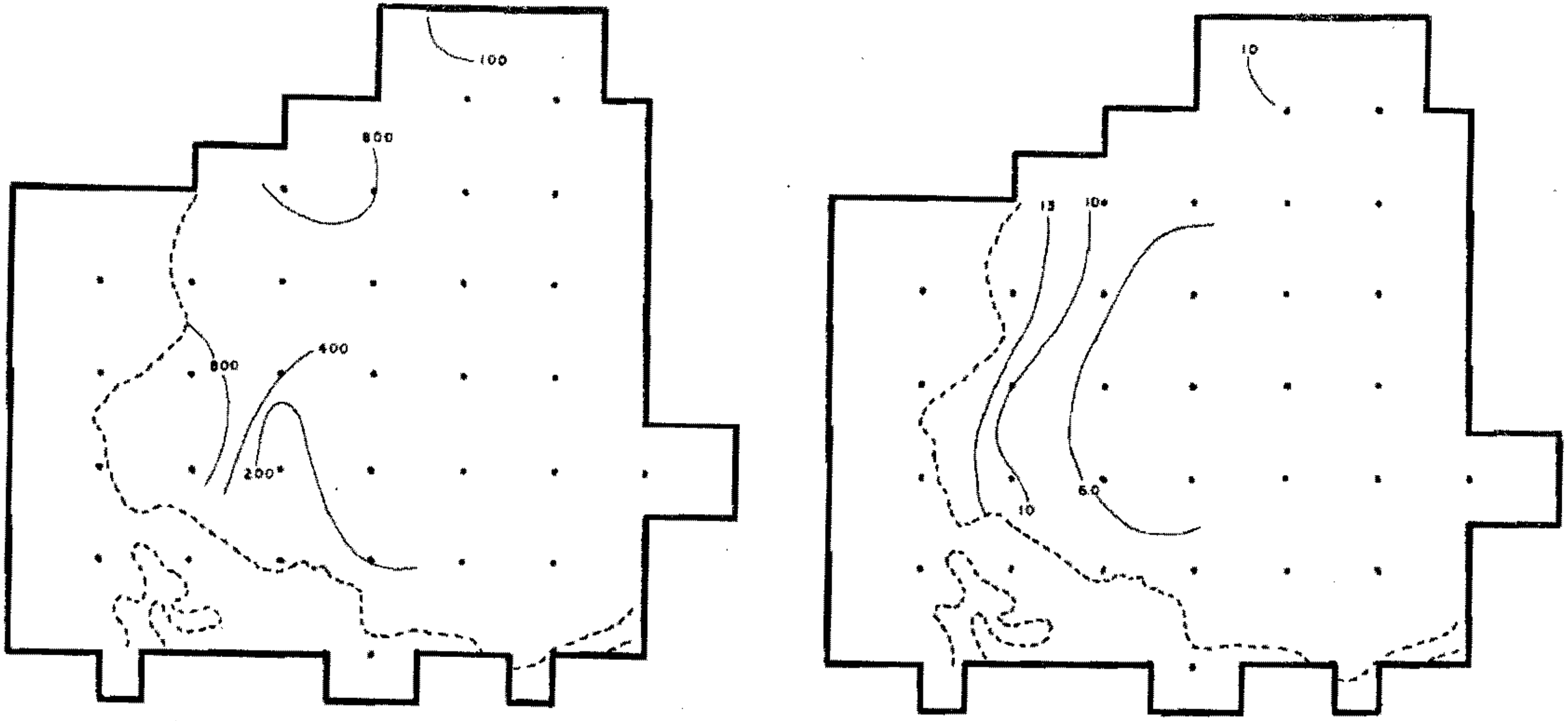
Figure 19. Na$^+$ and K$^+$.



