GEOLOGY, GROUNDWATER HYDROLOGY, AND HYDROGEOCHEMISTRY OF A PROPOSED SURFACE MINE AND LIGNITE GASIFICATION PLANT SITE NEAR DUNN CENTER, NORTH DAKOTA

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NORTH DAKOTA GEOLOGICAL SURVEY
Lee C. Gerhard, State Geologist
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Stephen R. Moran[1], John A. Cherry[2], Peter Fritz[2], William M. Peterson[3],
Mason H. Somerville[3], Steven A. Stancel[4], and James H. Ulmer[5]

1 Geology Division, Alberta Research Council, Edmonton, Alberta; formerly North Dakota Geological Survey

2 Department of Earth Sciences, University of Waterloo, Waterloo, Ontario

3 Engineering Experiment Station, University of North Dakota, Grand Forks, North Dakota

4 Department of Geology, State University of New York, Binghamton, Binghamton, New York; formerly North Dakota Geological Survey

5 Box 22, RR 1, Frazee, Minnesota; formerly Engineering Experiment Station, University of North Dakota

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1.0 INTRODUCTION

1.1 General Statement

The Dunn Center project was conducted by the University of North Dakota Engineering Experiment Station under contract from the Natural Gas Pipeline Company of America to assess the environmental impacts of a coal gasification plant in that area. The North Dakota Geological Survey cooperated in this project as part of its program of studying the stratigraphy and environments of deposition of lignite-bearing rocks in the western part of the state. This report provides a summary of the base-line data acquired for preparation of the environmental impact report.

1.2 Physiography and Topography

The project area in west-central North Dakota is located within the Knife River Upland, immediately east of the boundary between the glaciated and unglaciated portions of the Missouri Plateau section of the Great Plains Physiographic Province (fig. 1.2-1). The project area straddles the valley of Spring Creek, a tributary of the Knife River (fig. 1.2-2). The valley here is about 15 miles wide and 200 to 300 feet deep. The valley of the Little Missouri River lies about 4 miles north of the project area. The Little Missouri arm of Lake Sakakawea, which occupies this generally east-west trending valley, is about 400 feet below the general level of the project area. The rugged badlands topography that forms the walls of the Little Missouri River valley drops as much as 600 feet from the divide to the lake in a distance of 2 to 3 miles. About 2 to 4 miles south of the project area, the Knife River occupies a roughly east-west trending valley that lies about 200 feet below the general level of the project area. About 15 miles west of the project area, the Killdeer Mountains, which, along with the badlands, are the most striking feature of the landscape, form a prominent, flat-topped upland that reaches elevations about 3300 feet, 1100 feet above the general level of the project area. Smaller flat-topped buttes rising as much as 150 feet above their immediate surroundings cap the divide between Spring Creek and the Knife River in the southern part of the project area.

The topography of the project area is characterized, for the most part, by integrated drainage typical of the Great Plains. Approximately three-fourths of the area is described as strongly sloping (15 percent), sloping (40 percent), or gently sloping (16 percent). Of the remainder, most is nearly level (16 percent). Only about 10.5 percent of the acreage in the project area has strongly rolling, rolling, and undulating topography characterized by nonintegrated drainage (Natural Gas Pipeline Company of America, 1974, p. 2-111). Most of the nearly level topography in the project area lies on the nearly flat floors of two partially-filled glacial melt-water valley systems. One of these valley systems trends generally southeastward across the south-central part of the project area. The other trends generally north-south across the western end of the project area.

In most of the project area boulders are few and scattered, but in some places they are abundant. Lakes and ponds are limited to two types of settings. In the northern part of the project area, where remnants of glacial sediment are preserved, upland sloughs, such as characterize the glaciated Missouri Plateau, occur. Throughout the remainder of the project area, lakes and ponds are restricted to low places on the floors of the melt-water valleys. All of the large lakes in the project area, including Lake Ilo and Marshall Slough, are of this latter type.

1.3 Objectives and Scope

The major objective of the subsurface geologic and hydrologic studies was to describe, in as much detail as was feasible, the nature of the subsurface hydrological and hydrochemical systems prior to

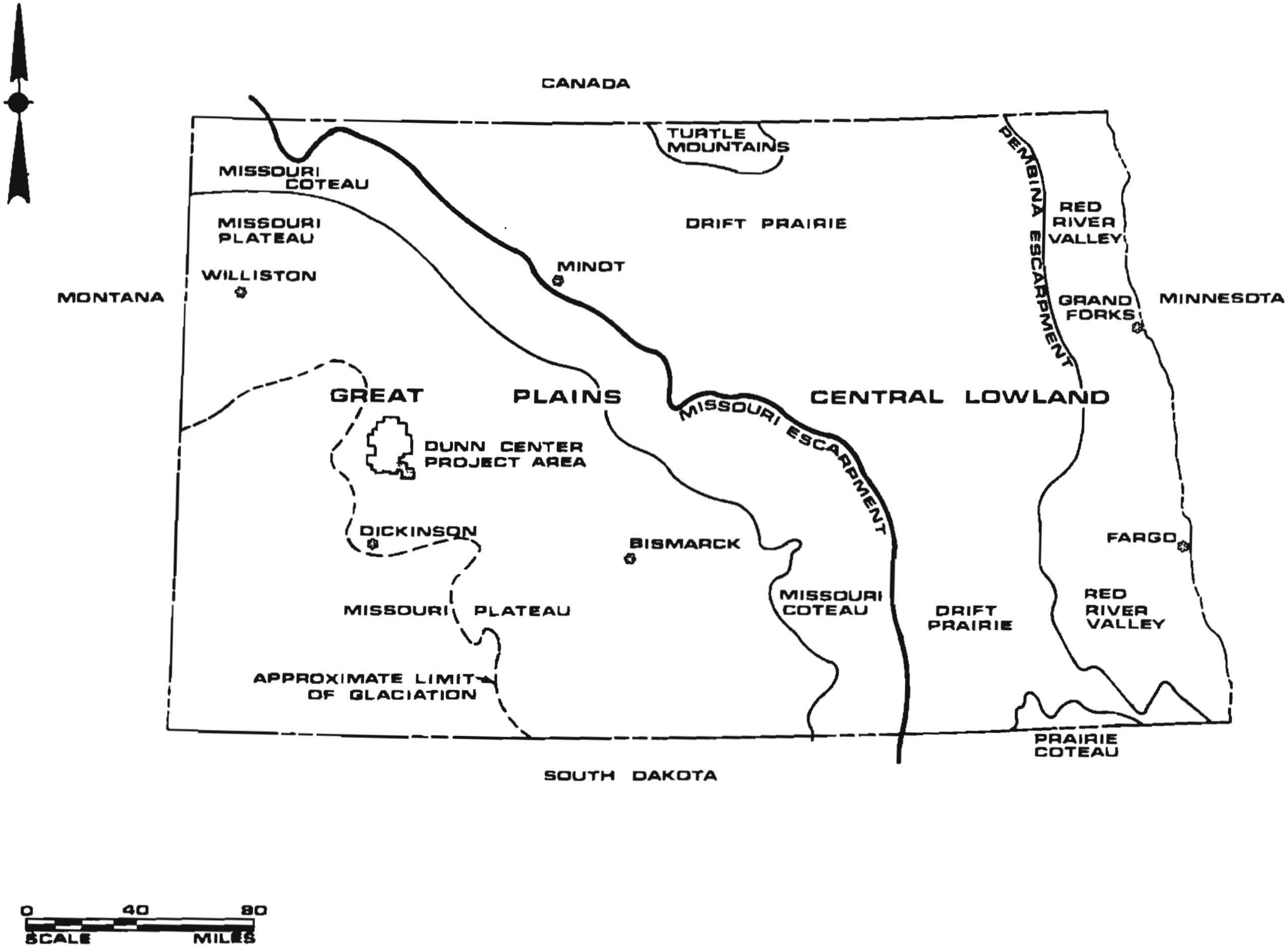

Figure 1.2-1 Physiographic divisions of North Dakota showing location of the Dunn Center project area.

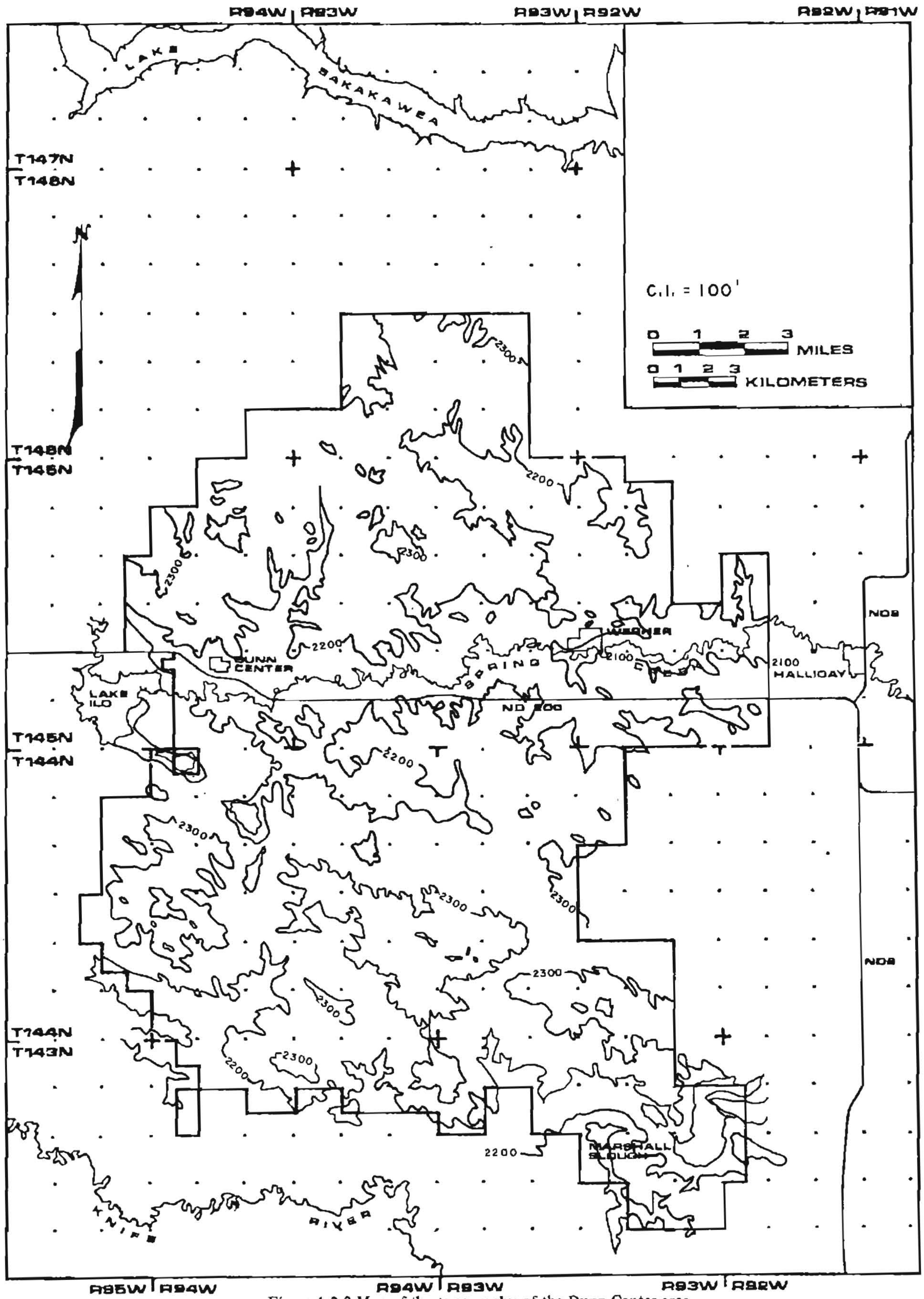

Figure 1.2-2 Map of the topography of the Dunn Center area.

mining. The base-line information that was obtained will serve to provide a basis for comparison with the conditions monitored during and after mining. In addition to providing base-line information, the field investigations were designed to meet the following specific objectives:

1. To assess the effects that strip mining will have on the groundwater environment outside of the area designated for mining. The main emphasis here was the determination of the influence of strip mining on the water-level and water-quality behavior in aquifers that are used for municipal and farm water supply outside of the mining area.