Na$^+$ in milligrams/liter

K$^+$ in milligrams/liter

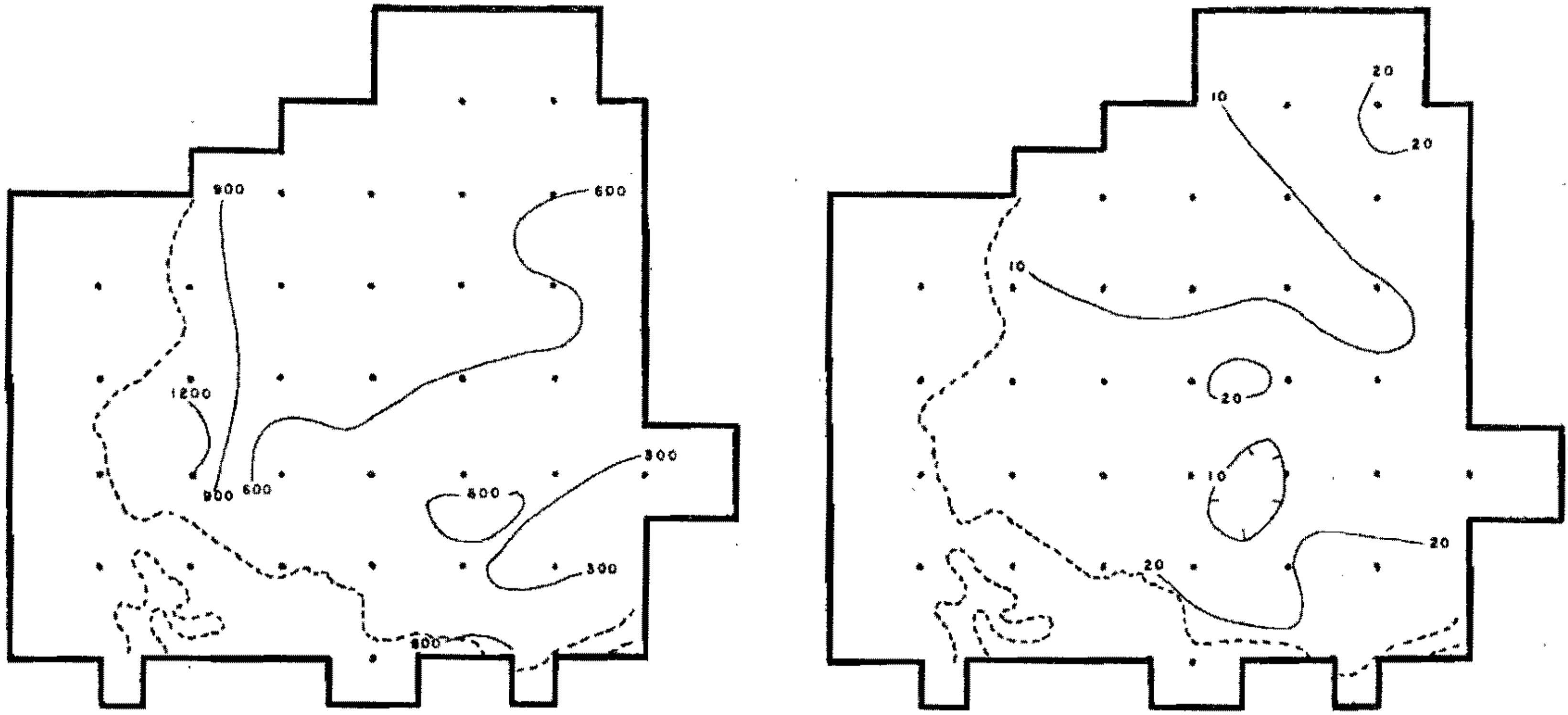
19b. Seam A and AB



Na$^+$ in milligrams/liter

K$^+$ in milligrams/liter

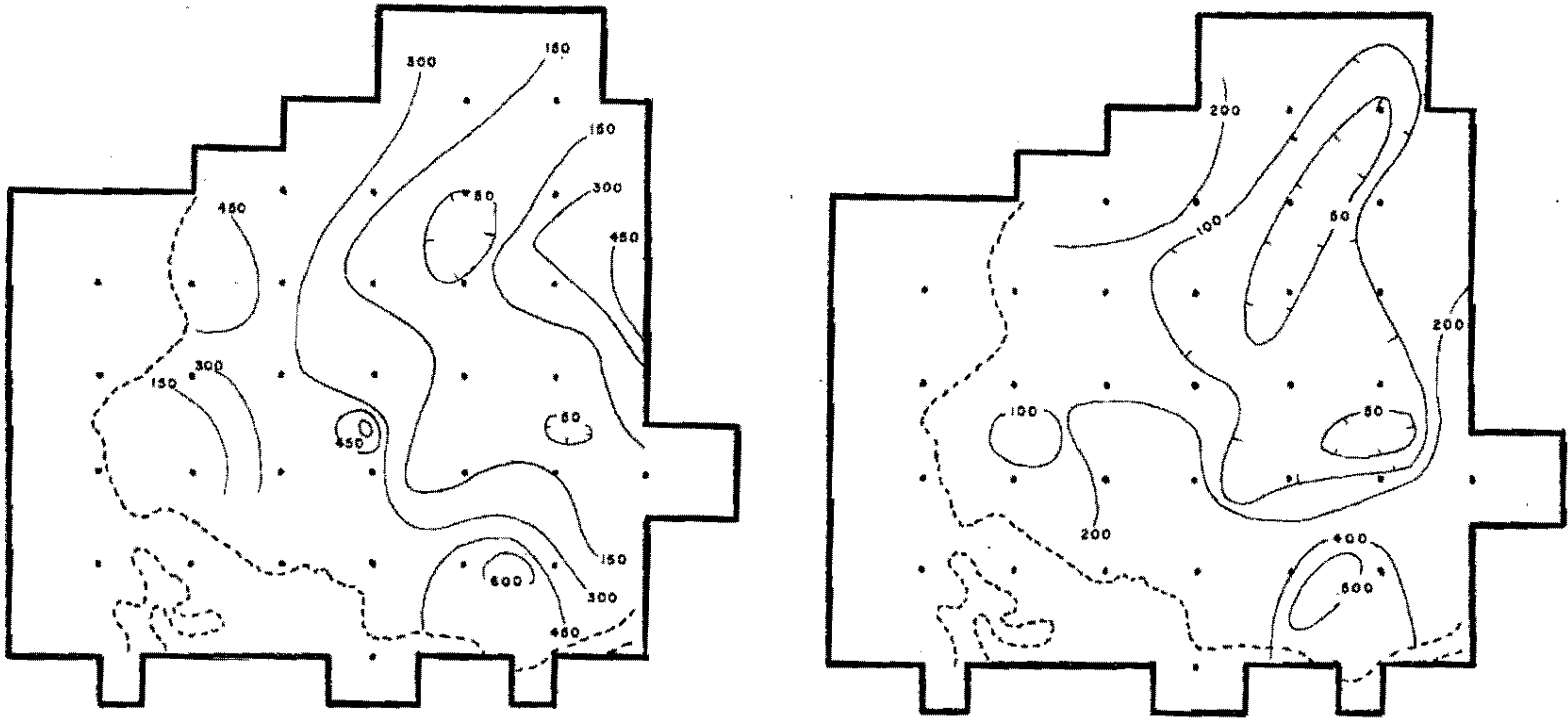
19c. Seam B



Na$^+$ in milligrams/liter

K$^+$ in milligrams/liter

19d. About 20 feet below Seam B and AB

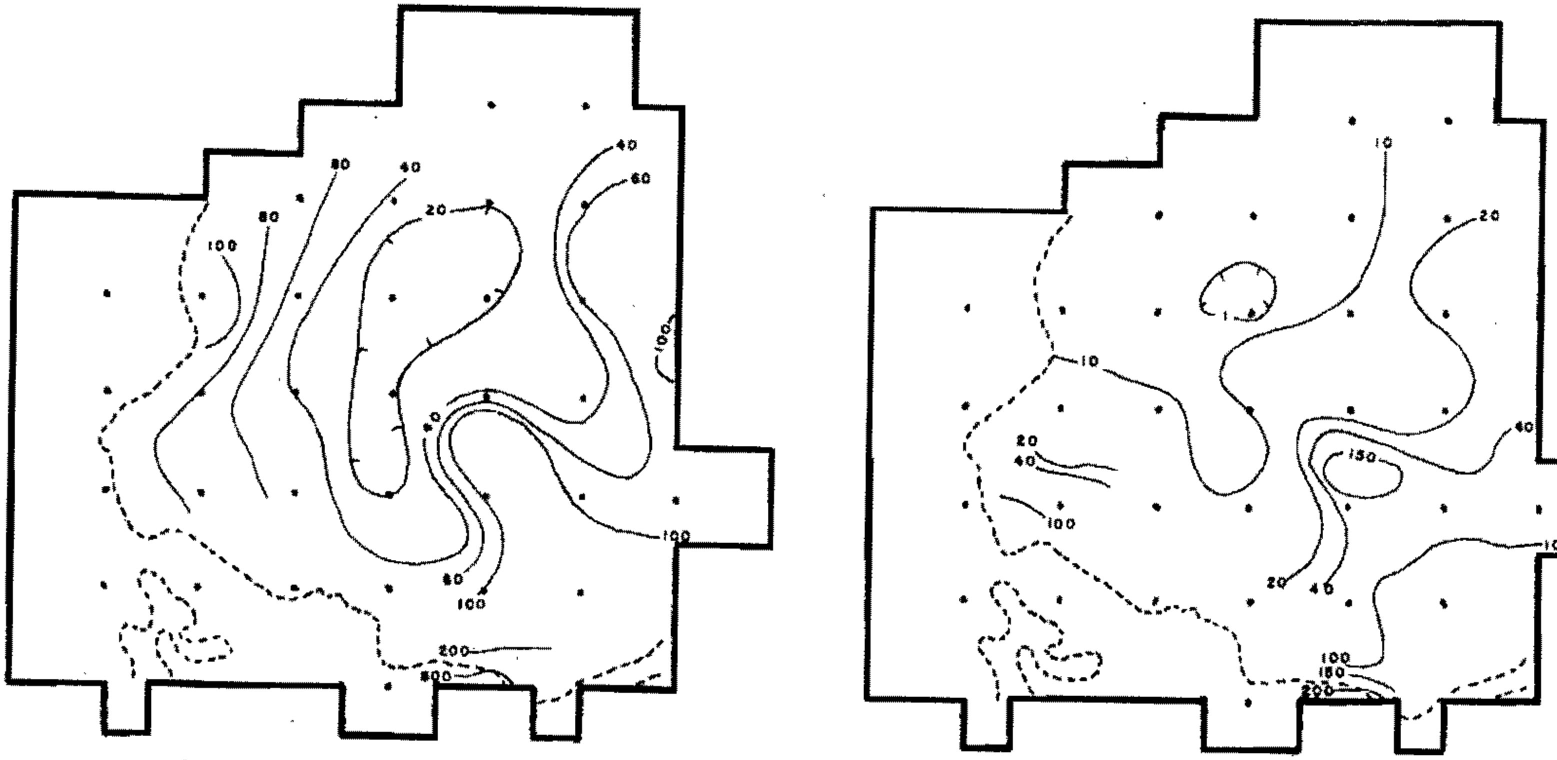


Ca^{++} in milligrams/liter

Mg^{++} in milligrams/liter

20a. About 20 feet above Seam A and AB

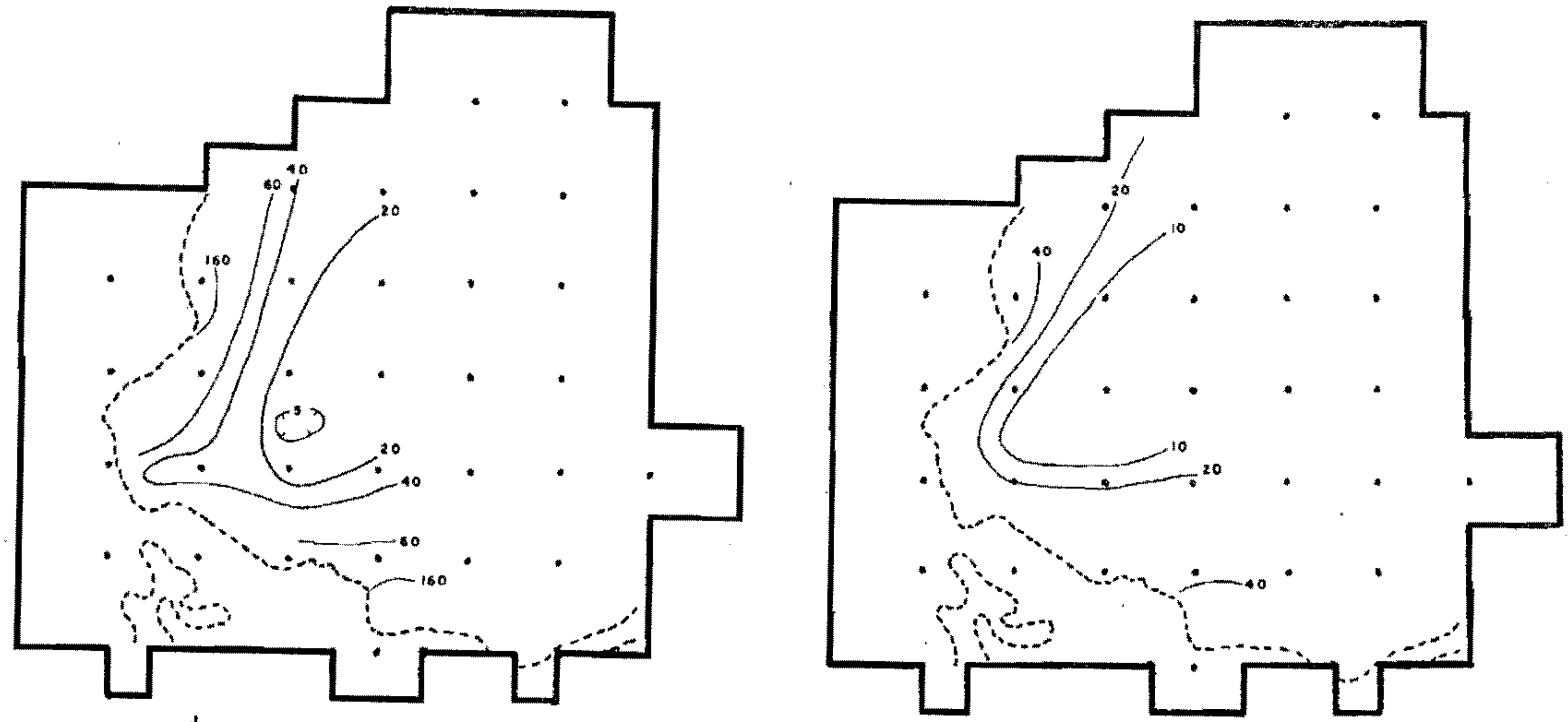
Figure 20. Ca^{++} and Mg^{++} .



Ca‡ in milligrams/liter

Mg‡ in milligrams/liter

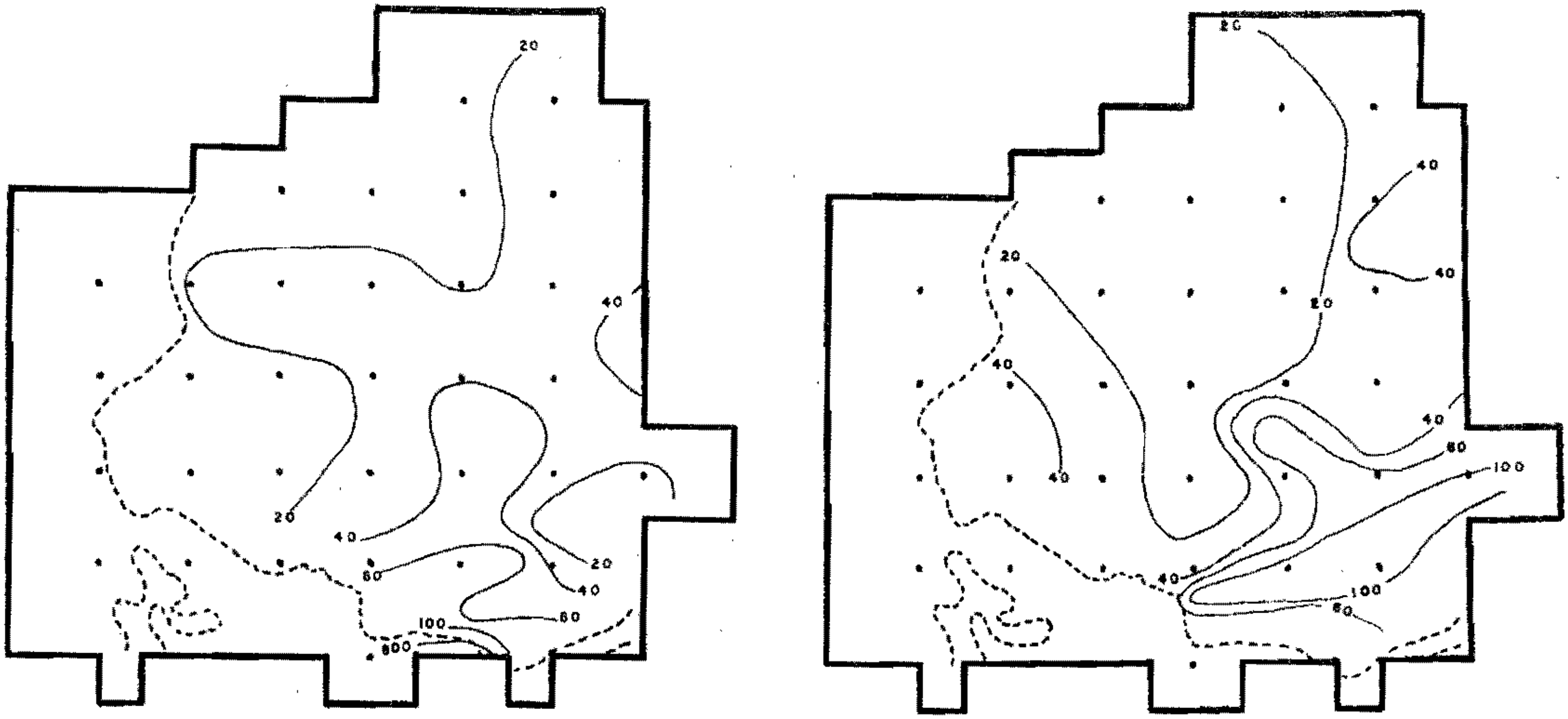
20b. Seam A and AB



Ca^{++} in milligrams/liter

Mg^{++} in milligrams/liter

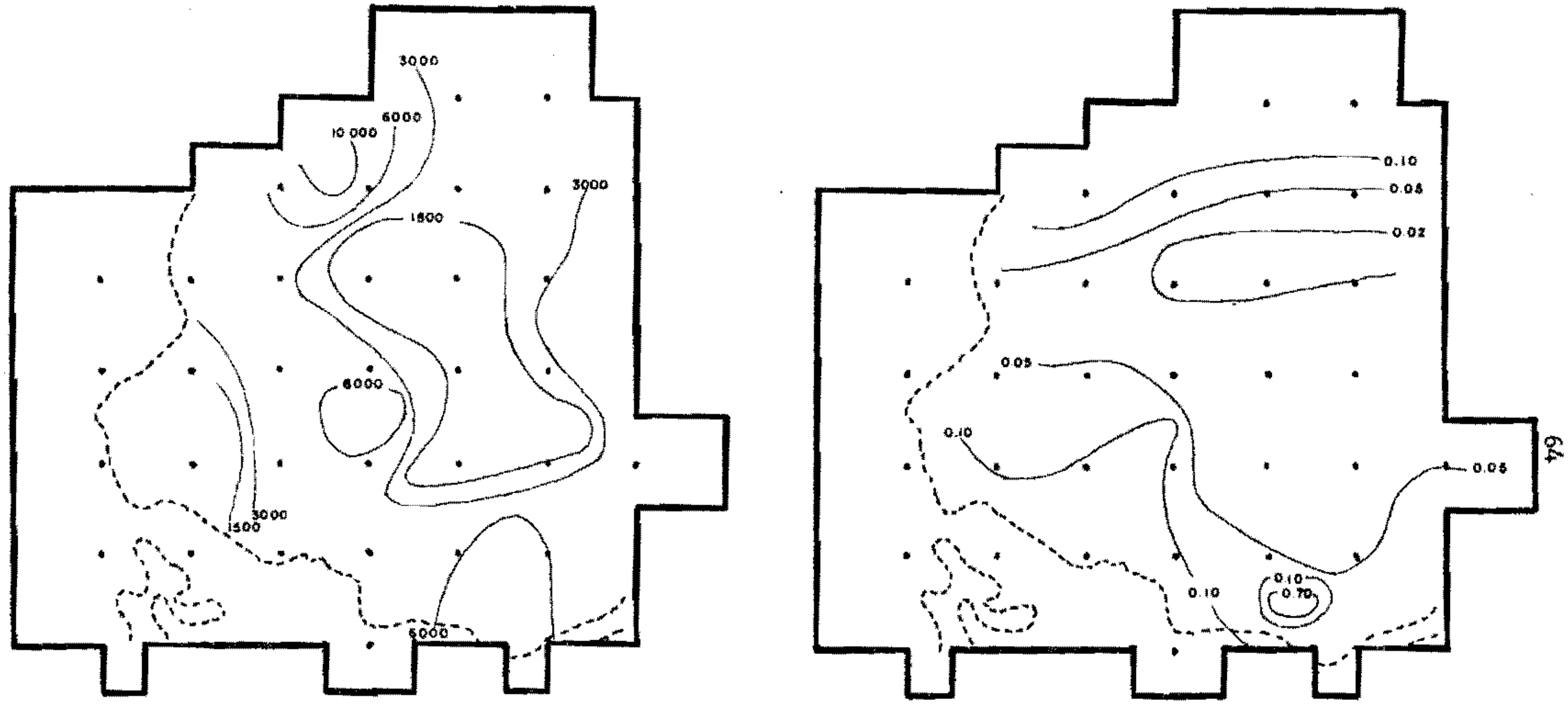
20c. Seam B



Ca^{++} in milligrams/liter

Mg^{++} in milligrams/liter

20d. About 20 feet below Seam B and AB

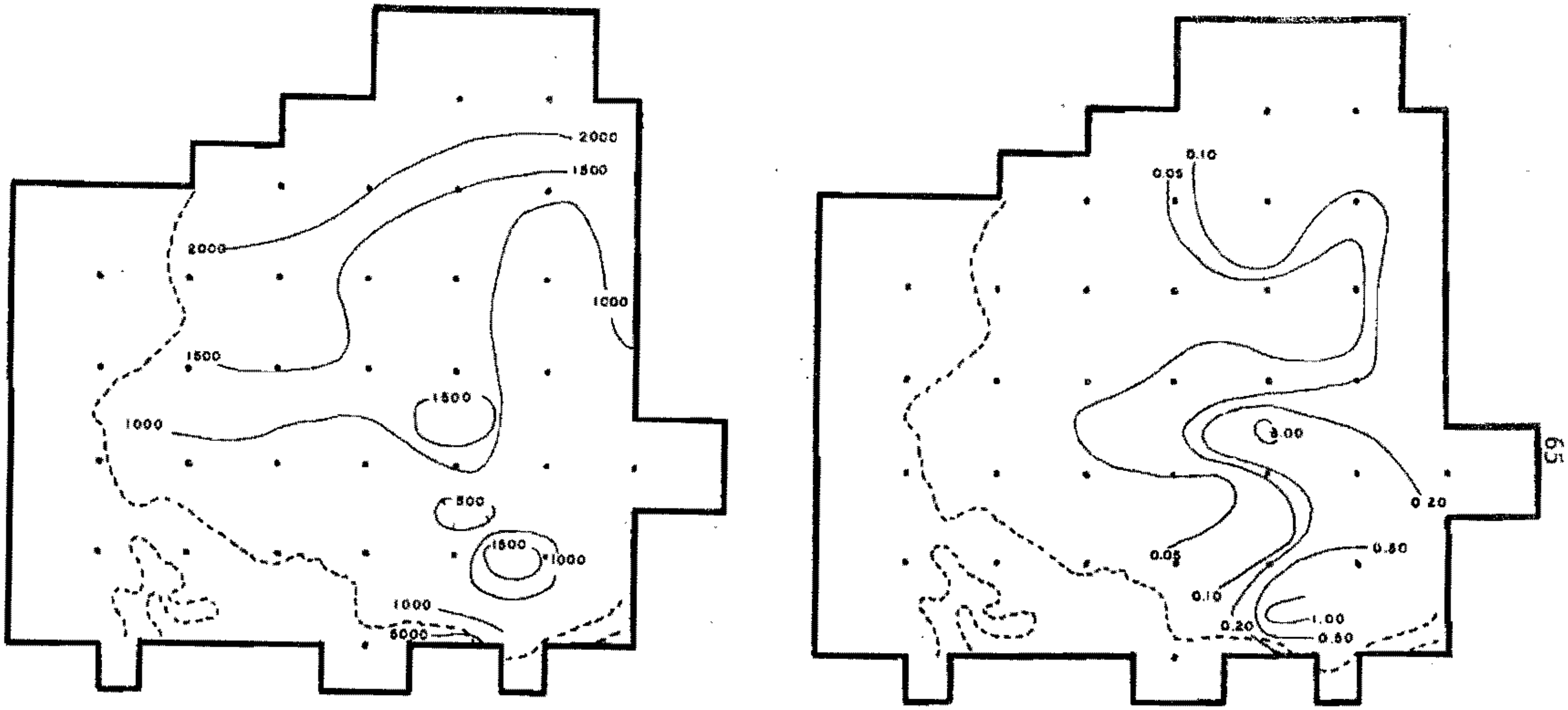


TDS in milligrams/liter

Fe in milligrams/liter

21a. About 20 feet above Seam A and AB

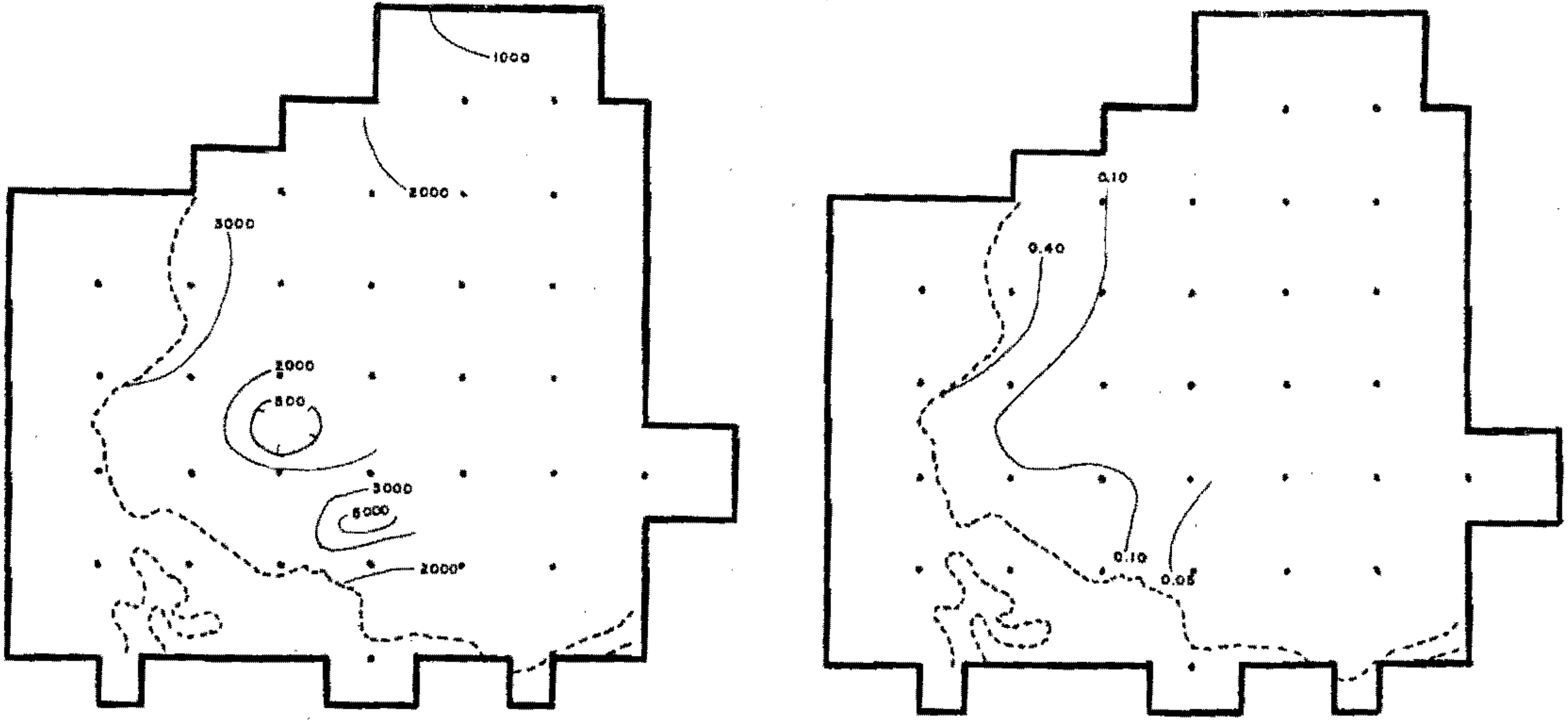
Figure 21. Total Dissolved Solids (TDS) and Fe.