2. To determine the feasibility of assuring domestic and livestock water supply of adequate quantity and quality from aquifers below the base of mining operations to enable reclaimed land to be resettled with farm development. The main emphasis here was on identifying and testing potential aquifers below the Dunn Center bed and on determining their potential for pollution from mining or reclamation activities.

3. To provide information to assist in the location and design of waste-management facilities, in location and design of lignite storage facilities, and to assess the effects of these facilities on the groundwater regime.

4. To provide information to assist in the design of land-reclamation schemes and in development of predictions regarding the potential effects of various land-reclamation options on the groundwater systems below, within, and outside of the reclamation area.

5. To provide the beginnings of a network of observation wells that can be used to monitor the subsurface effects of mining if mining should occur.

To accomplish the above objectives, the following types of field investigations were conducted between April and December 1975:

a. Inventory of domestic and stock wells in the study area and collection of water samples from a selected number of these wells.

b. Geologic test drilling and downhole geophysical logging to define the stratigraphic framework as a base for hydrological, water quality, and future land-reclamation studies.

c. Coring of representative intervals above and directly below the Dunn Center bed for purposes of (1) providing samples for trace element and other chemical studies of the mineral constituents, (2) observing the nature of the porosity and permeability (i.e., degree of fracturing, if any) of some of the silt and clay beds.

d. Installation of nests of observation wells for water-level monitoring, water sampling, and permeability testing.

e. Monitoring, sampling, and testing of the wells.

f. Packer tests (by pressure injection and pump-out methods) in uncased boreholes as they were drilled for the purpose of permeability testing and water sampling of aquifers and aquitards.

g. Pump testing of existing wells and monitoring the water level in nearby observation wells.

1.4 Methods of Study

The stratigraphic study for this project utilized three types of investigation. The more general, regional aspects of the stratigraphic discussion are based on a review of relevant literature. Those formations which are of particular importance to the project were studied in more detail utilizing geophysical logs and sample descriptions of available oil tests and municipal water wells. The most detailed study involved test drilling, geophysical logging, coring, and sampling of testholes at 68 sites throughout the project area. Appendix A-I is a list of the depths to the tops of the significant stratigraphic marker beds in all the testholes used for this study. Appendix A-II contains geophysical logs of UND stratigraphic testholes.

The exploration strategy utilized in conducting the geologic and hydrologic test drilling program was to first drill a series of deep testholes along a north-south cross section through the project area. These testholes were drilled to about 500 feet on one-mile centers to provide sufficient stratigraphic detail beneath the area of interest to permit correlation without difficulty. In addition, it was believed that this depth would be below the zone of surface-affected hydrologic activity. After initial stratigraphic correlations were made and the regional stratigraphic picture emerged to the point that specific marker beds could be confidently identified in the field, the drilling strategy was modified. Preliminary groundwater data confirmed that surface-affected hydrologic activity was in fact shallower than the initial testholes. Key stratigraphic marker beds that appeared to have hydrologic significance were selected and became the principal target of the exploration strategy throughout the remainder of the program.

More than 26,000 feet of test drilling at 68 sites was completed during the period from June to October 1975 (fig. 1.4-1). The drilling was accomplished using two forward-circulation rotary drilling rigs. Samples were collected at 5-foot intervals during the drilling of the stratigraphic testhole for each site. The driller maintained a log of the materials drilled and a Geolograph, which recorded drilling rate and served as a record of other activities associated with the drilling. A field log was kept by the geologist on the site. The samples were oven-dried at the site or at the field headquarters and were described in detail before being bagged. The stratigraphic testhole at each site was geophysically logged (resistance, natural gamma, gamma-gamma density, and caliper). Most sites were also logged using other probes for comparison of different combinations and capabilities.

Core holes were drilled at ten different sites within the project area (fig. 1.4-2). A total of 301 feet of 4-inch diameter core was recovered. The coring sites and intervals were selected to give a representative sampling of the lithologies in the overburden and below the Dunn Center bed. About 140 feet of the core was taken above and 160 feet below the Dunn Center bed. About 10 percent of the core below the Dunn Center bed was from material immediately underlying the lignite. Core samples that have not been destructively analyzed are stored in the North Dakota Geological Survey Core and Sample Library at the University of North Dakota, Grand Forks, North Dakota.

The analyses conducted on the core samples included: (1) the chemical and physical properties of the overburden, (2) bulk density, (3) spark source spectroscopy, (4) permeability, and (5) cation exchange capacity.

2.0 GEOLOGY

2.1 General Stratigraphic Framework

The Dunn Center project area is underlain by as much as 14,000 feet of sedimentary rock lying on a basement of Precambrian igneous and metamorphic rock. The sedimentary column (fig. 2.1-1) consists of limestone, dolomite, shale, sandstone, and evaporite having varying thickness and attitude (Carlson and Anderson, 1970). The varying lithology of the sedimentary column results in varying characteristics of strength, hydraulic conductivity, and mineral resource potential. Only the stratigraphic units which are potentially important to the Dunn Center project are described and discussed in this section.

The units that will be disturbed by mining, the Coleharbor Formation and upper part of the Sentinel Butte Formation, are clearly of significance for the project. Also important are the remainder of the Sentinel Butte Formation and the Bullion Creek Formation, both of which contain other lignite beds and provide the framework of varying hydraulic conductivity that controls much of the detail of groundwater flow under the area to be mined. The Cannonball Formation and much of the Montana, Colorado, and Dakota Groups are discussed because their very low hydraulic conductivity separates the deep, regional, groundwater-flow system into essentially isolated cells. The Ludlow, Hell Creek, and Fox Hills Formations and much of the Dakota Group are discussed because they contain significant aquifers. The permeable Minnelusa Formation and the overlying, very slightly permeable Opeche Formation are discussed because of their potential as a deep injection zone for disposal of aqueous

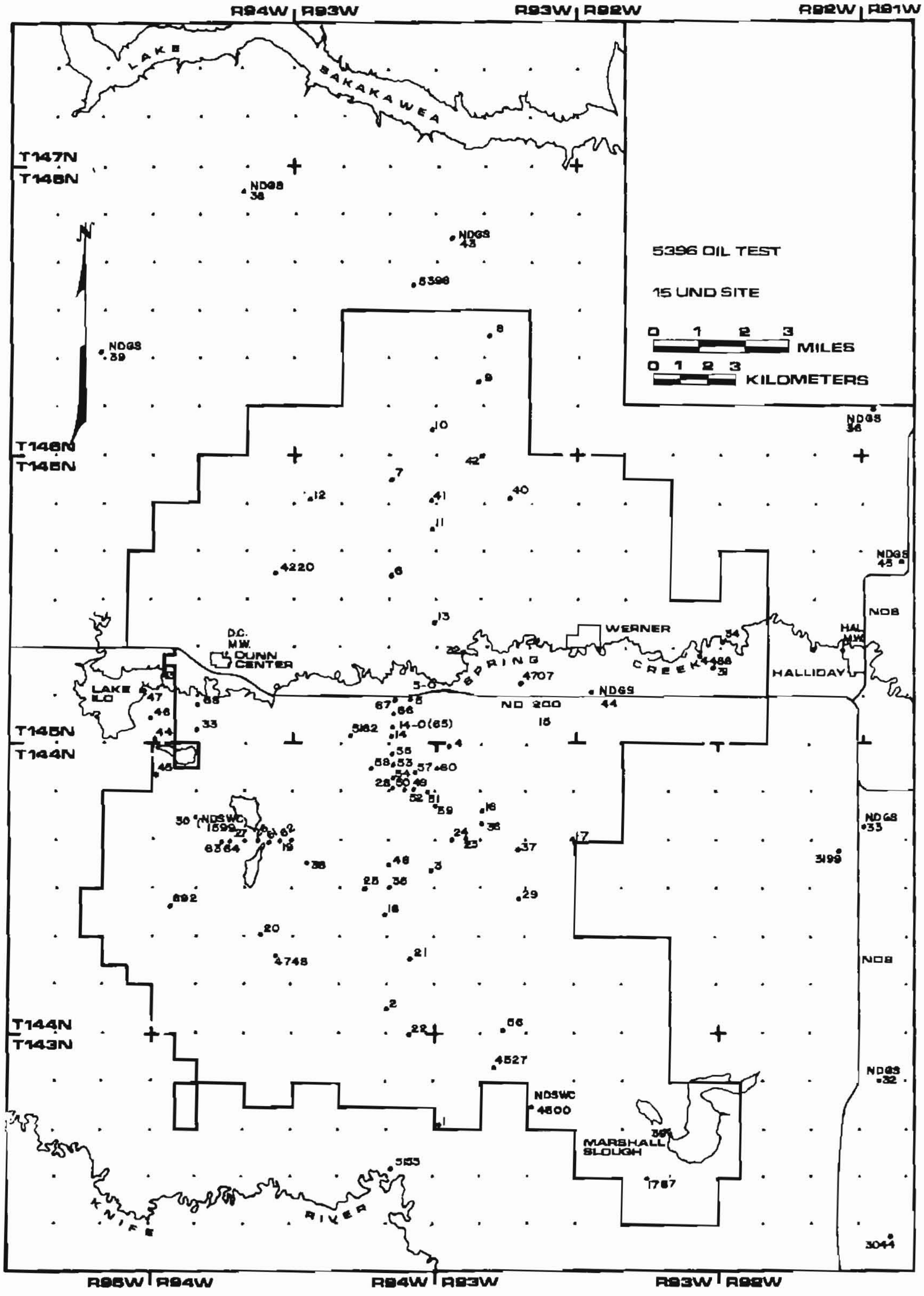

Figure 1.4.1 Map of the location of stratigraphic testholes in the Dunn Center area.