TDS in milligrams/liter

Fe in milligrams/liter

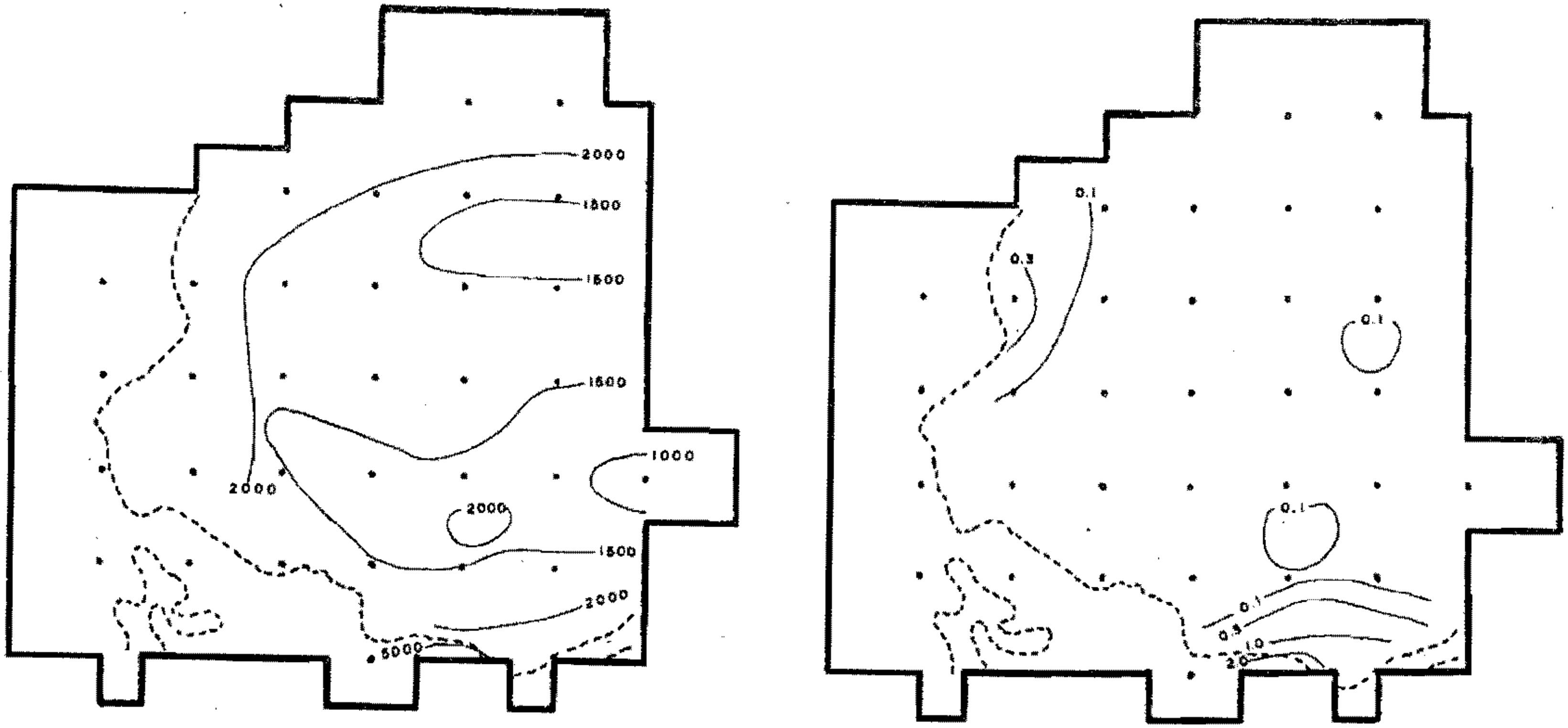
21b. Seam A and AB



TDS in milligrams/liter

Fe in milligrams/liter

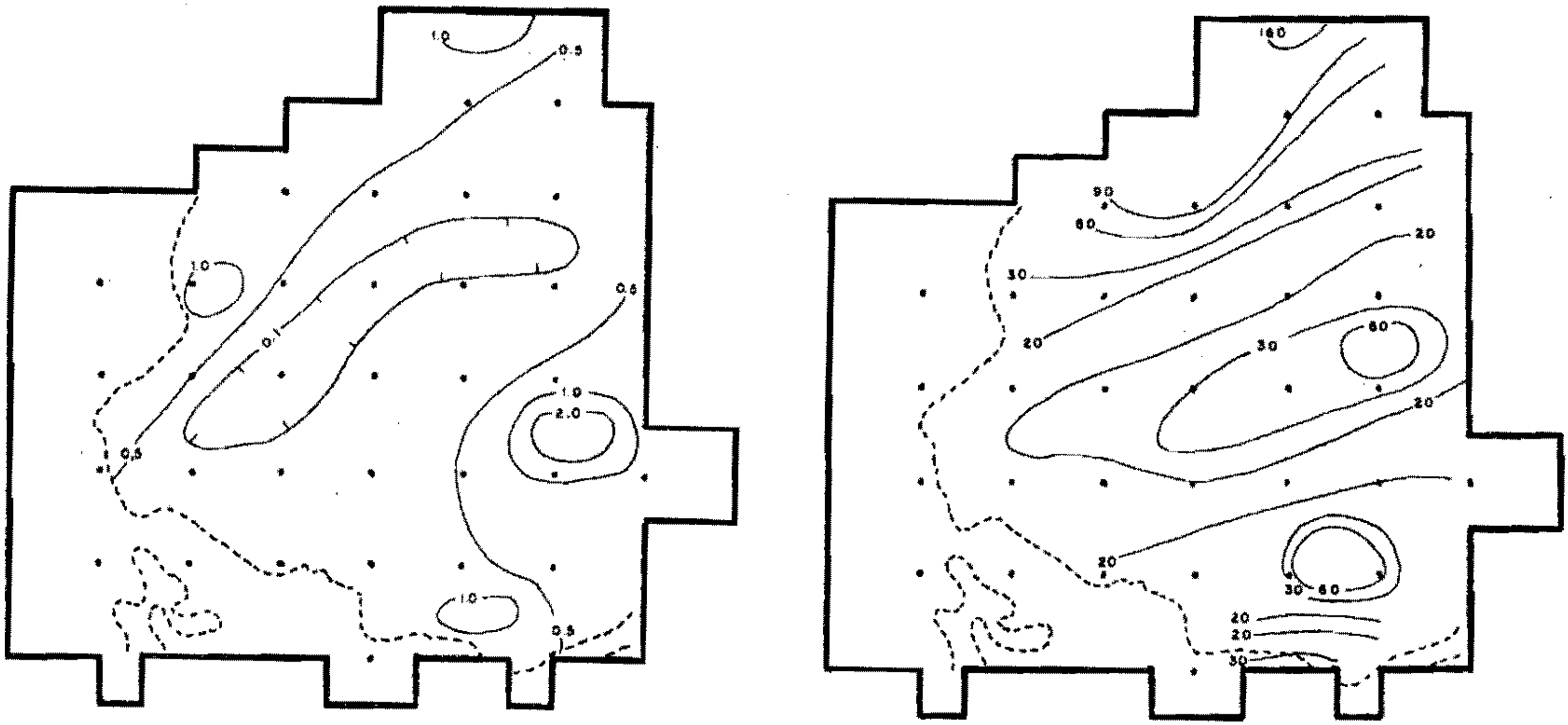
21c. Seam B



TDS in milligrams/liter

Fe in milligrams/liter

21d. About 20 feet below Seam B and AB

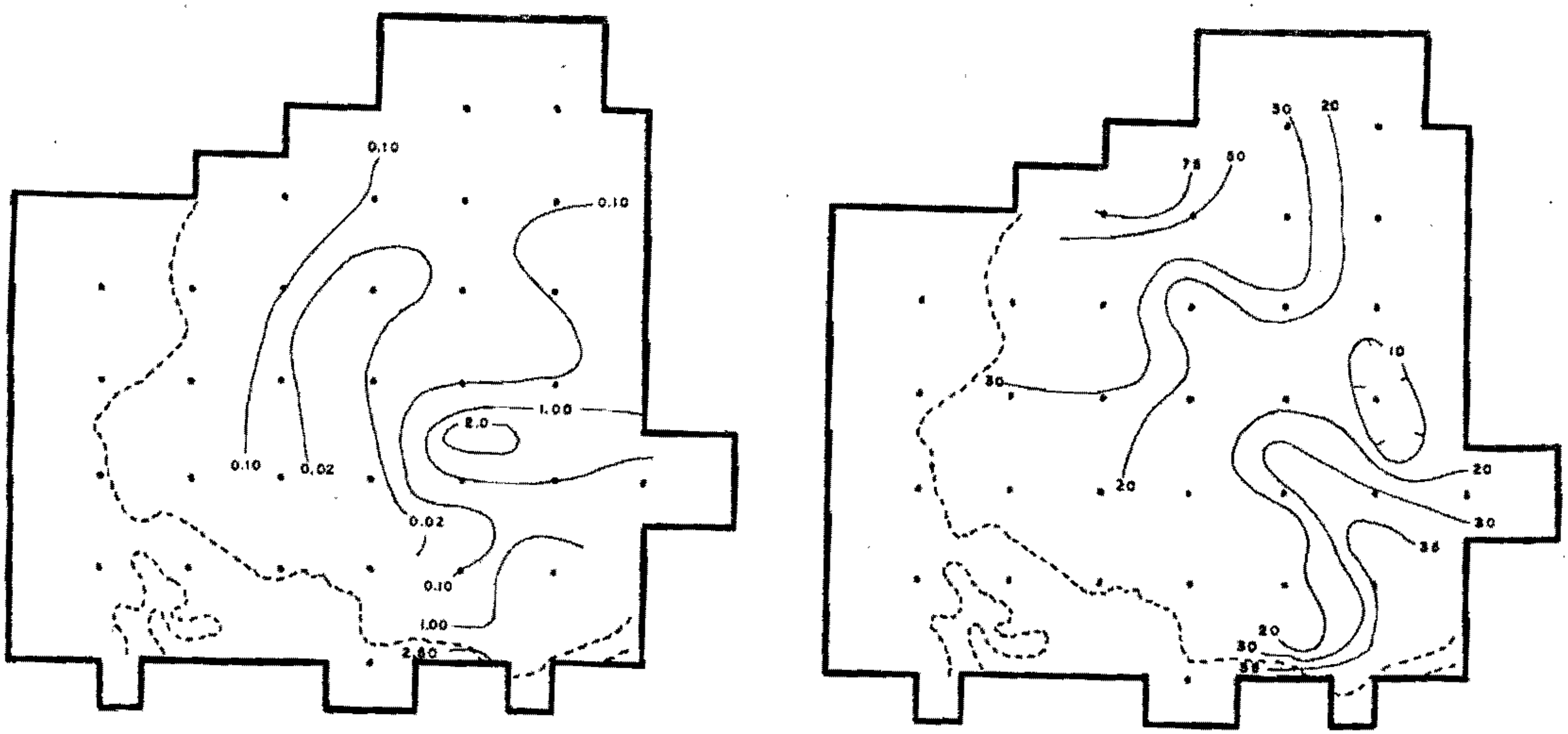


Mn in milligrams/liter

Cu in micrograms/liter

22a. About 20 feet above Seam A and AB

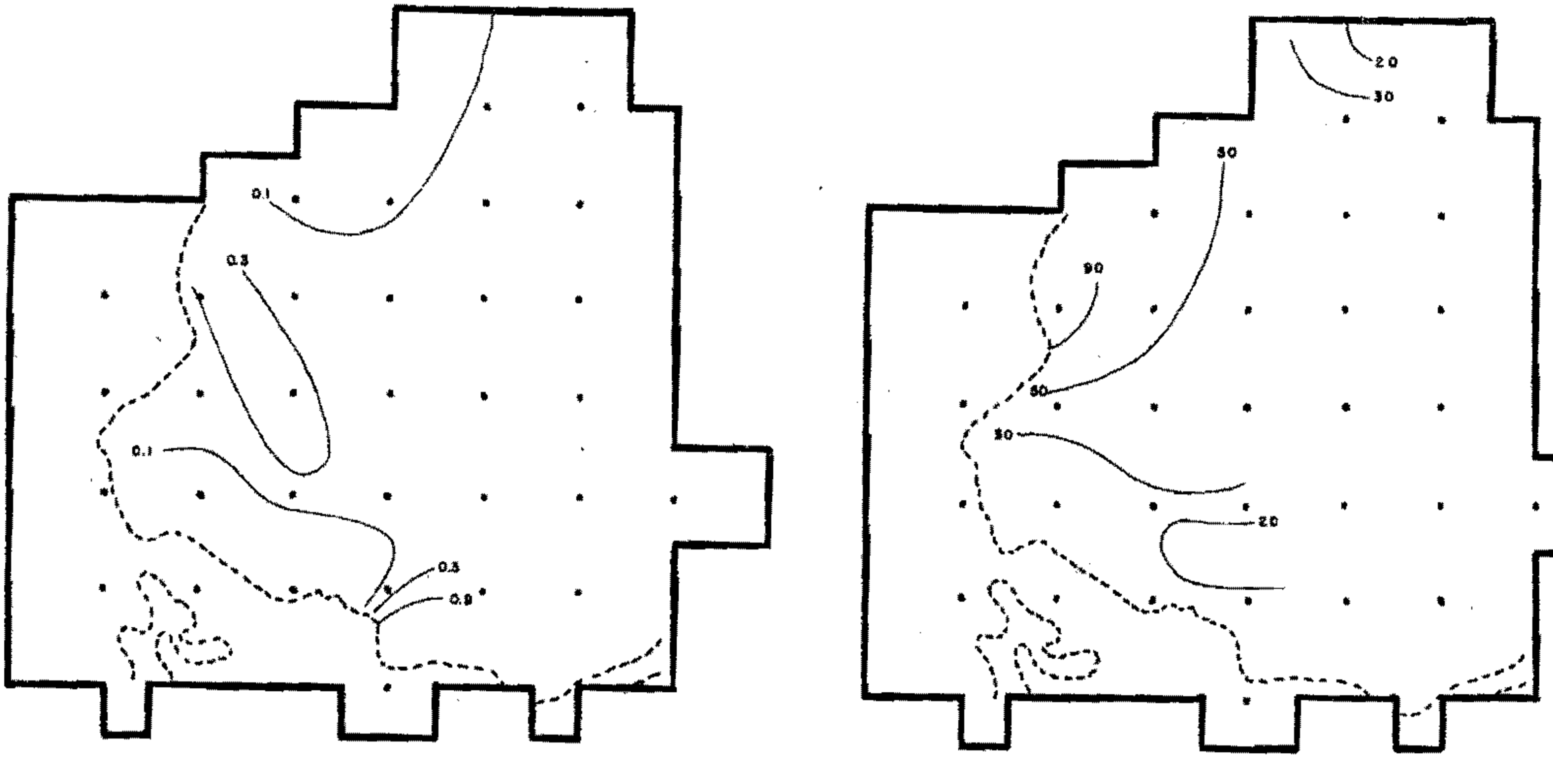
Figure 22. Mn and Cu



Mn in milligrams/liter

Cu in micrograms/liter

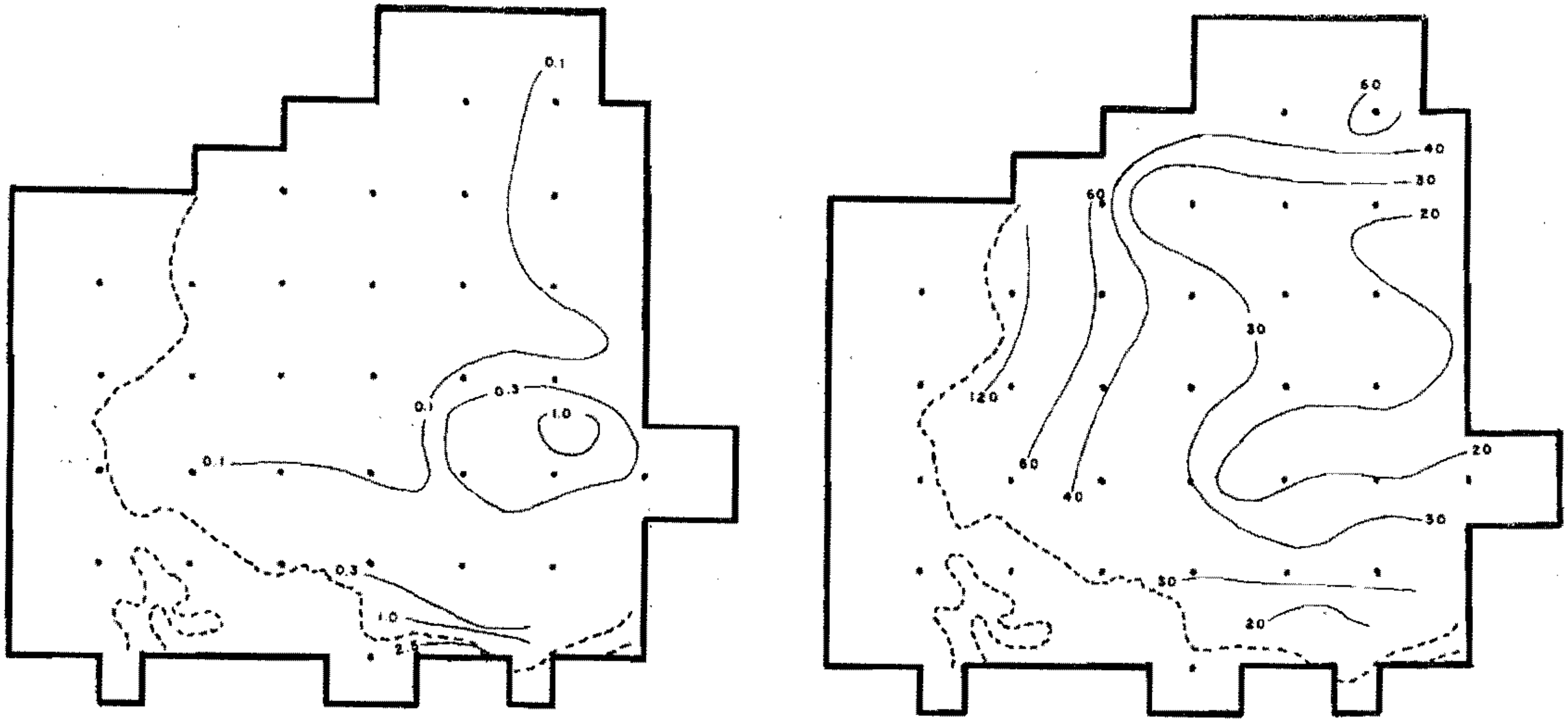
22b. Seam A and AB



Mn in milligrams/liter

Cu in micrograms/liter

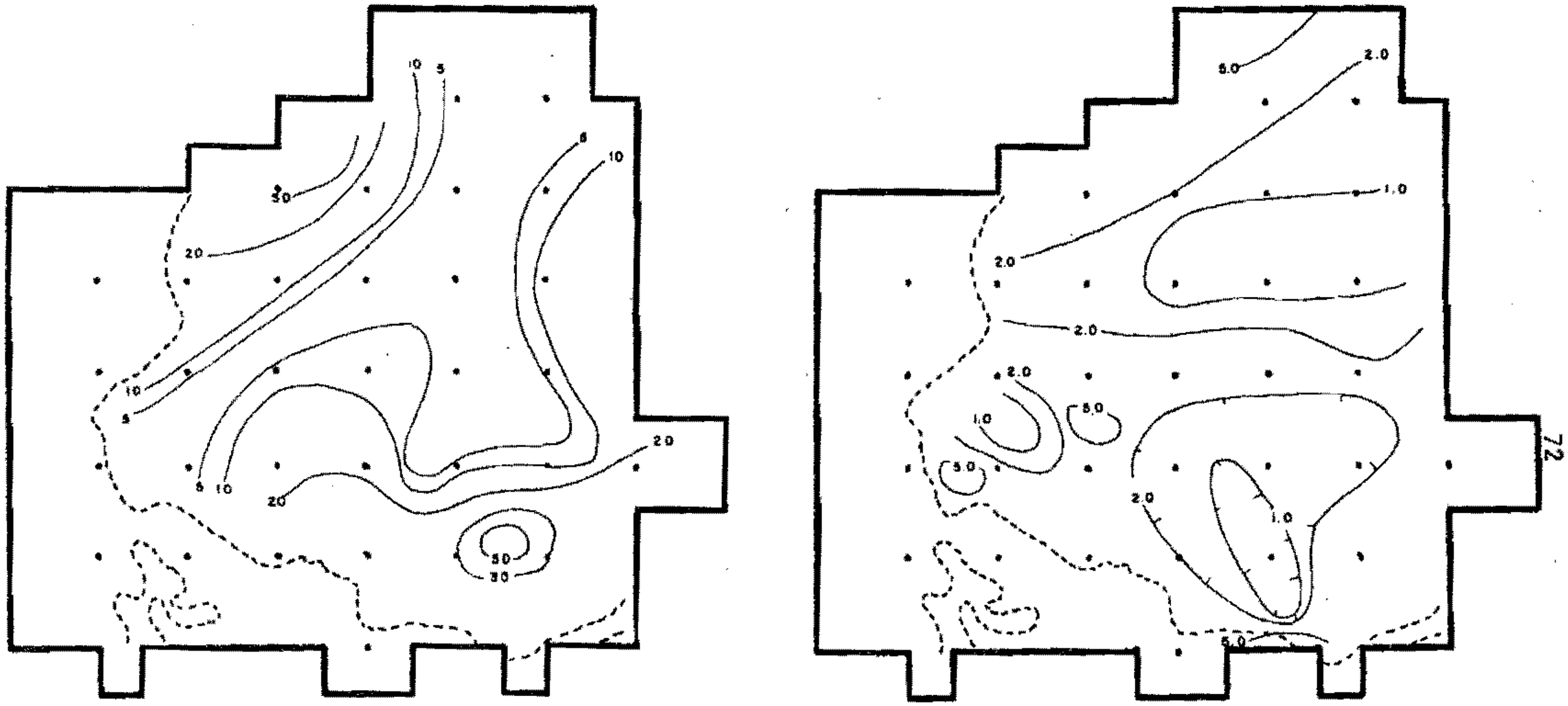
22c. Seam B



Mn in milligrams/liter

Cu in micrograms/liter

22d. About 20 feet below Seam B and AB

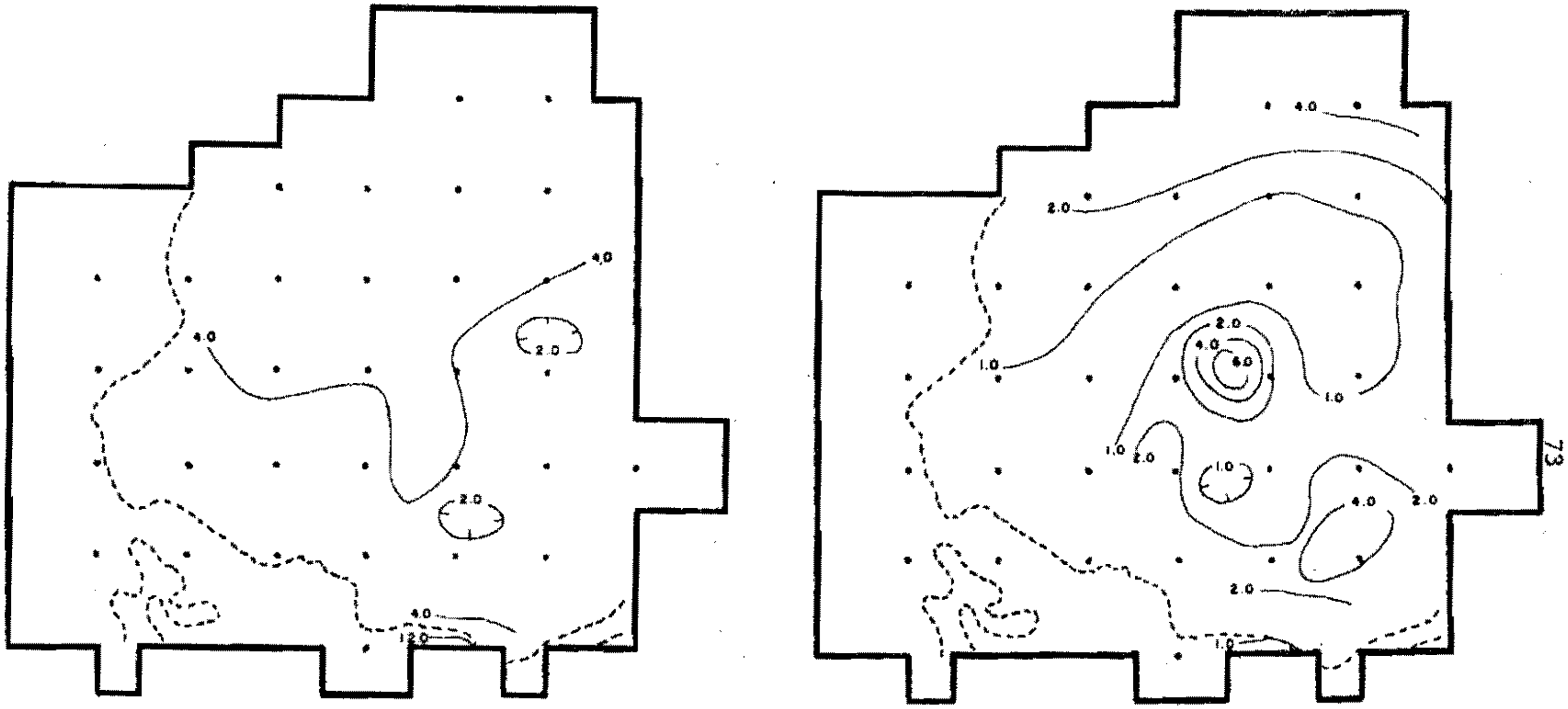


Pb in micrograms/liter

Cd in micrograms/liter

23a. About 20 feet above Seam A and AB

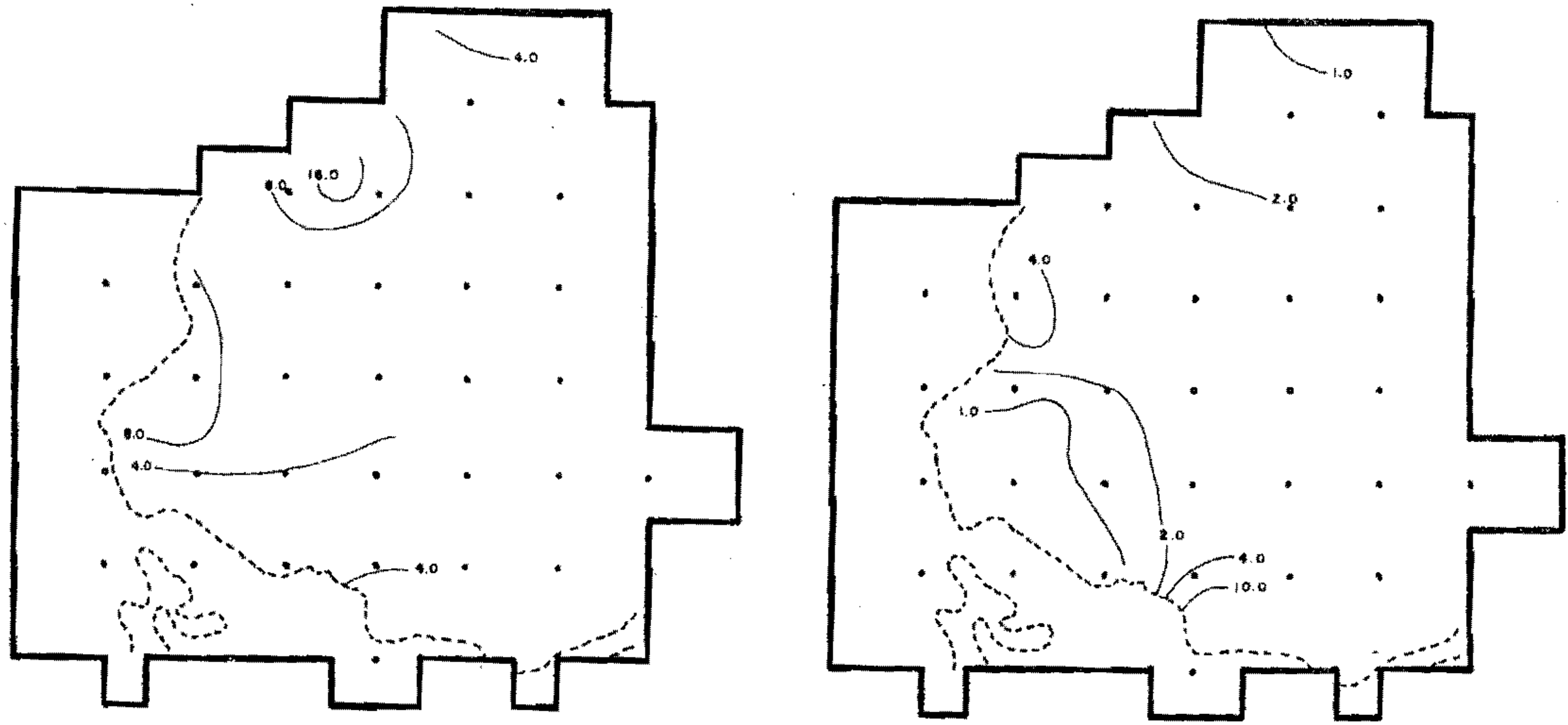
Figure 23. Pb and Cd.



Pb in micrograms/liter

Cd in micrograms/liter

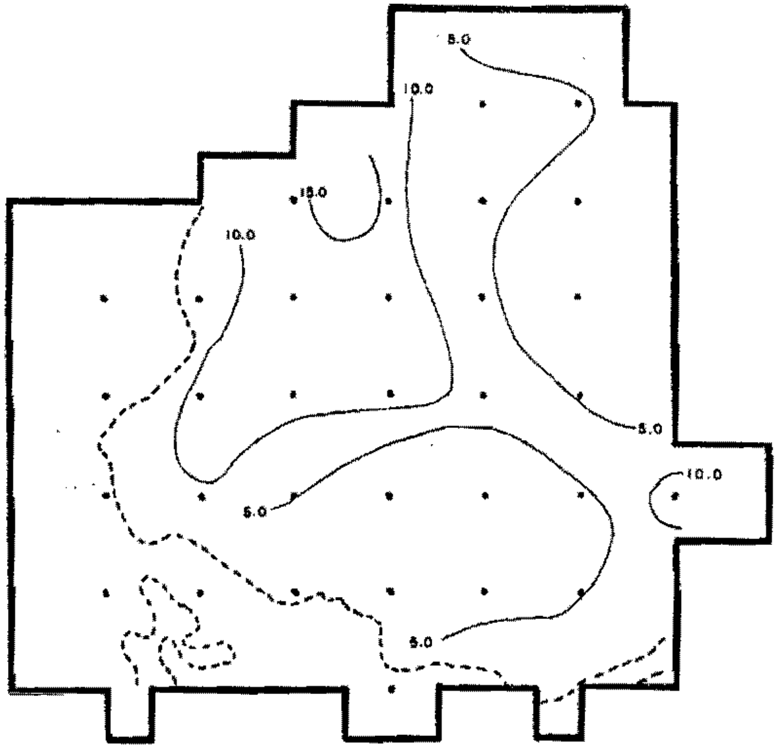
23b. Seam A and AB



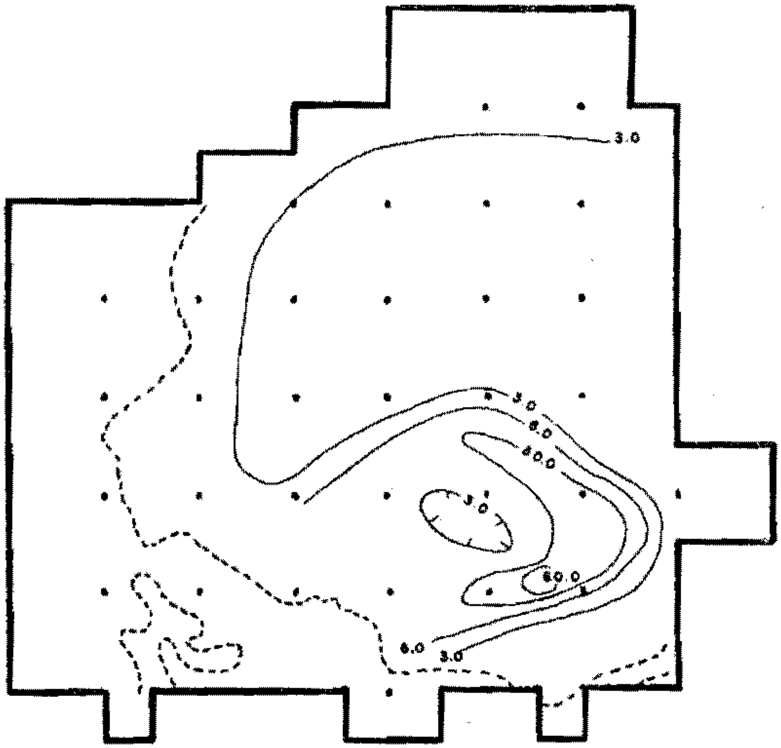
Pb in micrograms/liter

Cd in micrograms/liter

23c. Seam B



Pb in micrograms/liter



Cd in micrograms/liter

23d. About 20 feet below Seam B and AB

based on health criteria:

Nitrate	45 milligrams/liter
Cadmium	0.01
Lead	0.05

Nitrate (Figure 18) does not exceed the maximum limit. Cadmium concentrations (Figure 23) exceed the limit in the groundwater in part of Seam B and in a few locations below the lignite. A lead concentration (Figure 23) that is slightly higher than 0.05 milligrams/liter is found in one location in the till.