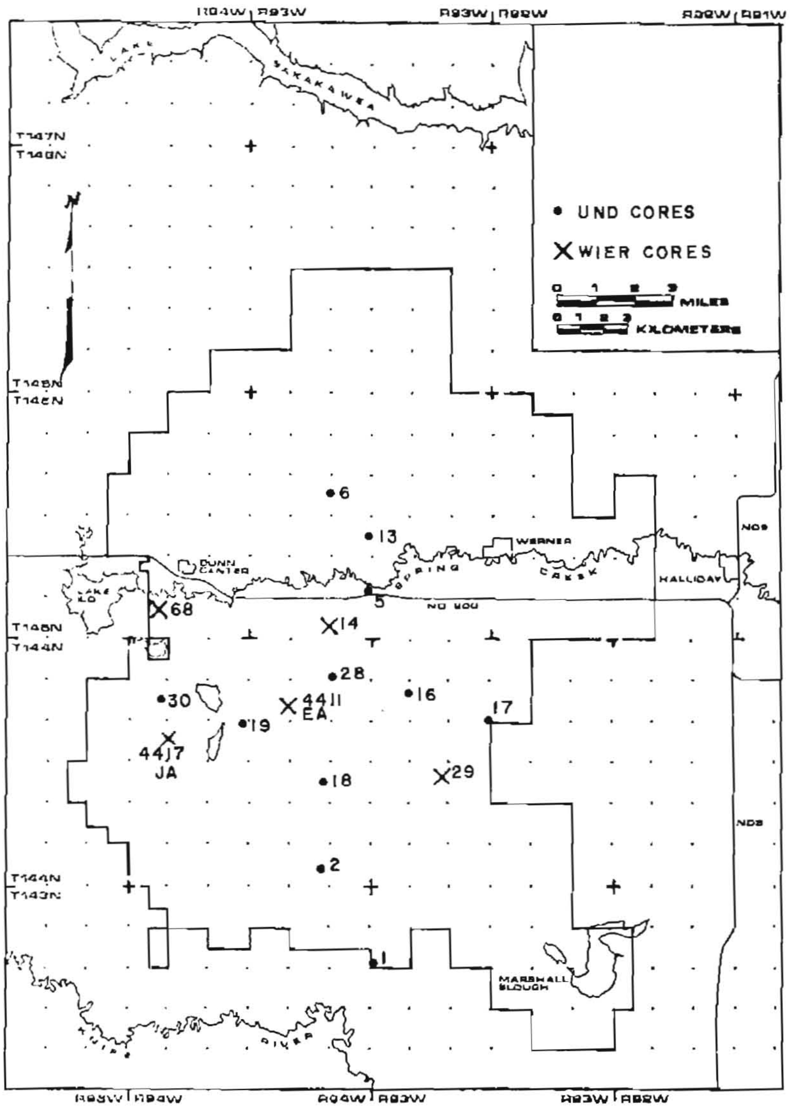

Figure 1.4.2 Map of the location of overburden core holes in the Dunn Center area.

wastes. Deep injection has been indicated as the planned means of disposing of 600 gpm of aqueous waste generated by a similar proposed gasification project located in Mercer County about 30 miles east of the Dunn Center area (Woodward-Clyde Consultants, 1975, p. 3-110). Stratigraphic units below the Minnelusa Formation and between the Opeche Formation and the Dakota Group are not discussed because they have no special significance for project activities.

2.1.1 Minnelusa Formation

The Minnelusa Formation consists of thick beds of well-sorted, clean sand and sandstone, with interbedded shale that is from a few feet to a few tens of feet thick (fig. 2.1.1-1). The formation ranges in thickness from about 150 feet to about 225 feet beneath the project area (fig. 2.1.1-2). Sand generally makes up about 90 percent of the total thickness of the formation, but in some areas as little as 40 percent of the formation is sand. In the project area, the Minnelusa Formation dips nearly due west at about 33 feet per mile (fig. 2.1.1-3). The top of the formation lies from 6750 to 7515 feet below the land surface at an elevation of about 5100 feet below sea level in the west and 4700 feet below sea level in the east.

ERA	SYSTEM	SEQUENCE	GROUP	FORMATION	DOMINANT LITHOLOGY
CENOZOIC	Quaternary	Tejas	Coleharbor		Pebble-loam, Sand, Gravel, Silt, Clay
	Tertiary	Zuni	Fort Union	Golden Valley	Silt, Clay, Sand
				Sentinel Butte	Silt, Sand, Clay, Lignite
				Bullion Creek	Silt, Sand, Clay, Lignite
				Slope	Silt, Clay, Sand, Lignite
				Cannonball	Marine Clay, Silt, Sand
				Ludlow	Silt, Clay, Sand, Lignite
MESOZOIC	Cretaceous			Hell Creek	Sandstone, Shale, Lignite
			Montana	Fox Hills	Marine Sandstone
				Pierre	Shale
			Colorado	Niobrara	Shale, Calcareous
				Carlile	Shale
				Greenhorn	Shale, Calcareous
				Belle Fourche	Shale
			Dakota	Mowry	Shale
				Newcastle	Sandstone
				Skull Creek	Shale
				Fall River	Sandstone, Shale
				Lakota	Sandstone, Shale
	Jurassic			Morrison	Shale, Clay
				Sundance	Shale, green and brown, Sandstone
				Piper	Limestone, Anhydrite, Salt, red Shale
	Triassic	Absaroka		Spearfish	Siltstone, Salt, Sandstone
PALEOZOIC	Permian			Minnekahta	Limestone
				Opeche	Shale, Siltstone, Salt
	Pennsylvanian			Minnelusa	Sandstone
				Amsden	Interbedded Dolomite Limestone, Shale, Sandstone
				Tyler	Shale, Sandstone
	Mississippian	Kaskaskia	Big Snowy	Heath	Shale
				Otter	Sandstone, Limestone
				Kibbey	Interbedded Limestone, Evaporites
				Madison	Limestone
				Bakken	Siltstone, Shale
	Devonian			Three Forks	Shale, Siltstone, Dolomite
				Birdbear	Limestone
				Duperow	Interbedded Dolomite, Limestone
				Souris River	Interbedded Dolomite, Limestone
				Dawson Bay	Dolomite, Limestone
				Prairie	Salt
				Winnipegosis	Limestone, Dolomite
	Silurian	Tippecanoe		Interlake	Dolomite
	Ordovician			Stonewall	Dolomite, Limestone
				Stony Mountain	Limestone, Dolomite
				Red River	Limestone, Dolomite
			Winnipeg	Roughlock	Calcareous Shale, Siltstone
				Ice Box	Shale
				Black Island	Sandstone
	Cambrian	Sauk		Deadwood	Limestone, Shale, Sandstone
	Precambrian				

Figure 2.1-1 Stratigraphy of the sedimentary rocks underlying the Dunn Center area.

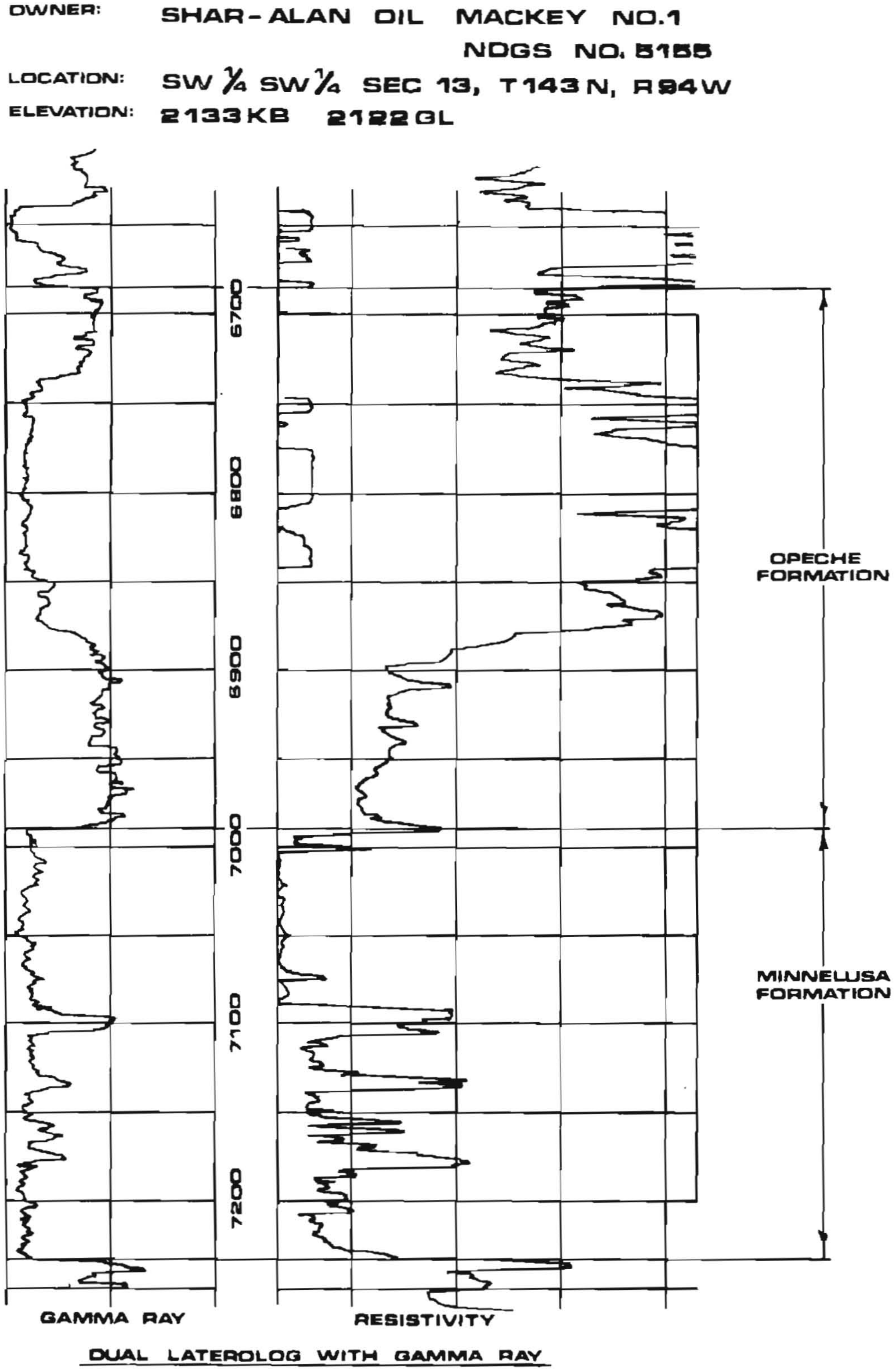

Figure 2.1.1-1 Geophysical log of the Minnelusa and Opeche Formations.

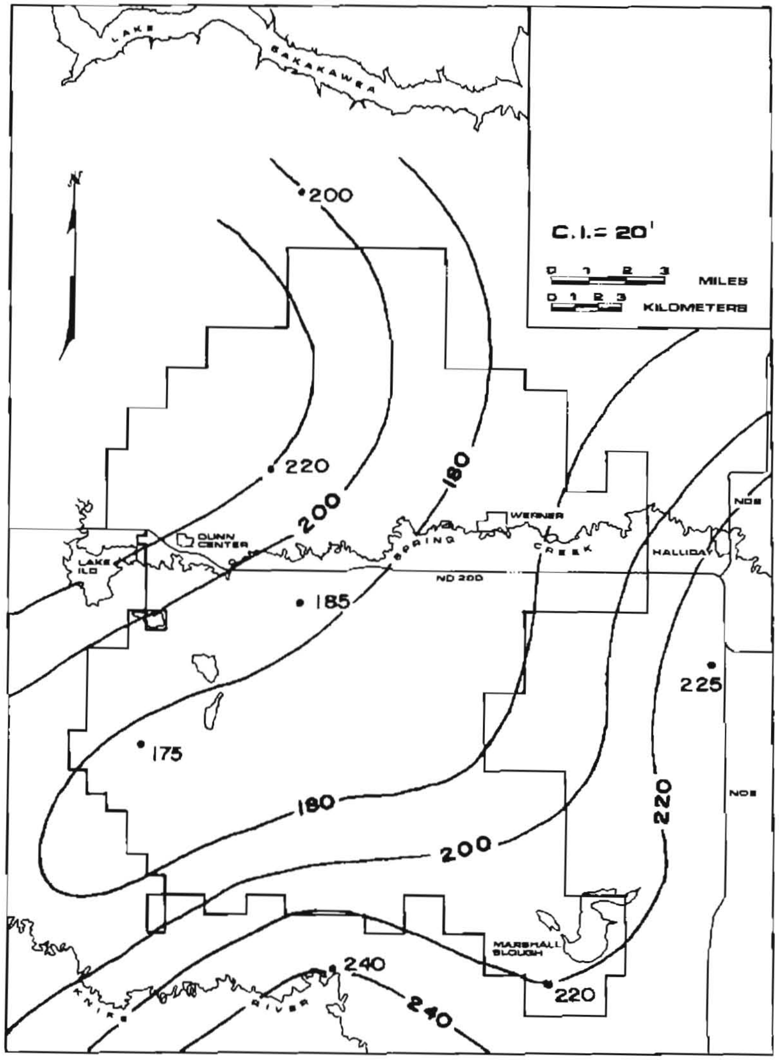

Figure 2.1.1-2 Map of the thickness of the Minnelusa Formation in the Dunn Center area.