V. MINING EFFECTS

A. EFFECTS WITHIN THE MINE SITE

Mining will probably begin in the southeast quarter of the mine site, where the lignite is thick and close to the surface. Calculations made by Moran and Cherry (1978) for quantities of groundwater flow into a strip mine pit are based on conditions similar to the conditions in the southeast quarter of the mine site. Based on their calculations, the volume rate of flow into a pit, a few hours after cutting the pit, will be about 2×10^{-5} to 2×10^{-6} cubic feet/second/horizontal foot of highwall (9×10^{-3} to 9×10^{-4} gallons/minute/horizontal foot of highwall). The flow into the pit will gradually decrease. About 100 days after the pit is cut, the volume rate of flow will be about 8×10^{-7} to 2×10^{-7} cubic feet/second/horizontal foot of highwall (4×10^{-4} to 9×10^{-5} gallons/minute/horizontal foot of highwall).

The above calculated volume rates of flow will probably be less than the actual flow for the following reasons. First, the recharge rate of the lignite at the proposed mine site is slightly higher than the recharge rate used by Moran and Cherry. Second, the calculated rates do not include overland flow of water into the pit. The quantities of overland flow may be significant, particularly during snowmelt. Third, the direction of flow in the silty clay below the lignite will reverse and will be into the lignite. Fourth, groundwater in the nearby buried valleys may begin to flow through the lignite toward the pit. The possibility of the buried valleys recharging the lignite will depend on the location of the pit.

After mining is complete, the original shallow aquifer system at the mine site will be destroyed and will be replaced by overburden. The replaced overburden will be a mixture of till and Sentinel Butte sediment. The hydraulic conductivity of the replaced overburden will be variable and will reflect the methods used to excavate and to fill the pit (Winczewski, 1977). The hydrogeochemical reactions caused by Sentinel Butte sediments underlying the till will probably cease. Therefore, the post-mining hydrogeochemistry will probably be similar to that within the till currently at the mine site. Based on current studies in North Dakota, the major difference between the pre-mining till hydrogeochemistry and the post-mining hydrogeochemistry will be that all post-mining concentrations of ions will be proportionally higher (Groenewold, 1978). Aquifers deeper than the mineable lignite will have to be tapped for potable water.

B. EFFECTS OUTSIDE OF THE MINE SITE

The lack of detailed stratigraphy and groundwater data in areas surrounding the proposed mine site places some uncertainty into the predicted outside effects. But, because most of the groundwater flows laterally in the lignite only a short distance, the removal of the lignite will probably have no major physical effect outside of the mine site. There is a possibility that nearby wells in the lignite might have lower water levels or dry up, temporarily or permanently, depending on pit locations. Water in nearby areas might obtain higher levels of total dissolved solids.

The amount of water that passes from the lignite at the mine site into the buried valleys is negligible when compared to the total amount of water within the buried valleys to the south. Also, if mining plans carefully incorporate the groundwater data in this report, the amount of water recharging the lignite from the buried valleys during mining should be negligible. Therefore, during mining and after reclamation, the water in the buried valleys to the south of the proposed mine site will probably not be affected chemically or physically. Because of the possibility of lignite recharge from the buried valleys during mining, more piezometers should be installed in the valleys to monitor the groundwater.

APPENDICES

APPENDIX I: Piezometer Statistics

Piezometer Number	Surface Elevation In Feet Above Sea Level (From The John T. Boyd Co.)	Total Depth From Surface In Feet (Meters)	Lithology Monitored; SB= Sentinel Butte	Relationship To The Lignite
306-1	1993	80.12(24.42)	SB silty clay	18' below Seam AB
306-2		52.20(15.91)	SB lignite	In Seam AB
306-3		22.97(7.00)	Till	21' above Seam AB
322-1	1984	101.08(30.81)	SB sand	17' below Seam B
322-2		78.81(24.02)	SB lignite	In Seam B
322-3		53.02(16.16)	Till	24' above Seam B
322-4		21.49(6.55)	Till	55' above Seam B
331-1	1987	74.80(22.80)	SB silty clay	22' below Seam B
331-2		52.36(15.96)	SB lignite	In Seam B
331-3		20.41(6.22)	Till	14' above Seam A
363-1	2005	108.04(32.93)	SB silty clay	32' below Seam B
363-2		73.33(22.35)	SB lignite	In Seam B
363-3		62.30(18.99)	SB lignite	In Seam A
363-4		35.60(10.85)	Till	20' above Seam A
368-1	1998	68.01(20.73)	SB silty clay	30' below Seam AB
368-2		33.10(8.89)	SB lignite	In Seam AB
396-1	1999	102.72(31.31)	SB silty clay	16' below Seam B
396-2(5)		86.48(26.36)	SB lignite	In Seam B
396-3		50.23(15.31)	SB lignite	In Seam A
396-4		19.72(6.01)	Till	26' above Seam A
429-1	2003	115.81(35.30)	SB silty clay	66' below Seam AB
429-2		59.61(18.17)	SB silty clay	18' below Seam AB
429-3		39.50(12.04)	SB lignite	In Seam AB
429-4		19.32(5.89)	Till	8' above Seam AB
430-1	1984	94.06(28.67)	SB silty clay	32' below Seam AB
430-2		59.02(17.99)	SB lignite	In Seam AB
430-3		24.97(7.61)	Till	18' above Seam AB
439-1	1961	155.81(47.49)	SB silty clay	---

510-1	2020	141.90(43.25)	SB silty clay	33' below Seam B
510-2		108.14(32.96)	SB lignite	In Seam B
510-3		77.82(23.72)	SB lignite	In Seam A
510-4		53.64(16.35)	SB silty clay	18' above Seam A
511-1	2041	156.59(47.73)	SB silty clay	20' below Seam B
511-2		123.75(37.72)	SB silty clay	1' above Seam B
511-3		103.25(31.47)	SB lignite	In Seam A
511-4		73.03(22.26)	Till	25' above Seam A
513-1	2021	116.90(35.63)	SB silty clay	21' below Seam AB
513-2		92.22(28.11)	SB lignite	In Seam AB
513-3		65.29(19.90)	Till	13' above Seam AB
515-1	2022	122.11(37.22)	SB silty clay	26' below Seam AB
515-2		92.16(28.09)	SB lignite	In Seam AB
515-3		61.88(18.86)	SB silty clay	19' above Seam AB
516-1	2007	71.65(21.84)	SB silty clay	17' below Seam AB
516-2		45.31(13.81)	SB lignite	In Seam AB
516-3		19.46(5.93)	Till	24' above Seam AB
518-1	2037	122.28(37.27)	SB silty clay	20' below Seam B
518-2		98.00(29.87)	SB lignite	In Seam B
518-3		78.94(24.06)	SB lignite	In Seam A
518-4		51.90(15.82)	Till	20' above Seam A
520-1	2040	111.84(34.09)	SB silty clay	22' below Seam B
520-2		85.53(26.07)	SB lignite	In Seam B
520-3		53.02(16.16)	Till	19' above Seam A
521-1	1954	75.07(22.88)	SB silty clay	---
521-2		35.43(10.80)	Pleist. sand	---
521-3		19.95(6.08)	Till	---
522-1	1990	66.60(20.30)	SB silty clay	19' below Seam AB
522-2		45.57(13.89)	SB lignite	In Seam AB
522-3		19.36(5.90)	Till	15' above Seam AB
523-1	2008	65.62(20.00)	SB silty clay	20' below Seam AB
523-2		43.01(13.11)	SB lignite	In Seam AB
523-3		21.78(6.64)	Till	12' above Seam AB
524-1	2015	72.60(22.13)	SB silty clay	18' below Seam AB
524-2		44.29(13.50)	SB lignite	In Seam AB
524-3		19.49(5.94)	Till	23' above Seam AB
525-1	2035	101.61(30.97)	SB silty clay	22' below Seam AB
525-2		74.48(22.70)	SB lignite	In Seam AB
525-3		45.67(13.92)	Pleist. gravel	22' above Seam AB

526-1	1996	79.92(24.36)	SB silty clay	21' below Seam AB
526-2		52.33(15.95)	SB lignite	In Seam AB
526-3		23.33(7.11)	Till	18' above Seam AB
527-1	1993	96.16(29.31)	SB silty clay	23' below Seam B
527-2		71.78(21.88)	SB lignite	In Seam B
527-3		40.78(12.43)	SB lignite	In Seam A
527-4		19.55(5.96)	Till	16' above Seam A
528-1	2025	132.05(40.25)	SB silty clay	21' below Seam B
528-2		108.56(33.09)	SB lignite	In Seam B
528-3		98.75(30.10)	SB lignite	In Seam A
528-4		71.33(21.74)	SB silty clay	19' above Seam A
529-1	2018	79.76(24.31)	SB silty clay	18' below Seam AB
529-2		58.46(17.82)	SB lignite	In Seam AB
529-3		34.12(10.40)	SB silty clay	20' above Seam AB
530-1	1991	80.84(24.64)	SB silty clay	20' below Seam AB
530-2		54.76(16.69)	SB lignite	In Seam AB
530-3		21.03(6.41)	Pleist. sand	22' above Seam AB
531-1	2035	120.14(36.62)	SB silty clay	18' below Seam AB
531-2		93.77(28.58)	SB lignite	In Seam AB
531-3		64.27(19.59)	Till	22' above Seam AB
532-1	2074	132.97(40.53)	SB silty clay	20' below Seam AB
532-2		109.48(33.37)	SB lignite	In Seam AB
532-3		81.92(24.97)	Till	19' above Seam AB

APPENDIX II: Hydrologic Data

Piezometer Number	Depth To Water From Surface in Feet (Meters) Measured On 10/12/78, Except 306 Which Was Measured On 7/25/78	Hydraulic Conductivity In Feet/Second (Meters/Second); VH= very high, greater than 10^{-3} feet/second
306-1	36.25(11.05)	$1 \times 10^{-6}(4 \times 10^{-7})$
306-2	36.12(11.01)	$2 \times 10^{-4}(6 \times 10^{-5})$
306-3	11.29(3.44)	VH
322-1	54.04(16.47)	$2 \times 10^{-7}(6 \times 10^{-8})$
322-2	53.35(16.26)	$2 \times 10^{-6}(7 \times 10^{-7})$
322-3	32.28(9.84)	$2 \times 10^{-8}(6 \times 10^{-9})$
322-4	DRY	---
331-1	40.12(12.23)	$9 \times 10^{-6}(3 \times 10^{-6})$
331-2	39.80(12.13)	VH
331-3	DRY	---
363-1	64.96(19.80)	$1 \times 10^{-8}(3 \times 10^{-9})$
363-2	56.89(17.34)	VH
363-3	55.84(17.02)	$7 \times 10^{-8}(2 \times 10^{-8})$
363-4	DRY	---
368-1	42.91(13.08)	$7 \times 10^{-9}(2 \times 10^{-9})$
368-2	29.17(8.89)	---
396-1	45.73(13.94)	---
396-2(5)	41.86(12.76)	VH
396-3	47.34(14.43)	---
396-4	2.72(0.83)	$1 \times 10^{-6}(4 \times 10^{-7})$
429-1	101.84(31.04)	---
429-2	32.32(9.85)	$2 \times 10^{-6}(6 \times 10^{-7})$
429-3	32.19(9.81)	---
429-4	DRY	---
430-1	22.64(6.90)	$1 \times 10^{-8}(3 \times 10^{-9})$
430-2	17.45(5.32)	VH
430-3	9.02(2.75)	---
439-1	64.99(19.81)	$3 \times 10^{-8}(1 \times 10^{-8})$

510-1	65.39(19.93)	1 x 10^{-7}(3 x 10^{-8})
510-2	61.09(18.62)	VH
510-3	66.40(20.24)	VH
510-4	45.08(13.74)	---
511-1	83.30(25.39)	6 x 10^{-8}(2 x 10^{-8})
511-2	83.04(25.31)	2 x 10^{-6}(6 x 10^{-7})
511-3	80.41(24.51)	3 x 10^{-5}(9 x 10^{-6})
511-4	56.46(17.21)	3 x 10^{-8}(8 x 10^{-9})
513-1	70.34(21.44)	7 x 10^{-9}(2 x 10^{-9})
513-2	50.75(15.47)	7 x 10^{-6}(2 x 10^{-6})
513-3	49.44(15.07)	2 x 10^{-6}(6 x 10^{-7})
515-1	45.37(13.83)	3 x 10^{-8}(1 x 10^{-8})
515-2	39.21(11.95)	VH
515-3	28.38(8.65)	2 x 10^{-8}(6 x 10^{-9})
516-1	21.78(6.64)	1 x 10^{-7}(4 x 10^{-8})
516-2	22.51(6.86)	2 x 10^{-6}(6 x 10^{-7})
516-3	6.79(2.07)	3 x 10^{-6}(8 x 10^{-7})
518-1	52.33(15.95)	2 x 10^{-8}(7 x 10^{-9})
518-2	45.80(13.96)	3 x 10^{-4}(1 x 10^{-4})
518-3	56.14(17.11)	5 x 10^{-5}(1 x 10^{-5})
518-4	40.22(12.26)	4 x 10^{-9}(1 x 10^{-9})
520-1	28.05(8.55)	3 x 10^{-8}(1 x 10^{-8})
520-2	24.48(7.46)	VH
520-3	22.83(6.96)	4 x 10^{-7}(1 x 10^{-7})
521-1	13.12(4.00)	1 x 10^{-7}(3 x 10^{-8})
521-2	8.37(2.55)	3 x 10^{-6}(1 x 10^{-6})
521-3	6.79(2.07)	7 x 10^{-9}(2 x 10^{-9})
522-1	33.50(10.21)	8 x 10^{-6}(2 x 10^{-6})
522-2	33.30(10.15)	VH
522-3	11.12(3.39)	8 x 10^{-8}(2 x 10^{-8})
523-1	31.73(9.67)	1 x 10^{-5}(3 x 10^{-6})
523-2	31.92(9.73)	VH
523-3	DRY	---
524-1	34.71(10.58)	8 x 10^{-7}(2 x 10^{-7})
524-2	34.32(10.46)	2 x 10^{-5}(6 x 10^{-6})
524-3	DRY	---