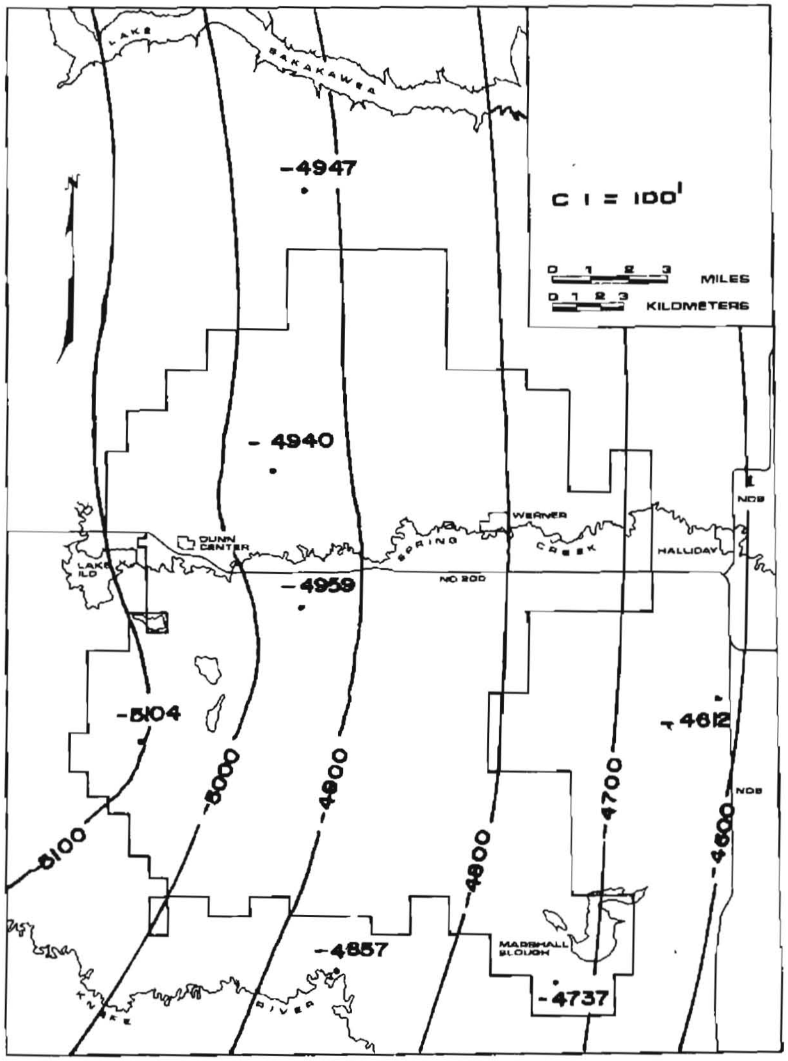

Figure 2.1.1-3 Map of the elevation of the top of the Minnelusa Formation in the Dunn Center area.

2.1.2 Opeche Formation

The Opeche Formation, which consists of interbedded salt and shale, directly overlies the Minnelusa Formation (fig. 2.1-1). Generally about half of the formation is salt and half is shale, although, in some places, the formation consists of as much as 90 percent salt; in other places the salt has been completely removed by solution. The Opeche Formation underlies the entire project area at depths of about 6400 to 7000 feet (app. A-I). The total thickness ranges from about 100 to 450 feet and averages 350 feet (fig. 2.1.2-1). The Opeche Formation serves as a very low permeability barrier that isolates the underlying Minnelusa Formation from permeable beds above it.

2.1.3 Dakota Group

The Dakota Group consists of two major lithologies. At the base of the group, the Fall River and Lakota Formations consist dominantly of sand and sandstone (fig. 2.1.3-1). Overlying these formations are the Skull Creek and Mowry Formations, which consist dominantly of shale, separated by the Newcastle Formation, which is sand or sandstone (fig. 2.1.3-1). The Fall River and Lakota Formations consist of thick beds of sand and sandstone interbedded with silty

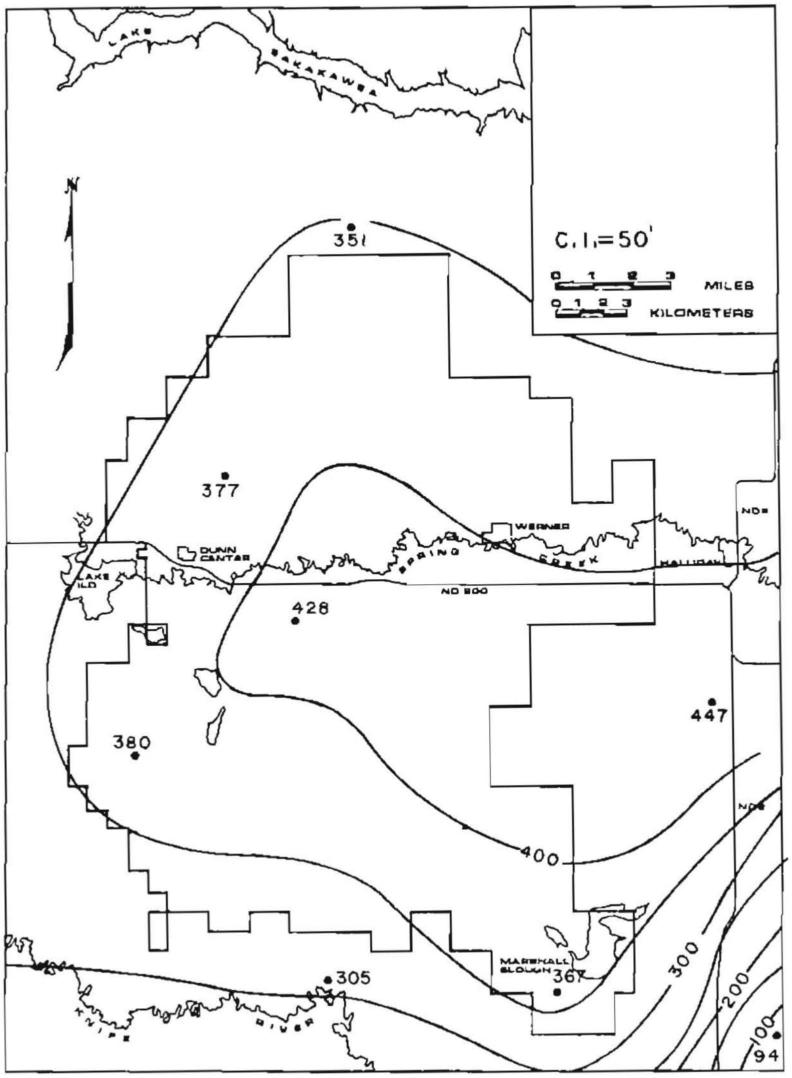

Figure 2.1.2-1 Map of the thickness of the Opeche Formation in the Dunn Center area.

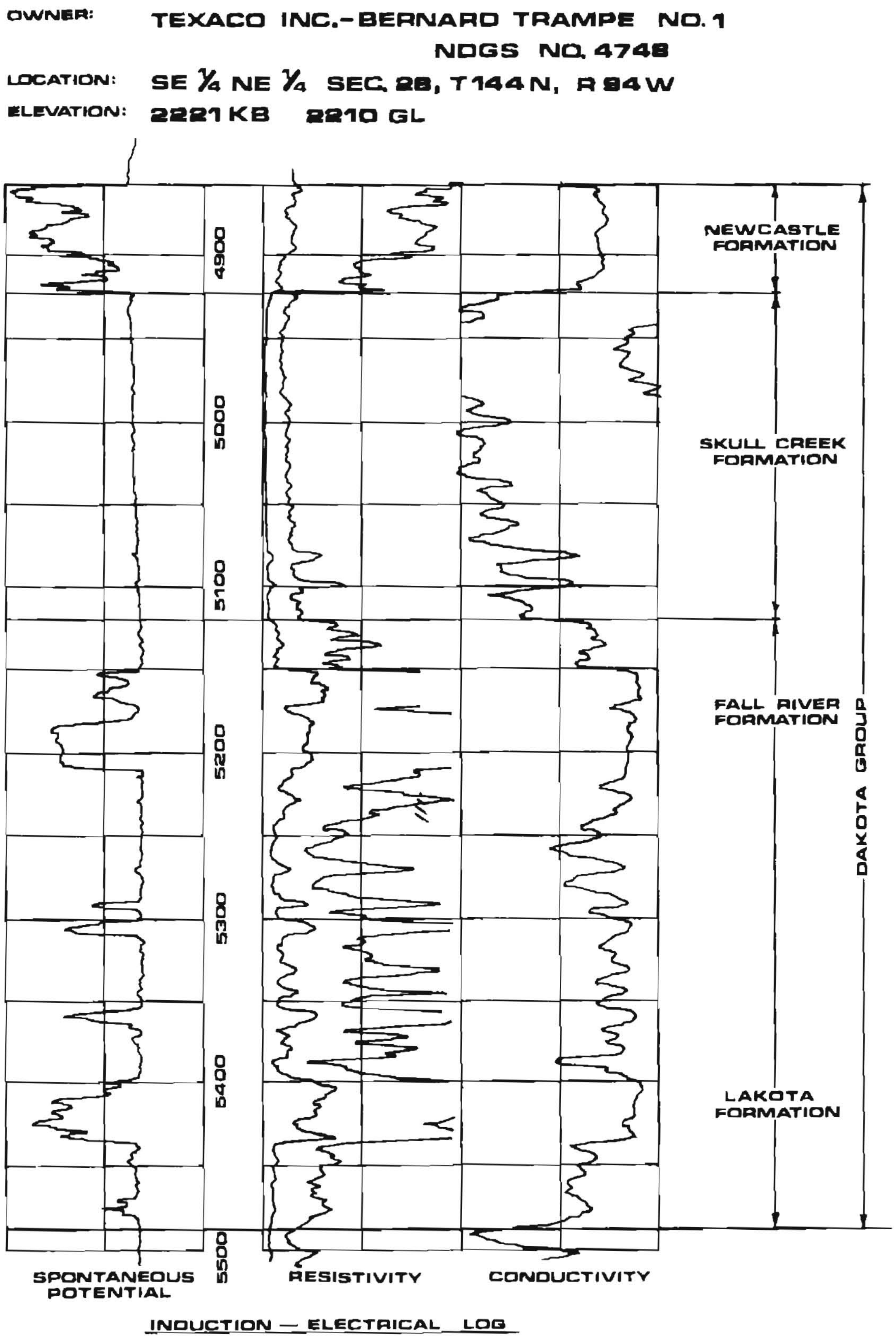

Figure 2.1.3-1 Geophysical log of the lower part of the Dakota Group.

sandstone, siltstone, and shale. Individual beds of sand and sandstone are from 20 to 60 feet thick. The Fall River and Lakota Formations have a total thickness of about 350 feet, ranging from 300 to 400 feet in the project area (fig. 2.1.3-2). The top of the Fall River Formation lies at depths of 4850 to 5370 feet below the land surface (app. A-1). Its elevation varies from about 2950 feet below sea level, in the western part of the project area, to about 2700 feet below sea level, in the east (fig. 2.1.3-3).

2.1.4 Colorado and Montana Groups

The shale of the Mowry Formation, at the top of the Dakota Group, is overlain by five formations consisting almost entirely of clay shale. These include the Belle Fourche, Greenhorn, Carlile, and Niobrara Formations of the Colorado Group, and the Pierre Formation of the Montana Group. With the exception of the sand and sandstone of the Newcastle Formation (fig. 2.1.3-1), which ranges in thickness from 10 to 50 feet and lies about 100 to 150 feet above the Fall River Formation, the entire interval from about 5000 feet to 2000 feet below land surface (app. A-I) consists of shale which effectively isolates groundwater flow in the Fall River, Lakota, and Newcastle Formations from overlying permeable zones. The top of this interval of shale, the Pierre Formation, is the absolute base of local and intermediate groundwater-flow systems under the project area (fig. 2.1.4-1).