525-1	57.09(17.40)	$2 \times 10^{-8}(5 \times 10^{-9})$
525-2	53.44(16.29)	$2 \times 10^{-6}(6 \times 10^{-7})$
525-3	15.88(4.84)	$4 \times 10^{-7}(1 \times 10^{-7})$
526-1	30.41(9.27)	$2 \times 10^{-8}(7 \times 10^{-9})$
526-2	30.58(9.32)	VH
526-3	8.83(2.69)	$1 \times 10^{-6}(3 \times 10^{-7})$
527-1	46.23(14.09)	$2 \times 10^{-8}(6 \times 10^{-9})$
527-2	42.22(12.87)	$8 \times 10^{-6}(2 \times 10^{-6})$
527-3	30.48(9.29)	VH
527-4	12.70(3.87)	---
528-1	61.48(18.74)	$5 \times 10^{-8}(2 \times 10^{-8})$
528-2	70.08(21.36)	$7 \times 10^{-6}(2 \times 10^{-6})$
528-3	64.63(19.70)	VH
528-4	41.34(12.60)	$3 \times 10^{-8}(9 \times 10^{-9})$
529-1	36.35(11.08)	$2 \times 10^{-6}(5 \times 10^{-7})$
529-2	33.60(10.24)	VH
529-3	8.79(2.68)	$8 \times 10^{-9}(2 \times 10^{-9})$
530-1	41.37(12.61)	$9 \times 10^{-9}(3 \times 10^{-9})$
530-2	11.71(3.57)	VH
530-3	8.99(2.74)	VH
531-1	71.98(21.94)	$2 \times 10^{-8}(5 \times 10^{-9})$
531-2	45.41(13.84)	$2 \times 10^{-6}(6 \times 10^{-7})$
531-3	27.66(8.43)	$3 \times 10^{-7}(1 \times 10^{-7})$
532-1	74.11(22.59)	$2 \times 10^{-8}(5 \times 10^{-9})$
532-2	73.75(22.48)	$2 \times 10^{-6}(6 \times 10^{-7})$
532-3	73.46(22.39)	$2 \times 10^{-8}(7 \times 10^{-9})$

APPENDIX III: Chemical Analyses

	306-1	306-2	306-3
Field pH	6.72	6.33	6.75
Specific conductance in micromhos/cm	2800	1320	6000
Field temperature in degrees Celsius	10.0	10.5	9.0
HCO_3^- in milligrams/liter	1244	622	564
$CO_3^{=}$ in milligrams/liter	13.2	7.9	3.9
OH^- in milligrams/liter	.023	.030	.015
$SO_4^{=}$ in milligrams/liter	691	453	3668
Cl^- in milligrams/liter	<1.0	10.9	40.4
NO_3^- in milligrams/liter	.11	---	.11
Na^+ in milligrams/liter	575	294	488
K^+ in milligrams/liter	19.7	12.5	37.4
Ca^{++} in milligrams/liter	58	121	456
Mg^{++} in milligrams/liter	45	76	530
Fe in milligrams/liter	.8064	1.014	.7556
Mn in milligrams/liter	.2078	.9455	1.1488
Cu in micrograms/liter	16.8	8.0	13.7
Pb in micrograms/liter	5.8	2.0	22.5
Cd in micrograms/liter	2.24	1.54	0.71
Total Dissolved Solids in milligrams/liter	1793	941	6286
Standard Error as a percentage	-4.6	11.4	0.9

	322-1	322-2	322-3	331-1	331-1 Dupli	331-2	363-1
Field pH	8.69	8.28	6.44	6.89	6.84	6.30	7.29
Field sp. cond.	2840	2160	5800	2200	2000	1650	3250
Field temperature	9.5	10.0	9.0	8.5	8.5	9.0	9.0
HCO_3	1062	600	1108	952	1247	731	531
CO_3	78.0	17.9	1.2	1.2	1.2	0.4	3.4
OH	.159	.065	.002	.003	.002	.001	.014
SO_4	610	919	2818	547	353	274	611
Cl	4.9	15.4	28.1	12.0	<1.0	<1.0	48.8
NO_3	1.00	.18	60.00	<0.10	<0.10	<0.10	0.10
Na	976	561	1600	375	298	171	593
K	9.6	10.7	23.5	12.5	13.3	9.0	11.2
Ca	15	50	204	73	158	161	26
Mg	16	18	182	127	74	53	17
Fe	.1000	.0585	.0370	.0750	.0131	.0302	.0613
Mn	.0904	.1057	1.0550	.3118	.3212	.9300	.2074
Cu	25.0	21.0	123.9	26.1	52.8	21.1	36.7
Pb	8.5	10.8	6.1	3.8	6.7	4.6	3.9
Cd	0.21	0.11	1.40	29.30	37.90	11.10	6.20
TDS	2020	1480	5250	1630	2630	1330	1460
Stan. Error	15.3	-2.4	9.6	5.8	-1.0	6.1	11.4

	363-2	363-3	368-1	368-2	396-1	396-2(5)
Field pH	6.75	6.60	7.22	6.57	10.24	7.17
Field sp. cond.	1400	950	3200	780	1840	3900
Field temp.	10.0	9.0	10.0	10.0	11.0	7.5
HCO_3	966	106	969	267	112	913
CO_3	1.2	0.2	8.2	3.8	164.0	36.9
OH	.003	.004	.002	.003	3.160	.087
SO_4	210	238	1049	245	649	1334
Cl	<1.0	<1.0	<1.0	52.7	<1.0	8.4
NO_3	0.40	1.50	0.12	0.85	0.70	<0.10
Na	274	132	701	37	440	860
K	6.0	6.0	14.2	7.3	45.7	13.6
Ca	48	24	43	78	3	38
Mg	25	19	45	52	14	39
Fe	.0471	.0369	.2786	.0507	2.715	.3140
Mn	.0537	.0092	.2909	.0328	.1245	.0417
Cu	17.0	17.0	26.2	19.5	264.5	24.6
Pb	2.5	2.3	3.3	1.8	32.3	3.8
Cd	2.40	2.60	2.02	1.11	59.00	0.40
TDS	5380	650	2320	493	1137	2520
Stan. Error	-10.2	12.3	-1.8	-5.5	8.9	-1.6

N.B.: Water analysis for 396-1 was not used in this report

	396-2(5) Dupli	396-3	396-4	429-1	429-2	429-3
Field pH	7.17	7.75	7.92	6.35	6.52	6.41
Field sp. cond.	3900	1290	1110	2800	2650	2090
Field temp.	7.5	11.0	9.5	11.0	9.0	11.0
HCO_3	964	683	607	1121	1316	710
CO_3	38.0	6.6	4.7	6.7	1.5	4.3
OH	.085	.021	.017	.013	.002	.013
SO_4	1275	446	411	971	422	920
Cl	1.0	<1.0	<1.0	15.5	<1.0	16.4
NO_3	<0.10	0.12	0.58	0.50	<0.10	0.20
Na	881	72	72	587	429	193
K	12.9	15.0	7.1	13.6	10.5	15.7
Ca	37	88	65	60	59	150
Mg	103	110	129	56	73	168
Fe	---	---	.1514	.1528	.0137	3.217
Mn	---	---	.4371	.0680	.3849	2.383
Cu	---	---	12.0	25.3	14.9	31.1
Pb	---	---	3.0	11.9	2.7	4.6
Cd	---	---	5.49	1.83	37.60	1.32
TDS	2650	836	765	2086	1890	1841
Stan. Error	5.8	-10.1	-4.2	-8.0	-4.4	-2.0

	430-1	430-2	430-2 Dupli	430-3	439-1	510-1	510-2
Field pH	10.85	8.45	8.45	7.86	7.23	7.42	7.63
Field sp. cond.	1350	1510	1510	8000	2130	4200	4100
Field temp.	7.5	7.5	7.5	9.5	8.5	9.5	9.0
HCO_3	265	623	626	581	817	1180	1218
CO_3	155.0	9.1	15.6	2.8	3.9	6.7	6.8
OH	1.26	.032	.054	.010	.010	.012	.012
SO_4	165	323	353	5293	521	1530	1401
Cl	7.6	<1.0	<1.0	320.0	<1.0	30.0	12.2
NO_3	0.25	<0.10	<0.10	<0.10	0.36	<0.10	<0.10
Na	313	395	380	1578	653	1300	976
K	4.8	9.0	9.0	44.0	5.8	13.0	7.5
Ca	4	16	12	602	19	8	54
Mg	3	2	12	320	10	53	10
Fe	.2690	.0913	.0350	.1030	.0520	.0396	.0212
Mn	.0203	.0160	.0159	.1490	.1090	.0939	.0973
Cu	35.0	13.3	12.8	30.6	11.8	61.1	21.2
Pb	5.8	3.0	5.5	19.0	3.4	13.0	10.4
Cd	0.75	2.10	2.40	1.40	0.49	4.42	0.44
TDS	650	950	750	8540	1450	3060	2870
Stan. Error	3.7	3.2	0.6	-1.1	10.8	8.2	-3.7

N.B.: Water analysis for 430-1 was not used in this report

	510-3	510-4	511-1	511-2	511-3	511-4	513-1
Field pH	7.17	7.13	7.72	7.07	6.89	6.80	8.30
Field sp. cond.	1620	760	2750	4500	2400	4000	2700
Field temp.	10.0	11.0	10.0	9.0	8.5	9.0	8.0
HCO_3	763	228	1131	861	889	631	1047
CO_3	1.9	0.8	10.5	3.6	2.0	1.4	20.7
OH	.005	.008	.020	.009	.005	.005	.043
SO_4	289	298	1061	1790	589	2265	558
Cl	3.9	30.5	23.1	15.7	17.0	9.6	25.9
NO_3	0.10	0.10	0.35	0.50	<0.10	0.32	0.56
Na	337	124	960	777	483	356	635
K	7.6	5.7	10.1	14.0	11.4	14.9	21.0
Ca	66	42	25	167	123	539	27
Mg	23	33	24	45	7	163	12
Fe	.0321	.0672	.3245	.4810	.0293	.0399	.0372
Mn	.1659	.0594	.0390	.3012	.3644	1.513	.0434
Cu	22.4	20.4	127.6	99.5	30.0	25.4	30.0
Pb	3.3	2.0	8.7	8.0	4.3	18.7	13.1
Cd	0.57	0.53	3.30	4.67	1.38	1.72	1.20
TDS	1090	450	2180	3280	1970	4030	1630
Stan. Error	3.5	-2.4	4.1	-5.9	1.0	-1.5	0.4

	513-2	513-3	515-1	515-2	515-3	516-1	516-2
Field pH	8.16	7.66	7.36	6.95	7.14	7.13	6.88
Field sp. cond.	1800	4000	2600	1020	4200	2140	1840
Field temp.	8.0	8.0	9.5	9.0	9.5	9.0	8.5
HCO_3	722	1621	869	314	913	1005	562
CO_3	17.2	7.2	9.0	1.6	6.7	6.9	1.3
OH	.050	.009	.022	.011	.016	.015	.005
SO_4	362	1134	823	246	1697	588	400
Cl	<1.0	19.2	<1.0	9.5	15.1	<1.0	20.9
NO_3	0.10	0.67	0.12	<0.10	0.13	0.12	0.10
Na	403	806	656	215	930	586	315
K	15.0	25.0	7.2	3.8	14.1	10.2	6.9
Ca	32	161	23	32	85	27	73
Mg	17	88	24	12	83	47	33
Fe	.0533	.0308	.1191	.0223	.0409	.0264	.0305
Mn	.0705	.2810	.0556	.0318	.1307	.1547	.1880
Cu	14.7	32.9	63.3	9.7	70.0	15.3	12.2
Pb	4.2	5.7	3.7	1.9	10.0	4.8	6.0
Cd	7.10	4.00	1.33	0.38	1.41	1.42	0.72
TDS	1100	2760	1950	720	3020	1320	930
Stan Error	2.3	0.0	0.2	6.4	1.0	3.3	5.4

	516-3	518-1	518-2	518-3	518-4	520-1	520-1 Dupli
Field pH	6.81	7.83	6.98	7.21	6.86	7.80	7.80
Field sp. cond.	2720	2380	3550	3500	>8000	3000	3000
Field temp.	10.5	9.0	8.5	10.0	9.0	8.0	8.0
HCO_3	564	1799	1054	999	1323	1162	1174
CO_3	1.7	24.6	4.4	4.4	4.7	34.7	2.6
OH	.006	.030	.009	.010	.008	.065	.048
SO_4	1302	253	1158	1320	5968	679	682
Cl	24.6	3.6	24.3	17.8	146.7	<1.0	16.0
NO_3	0.13	0.20	<0.10	<0.10	<0.10	0.10	0.20
Na	127	757	807	1150	2751	828	784
K	12.2	5.5	6.3	7.7	38.3	14.0	14.7
Ca	422	8	25	58	371	6	22
Mg	105	13	18	8	283	24	8
Fe	.0196	.0712	.0602	.0725	.1784	.0262	.1020
Mn	.0638	.0533	.0346	.1137	.5116	.0486	.0517
Cu	21.5	25.4	53.1	76.7	96.4	44.4	31.0
Pb	10.8	18.7	17.0	5.7	32.5	2.8	7.5
Cd	0.50	1.72	2.16	2.06	3.24	3.80	3.50
TDS	2140	2050	2460	2580	10940	2080	2040
Stan. Error	-2.1	-1.6	-5.4	9.4	3.9	5.9	3.2