2.1.5 Fox Hills, Hell Creek, and Ludlow Formations

The Fox Hills Formation consists of laterally continuous, alternating beds of sand, silt, and clay that are traceable throughout the project area. Individual sand beds are several tens of feet thick. The sand is generally clean and well sorted.

In this study, the top of the Fox Hills Formation has been arbitrarily placed at the top of the highest well-developed, thick sand section in the lower part of the interval between the Pierre and Cannonball Formations (fig. 2.1.5-1). It is not known whether this contact corresponds to the top of the formation as recognized in outcrop. It may actually lie within the Hell Creek Formation. As here defined, the Fox Hills Formation consists of two or three beds of sand, which range in thickness from 20 to 70 feet, separated by beds of silt and clay. In ten testholes in the study area, the Fox Hills Formation varied in thickness from 190 feet to 297 feet (fig. 2.1.5-2). The elevation of the top of the formation varied from 570 feet to 838 feet (fig. 2.1.5-3).

The Hell Creek Formation consists of alternating beds of silt, sand, clay, and minor lignite. Individual beds are not as laterally traceable as those in the underlying Fox Hills Formation. Although sand beds are generally less well sorted than in the Fox Hills Formation, they do constitute potential aquifers in some places. In the project area, the Hell Creek Formation generally consists of fine-grained material. It is bounded below by the arbitrarily defined top of the Fox Hills Formation, as described above. The upper contact of the Hell Creek Formation is the base of the first significant lignite bed above the Fox Hills Formation (fig. 2.1.5-1, -4, and -5). Defined in this way, this contact is very difficult to pick without a very good gamma-ray and gamma-gamma density log of the hole. It was recognized in six testholes in the area. The thickness of the Hell Creek Formation varied from 74 to 165 feet.

The Ludlow Formation consists of alternating beds of silt, sand, clay, and lignite. It is very similar in characteristics to the Bullion Creek and Sentinel Butte Formations. In this study, both the upper and lower contacts of the Ludlow are placed on lignite beds. The lower contact is discussed above; the upper contact is placed at the top of the first lignite bed below the thick silt and clay of the Cannonball Formation (fig. 2.1.5-4, -5). The thickness of the Ludlow Formation in the project area varies from 99 to 200 feet.

2.1.6 Cannonball Formation

The Cannonball Formation consists primarily of silt and clay. The middle part of the formation contains two beds of sand that occur throughout the project area (figs. 2.1.5-1, 2.1.5-4, 2.1.5-5, 2.1.6-1); in some places, sand also occurs at the top

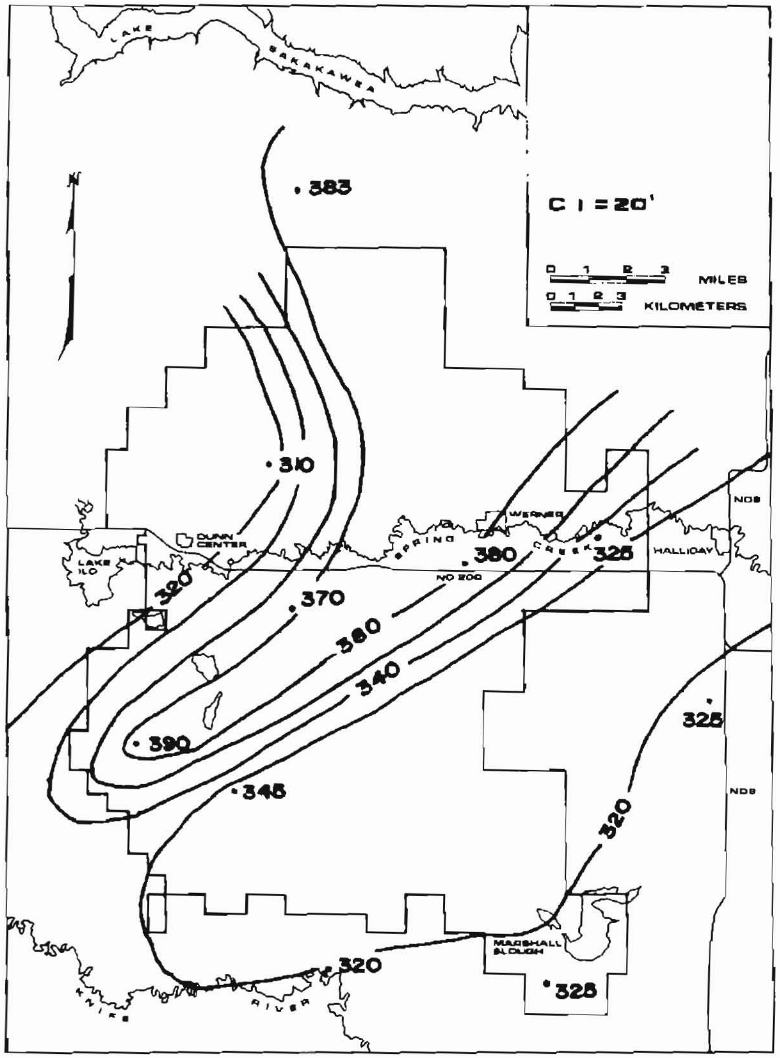

Figure 2.1.3-2 Map of the thickness of the Lakota and Fall River Formations in the Dunn Center area.

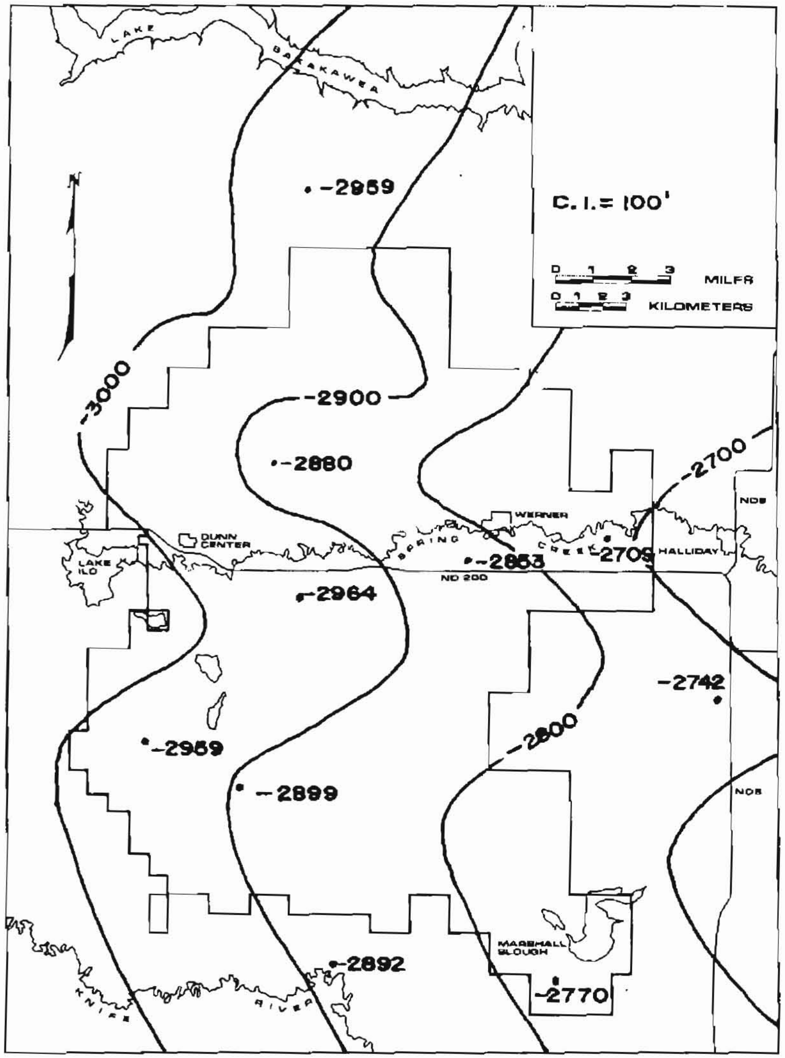

Figure 2.1.3-3 Map of the elevation of the top of the Fall River Formation in the Dunn Center area.

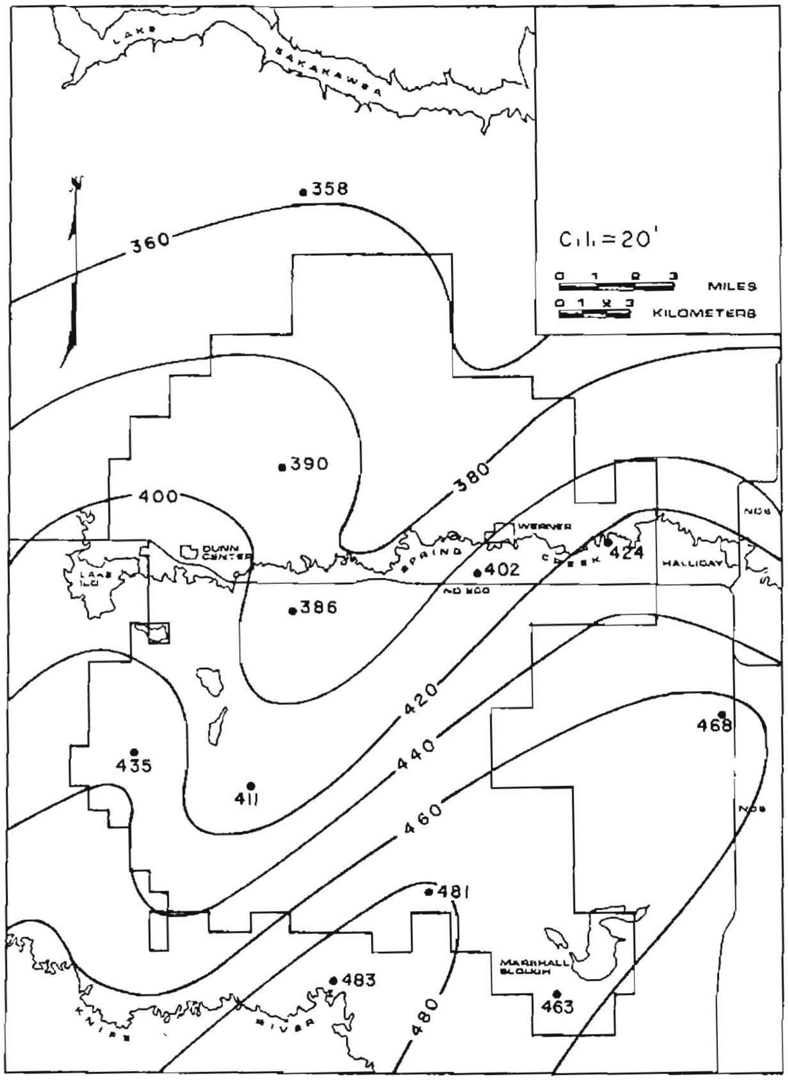

Figure 2.1.4-1 Map of the elevation of the top of the Pierre Formation in the Dunn Center area.

and base of the formation. The sand beds are generally about 25 feet thick, and the clay beds are about 50 feet thick. The top of the Cannonball Formation is from 1135 to 1265 feet above sea level (fig. 2.1.6-2) at depths of about 850 to 1250 feet below the land surface (app. A-I). The thickness of the Cannonball Formation ranges from 205 to 290 feet with the greatest thickness in an east-northeast-trending belt from south of Dunn Center to north of Halliday (fig. 2.1.6-3).

The Cannonball Formation serves as a very low-permeability barrier that effectively isolates groundwater in the Ludlow, Hell Creek, and Fox Hills Formations from the overlying Bullion Creek and Sentinel Butte Formations. It is probably the base of intermediate groundwater-flow systems. Except where drain-down cones have been developed by pumping or flowing wells, potentiometric head in aquifers below the Cannonball Formation will not reflect local topographic effects.

2.1.7 Bullion Creek Formation

The Bullion Creek Formation (formerly Tongue River Formation) (Clayton and others, 1977) underlies the entire project area. It consists of alternating beds of silt, clay, sand, and lignite. In the

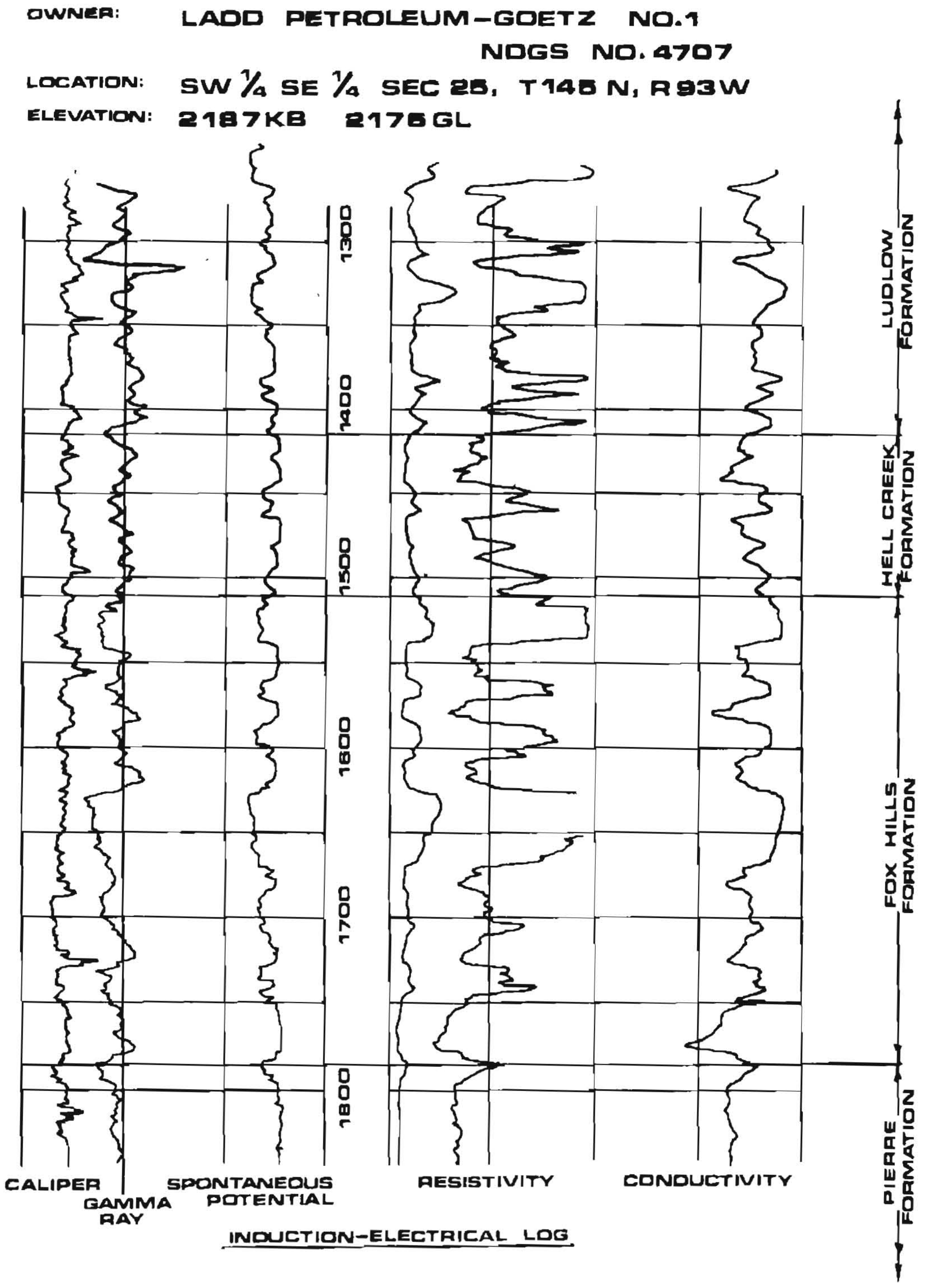

Figure 2.1.5-1 Geophysical log of the Fox Hills, Hell Creek, and Ludlow Formations.

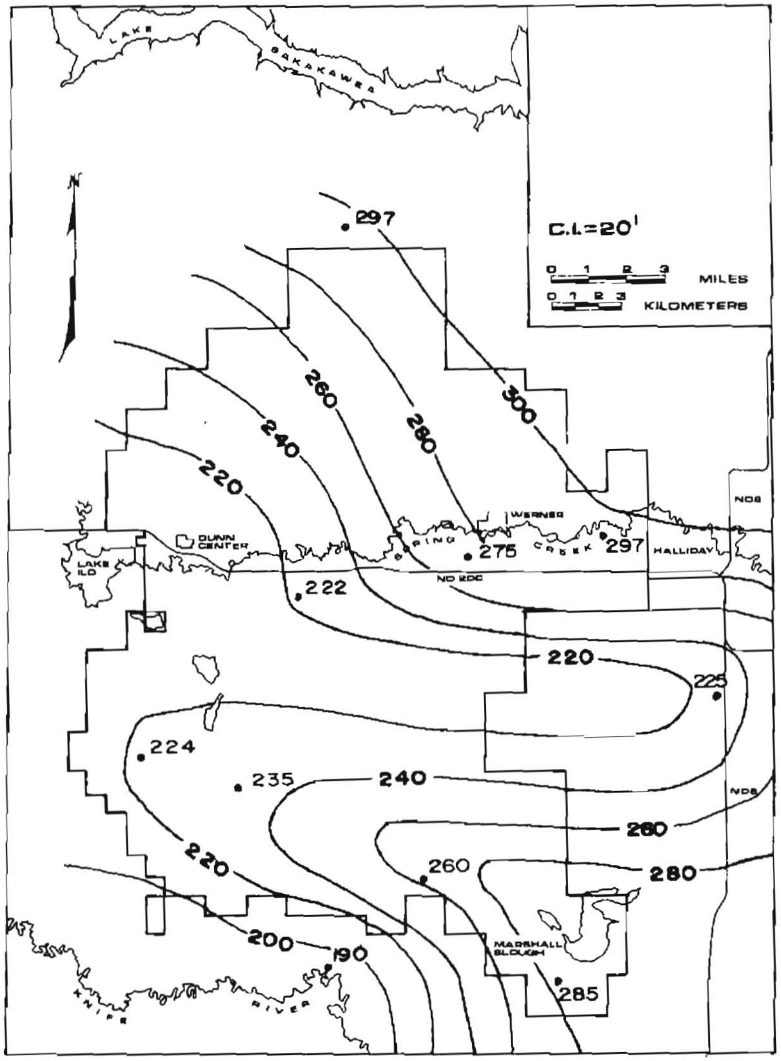

Figure 2.1.5-2 Map of the thickness of the Fox Hills Formation in the Dunn Center area.

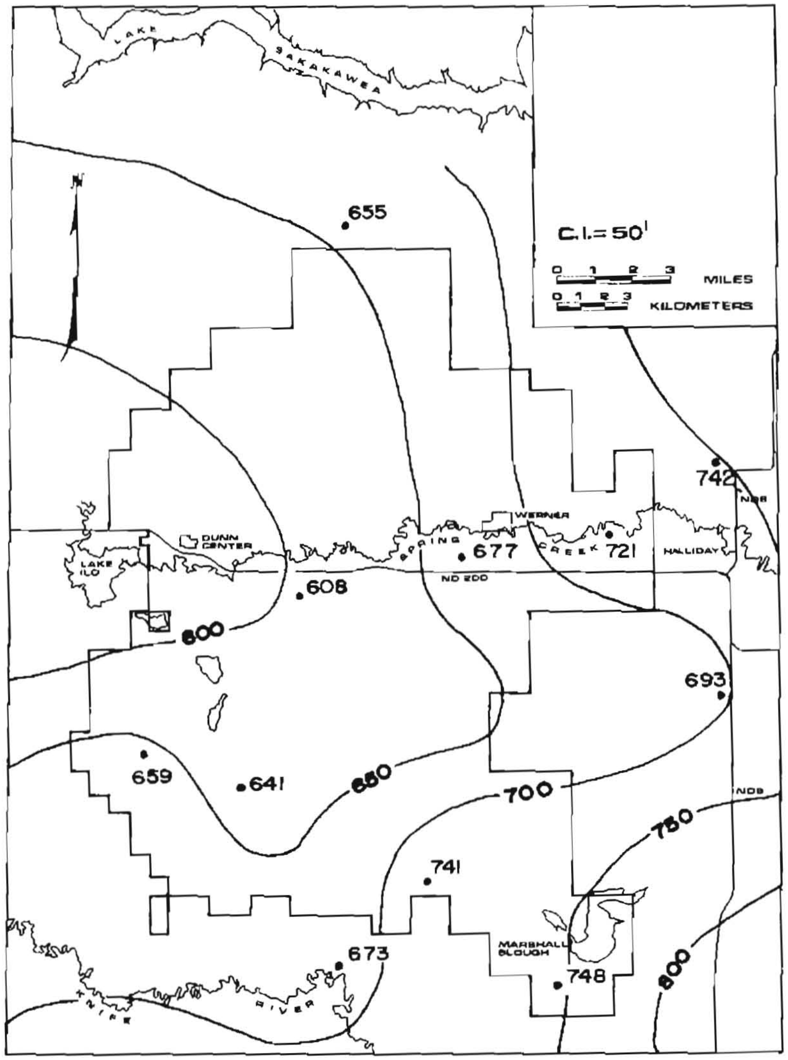

Figure 2.1.5-3 Map of the elevation of the top of the Fox Hills Formation in the Dunn Center area.