	520-2	520-3	521-1	521-1 Dupli	521-2	521-3	522-1
Field pH	7.44	7.11	6.76	6.76	6.86	7.02	6.69
Field sp. cond.	1400	3000	5250	5250	5100	5500	2150
Field temp.	8.0	7.5	8.5	8.5	10.0	12.0	9.0
HCO_3	581	608	983	1015	1013	663	587
CO_3	6.9	3.4	1.4	2.5	0.5	2.9	4.3
OH	.026	.012	.003	.005	.001	.010	.016
SO_4	284	1540	2675	2732	2709	345	723
Cl	<1.0	15.5	37.5	30.6	41.7	61.5	<1.0
NO_3	<0.10	<0.10	0.18	<0.10	0.11	0.10	<0.10
Na	273	305	623	652	369	462	233
K	12.0	22.0	41.0	40.0	31.0	31.0	38.0
Ca	39	251	808	836	831	548	79
Mg	17	140	49	29	208	451	119
Fe	.0714	.3310	2.048	5.790	.2020	.0936	.0323
Mn	.0976	1.396	2.922	2.729	2.936	.4260	.2650
Cu	20.0	164.0	17.8	13.4	37.8	36.8	33.3
Pb	3.5	2.5	6.5	8.1	13.3	29.1	4.8
Cd	0.90	5.70	1.10	0.60	0.90	6.00	80.10
TDS	960	2560	5300	5260	5170	6520	1530
Stan. Error	0.6	-5.9	-0.3	-0.7	0.9	62.2	0.0

	522-2	522-3	523-1	523-2	524-1	524-2	525-1
Field pH	6.63	6.69	6.73	6.58	6.92	6.93	7.23
Field sp. cond.	2200	7000	1500	1275	1425	1300	1800
Field temp.	9.0	9.5	9.0	9.5	8.0	8.0	7.0
HCO_3	528	701	1022	524	724	634	781
CO_3	2.6	5.2	7.2	4.4	8.1	5.1	20.8
OH	.010	.016	.015	.018	.024	.017	.058
SO_4	783	4062	118	206	252	264	336
Cl	<1.0	44.5	<1.0	<1.0	<1.0	8.8	<1.0
NO_3	<0.10	13.60	0.52	<0.10	<0.10	<0.10	<0.10
Na	141	793	266	40	245	102	377
K	16.0	30.1	17.0	8.4	15.0	12.3	16.7
Ca	181	661	5	113	6	70	37
Mg	148	563	103	108	106	92	25
Fe	.7500	.0196	.0530	.3470	.0321	.1260	.0219
Mn	1.176	.7070	.1360	.7290	.1490	.3290	1.174
Cu	24.8	69.5	33.3	38.5	26.8	22.4	12.4
Pb	3.1	54.2	3.7	2.6	11.0	2.5	7.5
Cd	4.70	3.90	41.80	4.30	2.00	1.40	1.60
TDS	1870	7370	1150	840	910	790	1070
Stan. Error	5.0	8.0	3.2	11.6	7.1	-1.6	0.6

	525-2	525-3	526-1	526-2	526-3	527-1	527-2
Field pH	7.15	6.95	7.34	7.12	6.95	6.53	8.07
Field sp. cond.	1325	580	2230	1340	1460	2250	650
Field temp.	8.0	8.5	8.5	8.5	10.0	8.0	7.5
HCO_3	550	798	974	560	573	792	358
CO_3	10.4	12.5	6.4	1.5	1.8	4.7	5.4
OH	.041	.034	.014	.006	.007	.013	.032
SO_4	410	177	355	264	367	679	128
Cl	6.7	<1.0	<1.0	14.5	<1.0	16.3	4.9
NO_3	<0.10	<0.10	0.10	0.11	0.11	<0.10	0.11
Na	257	79	561	306	146	562	182
K	12.9	7.1	7.3	4.9	6.4	18.0	6.0
Ca	41	47	28	28	117	16	5
Mg	28	21	19	18	61	33	4
Fe	.1820	.0464	.0252	.0193	.0317	.0274	.0904
Mn	1.296	2.014	.0877	.1315	.2210	.0636	.3880
Cu	8.6	6.9	18.2	18.2	18.2	19.1	39.1
Pb	3.0	2.1	4.3	4.3	3.7	5.7	4.7
Cd	1.40	1.30	0.61	0.61	0.30	1.80	1.40
TDS	---	650	1400	610	980	1470	440
Stan. Error	-6.5	-38.1	7.7	3.7	0.8	1.1	-1.1

	527-3	527-4	528-1	528-2	528-3	528-4	529-1
Field pH	6.93	7.66	12.33	10.71	7.48	11.31	7.42
Field sp. cond.	1310	6000	>8000	2350	3000	2200	2500
Field temp.	7.5	9.0	11.0	11.0	10.0	11.0	8.0
HCO_3	732	538	7	106	921	56	1016
CO_3	7.3	2.3	1053	408	7.1	351	9.6
OH	.021	.009	339.	8.330	.017	13.500	.020
SO_4	172	2842	306	478	783	528	735
Cl	8.4	465.0	12.1	6.3	10.1	<1.0	<1.0
NO_3	0.20	7.50	0.30	0.13	0.15	0.16	<0.10
Na	245	983	856	604	815	561	551
K	13.0	30.8	91.8	54.8	7.7	16.7	19.2
Ca	46	327	77	12	30	9	70
Mg	27	234	19	4	10	35	28
Fe	.0477	.0411	.0327	.0327	.0274	.0160	.0913
Mn	.0380	.0643	.7200	.0049	.0237	.0026	.1080
Cu	25.8	27.7	150.3	26.4	45.0	30.5	18.0
Pb	2.3	16.8	47.4	6.7	12.2	7.3	3.4
Cd	0.80	5.70	0.77	1.03	0.90	0.89	1.10
TDS	---	5120	2110	1620	1870	1300	1650
Stan. Error	-1.7	-1.4	3.5	5.8	8.6	8.8	-3.3

N.B.: Water analyses for 528-1, 528-2, and 528-4 were not used in this report

	529-2	529-3	530-1	530-2	530-3	531-1	531-2
Field pH	7.19	7.05	7.63	7.37	7.03	7.66	7.09
Field sp. cond.	1650	3800	2700	1920	1110	2200	1780
Field temp.	7.5	9.0	10.0	8.5	10.5	9.0	8.5
HCO_3	690	450	1387	809	498	1090	711
CO_3	4.1	2.4	10.7	3.0	1.8	6.7	3.2
OH	.013	.011	.017	.008	.008	.013	.009
SO_4	440	2409	495	598	807	460	287
Cl	11.7	41.2	59.3	<1.0	11.6	20.8	<1.0
NO_3	0.21	0.16	0.19	0.10	7.30	0.14	0.10
Na	344	261	829	615	505	672	500
K	15.3	28.0	6.7	4.2	4.0	6.3	3.7
Ca	100	510	25	12	64	13	5
Mg	39	241	8	<1.0	67	7	3
Fe	.1910	.0320	.0354	.0262	.0163	.0245	.1217
Mn	.4470	.5530	.0571	.0128	.0111	.0342	.0230
Cu	16.8	21.2	34.5	18.8	11.4	29.5	43.6
Pb	3.7	19.4	13.6	5.9	2.7	5.1	6.3
Cd	1.80	4.30	1.42	0.77	0.54	2.22	0.80
TDS	1000	4150	1640	1220	700	1420	1040
Stan. Error	5.8	-1.3	4.1	3.2	9.4	3.9	11.4

	531-3	532-1	532-2	532-3
Field pH	7.32	7.33	7.72	7.46
Field sp. cond.	2100	3100	1825	1500
Field temp.	9.0	8.0	7.5	8.0
HCO_3	1050	1063	752	496
CO_3	5.9	9.2	9.4	3.7
OH	.012	.019	.027	.016
SO_4	309	675	441	289
Cl	3.0	5.6	<1.0	13.2
NO_3	<0.10	0.18	<0.10	<0.10
Na	572	727	419	249
K	6.3	20.2	13.5	16.4
Ca	14	38	32	94
Mg	22	22	16	25
Fe	.0176	.0700	.1340	.1370
Mn	.1145	.1170	.0830	.2590
Cu	16.5	61.7	18.0	36.7
Pb	2.9	7.5	5.7	4.5
Cd	0.66	3.10	4.50	1.70
TDS	1270	2460	2040	1580
Stan. Error	7.1	5.7	-0.9	10.2

APPENDIX IV: WATEQ Analysis

KEY:	IAP	Ion Activity Product
	K	Equilibrium Constant
	SD	Standard Deviation
	N	Number of samples analyzed

Water in the pebble loam (till) from piezometers about 20 feet above the lignite

	Calcite	Gypsum	Siderite
Mean of log(IAP/K)	+0.42	-0.92	-1.36
SD	0.46	2.41	0.62
N	14	14	14

Water in the silty clay from piezometers about 20 feet above the lignite

	Calcite	Gypsum	Siderite
Mean of log(IAP/K)	0.00	-0.96	-1.45
SD	0.43	0.94	0.43
N	4	4	4

Water in the lignite

	Calcite	Gypsum	Siderite
Mean of log(IAP/K)	-0.06	-1.84	-1.07
SD	0.61	1.88	0.76
N	32	32	32

Water in the silty clay from piezometers about 20 feet below the lignite

	Calcite	Gypsum	Siderite
Mean of log(IAP/K)	-0.03	-2.12	-0.76
SD	0.62	2.33	1.06
N	29	29	29

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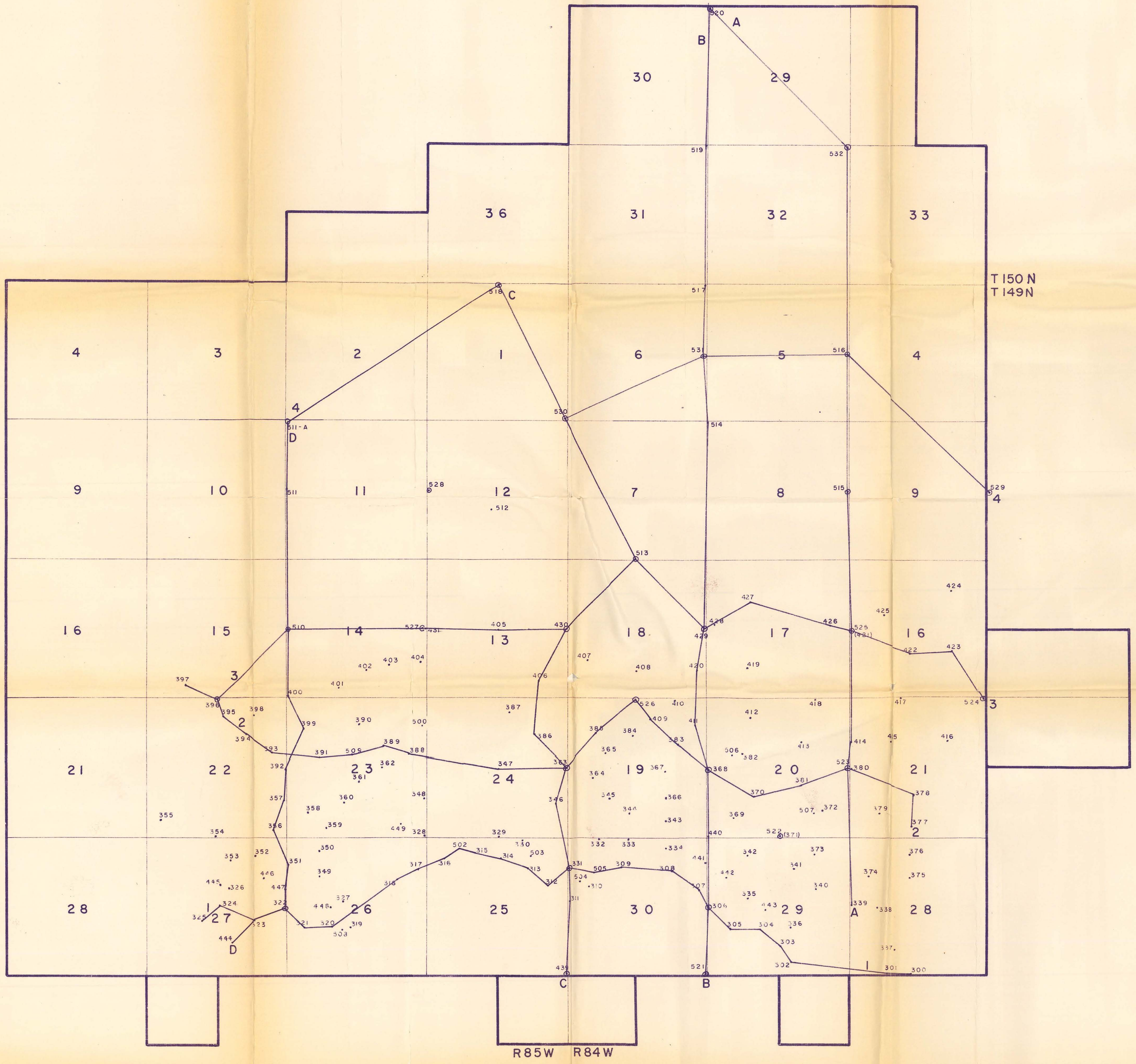
PLATE I: THE PROPOSED GARRISON LIGNITE MINE



332 TEST HOLE LOCATION AND NUMB
(COURTESY OF THE JOHN T. BOY COMPANY)

⊙ 513 PIEZOMETER NEST LOCATION AND NUMBER

D CROSS-SECTION LOCATION AND DESIGNATION
(SEE FIGURE 6)

SCALE:
1 MILE