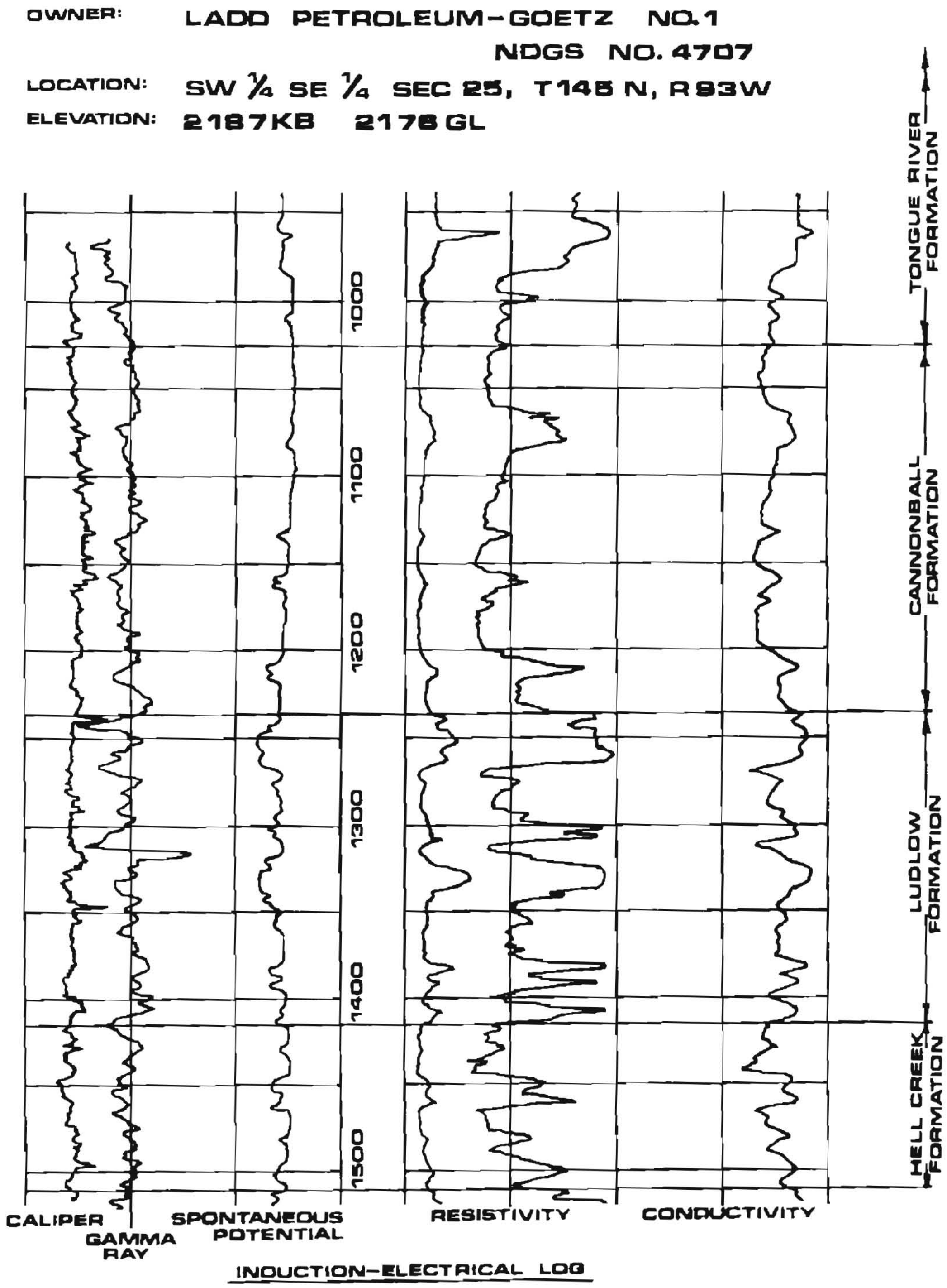

Figure 2.1.5-4 Geophysical log of the Hell Creek, Ludlow, and Cannonball Formations and the base of the Bullion Creek Formation.

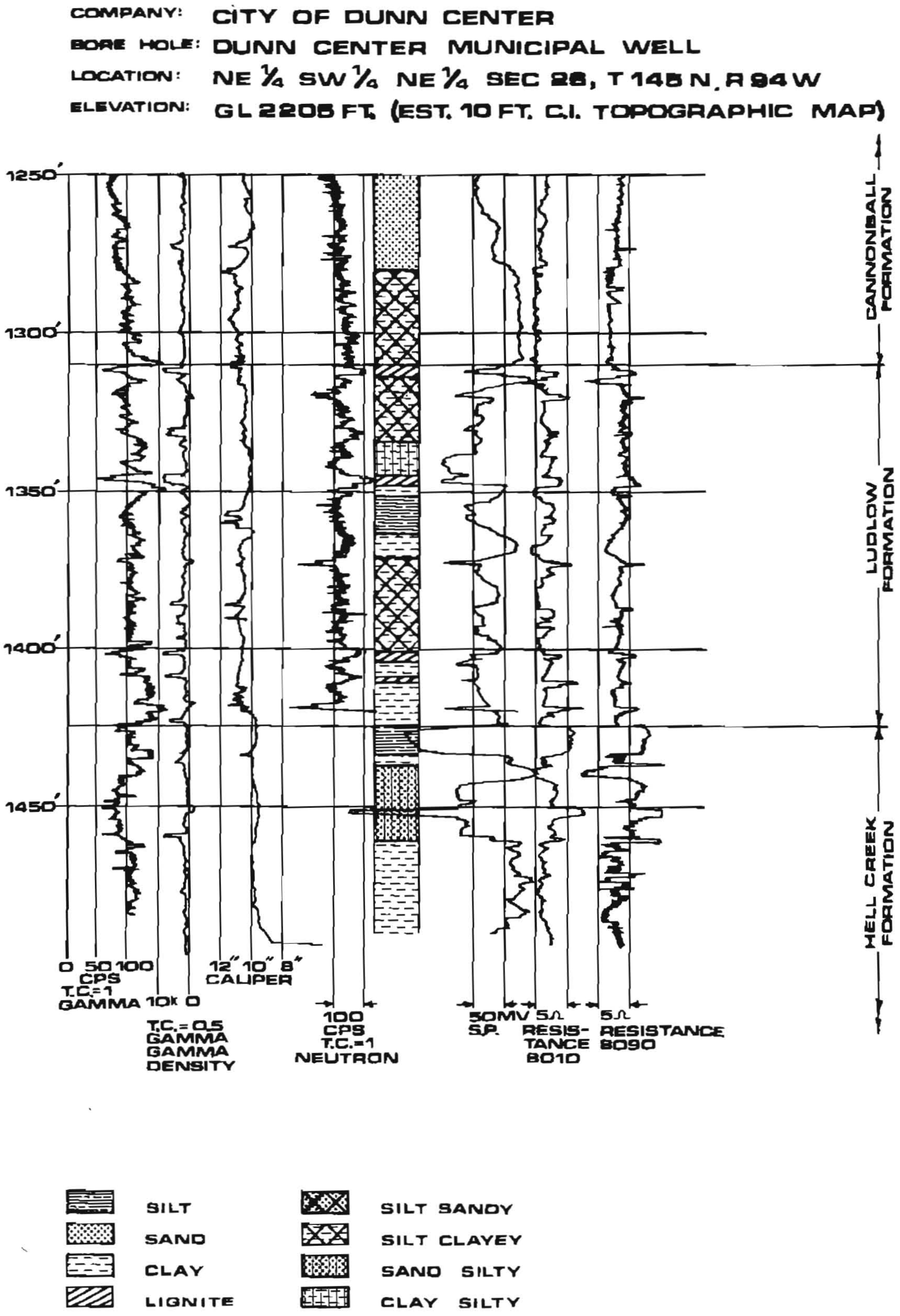

Figure 2.1.5-5 Geophysical log of the Hell Creek and Ludlow Formations and the base of the Cannonball Formation.

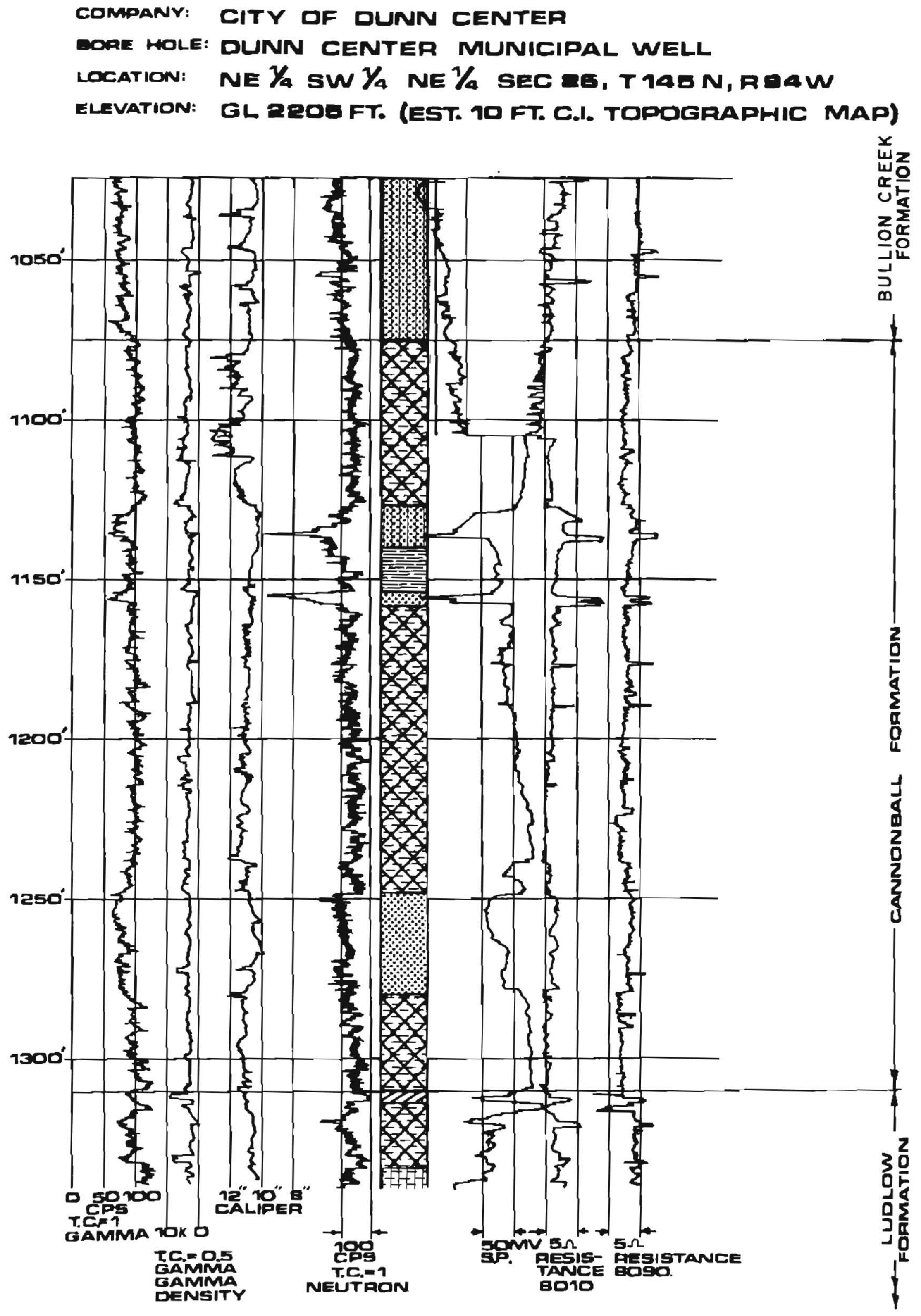

Figure 2.1.6-1 Geophysical log of the Cannonball Formation. See figure 2.1.5-5 for explanation of lithologic symbols.

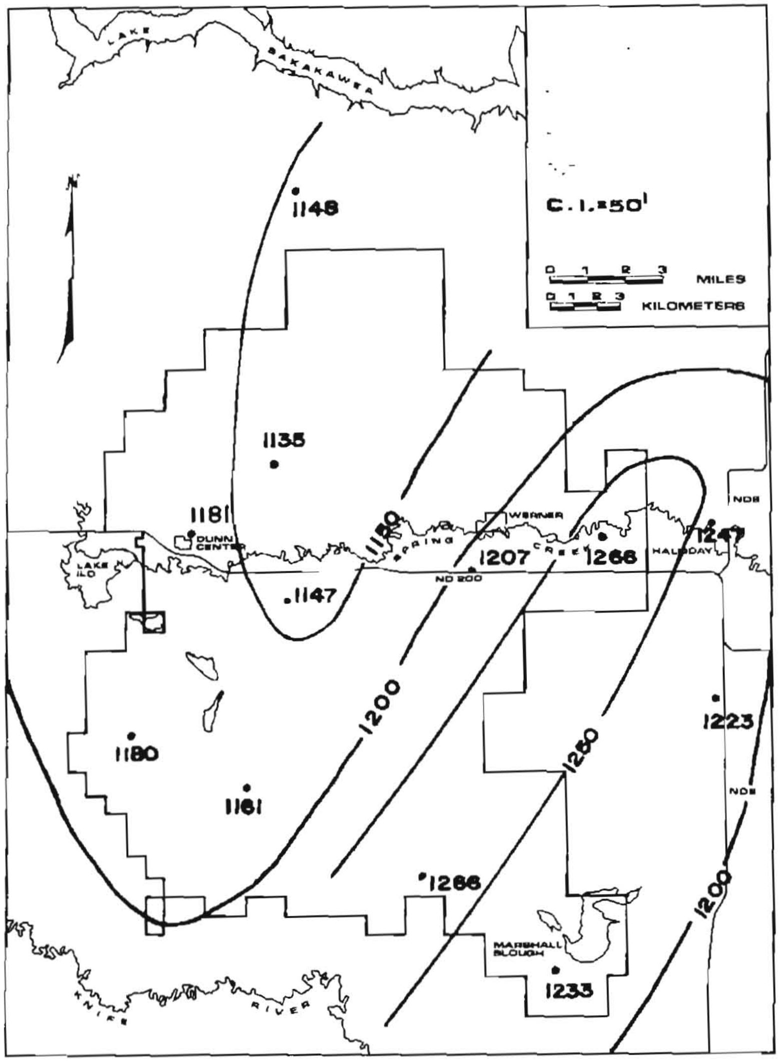

Figure 2.1.6-2 Map of the elevation of the top of the Cannonball Formation in the Dunn Center area.

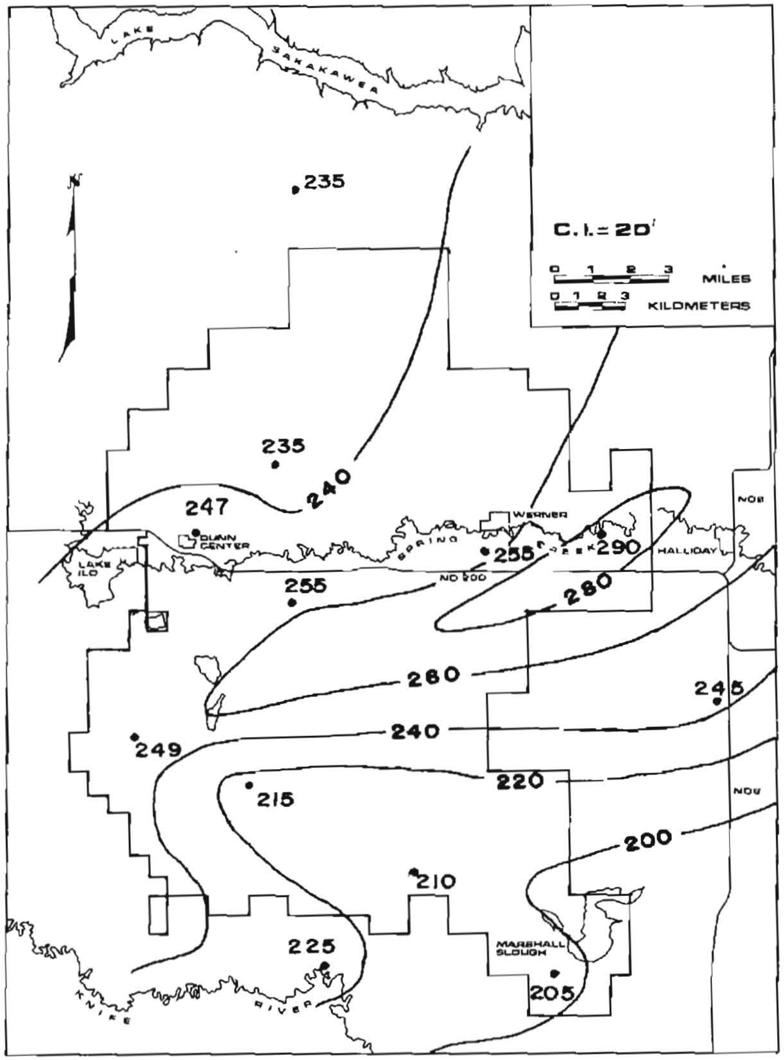

Figure 2.1.6-3 Map of the thickness of the Cannonball Formation in the Dunn Center area.

project area, it varies in thickness from about 700 feet in the west to about 450 feet in the east (fig. 2.1.7-1). The basal contact of the Bullion Creek Formation has been arbitrarily placed at the top of a thick silt and clay section of the Cannonball Formation (fig. 2.1.7-2). The base of the Bullion Creek Formation, thus defined, is generally a gradational sequence of silt and sand that becomes progressively sandier upward. A thin lignite generally occurs in the upper part of this sequence. No "basal Bullion Creek sand" was recognized in the project area.

No definitive basis to readily identify the upper contact of the Bullion Creek Formation in the subsurface has been established. Observations by Moran and Stancel along the wave-eroded bluffs of Lake Sakakawea north of the project area indicate that no exposures of the Bullion Creek Formation are present. The upper contact of the formation is therefore arbitrarily placed at the base of the first widespread marker bed below 1850 feet, the elevation of the reservoir. This is a prominent lignite bed that is here informally named the J-lignite (fig. 2.1.7-3).

The Bullion Creek Formation contains sand and coal beds that are potential aquifers. In addition, the Bullion Creek

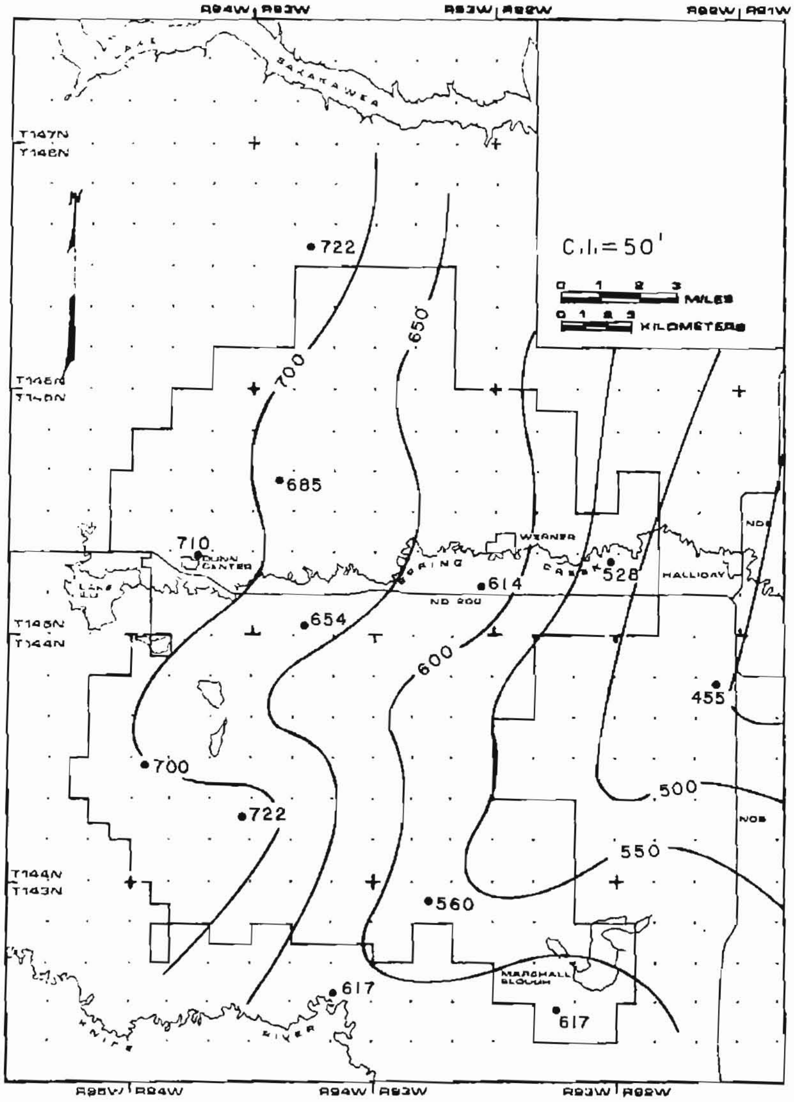

Figure 2.1.7-1 Map of the thickness of the Bullion Creek Formation in the Dunn Center area.

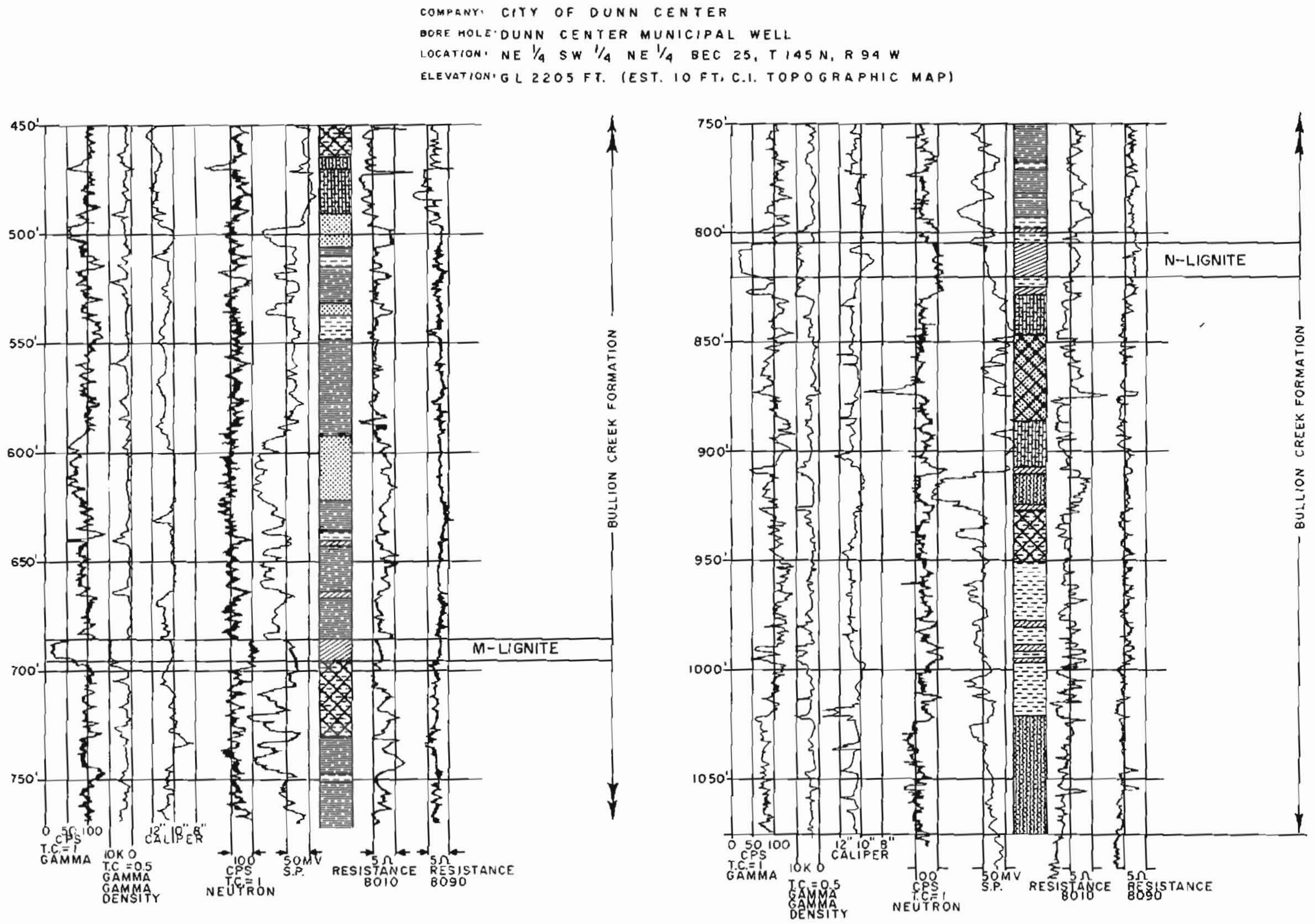

Figure 2.1.7-2 Geophysical log of the lower and middle part of the Bullion Creek Formation. See figure 2.1.7-3 for explanation of lithologic symbols.

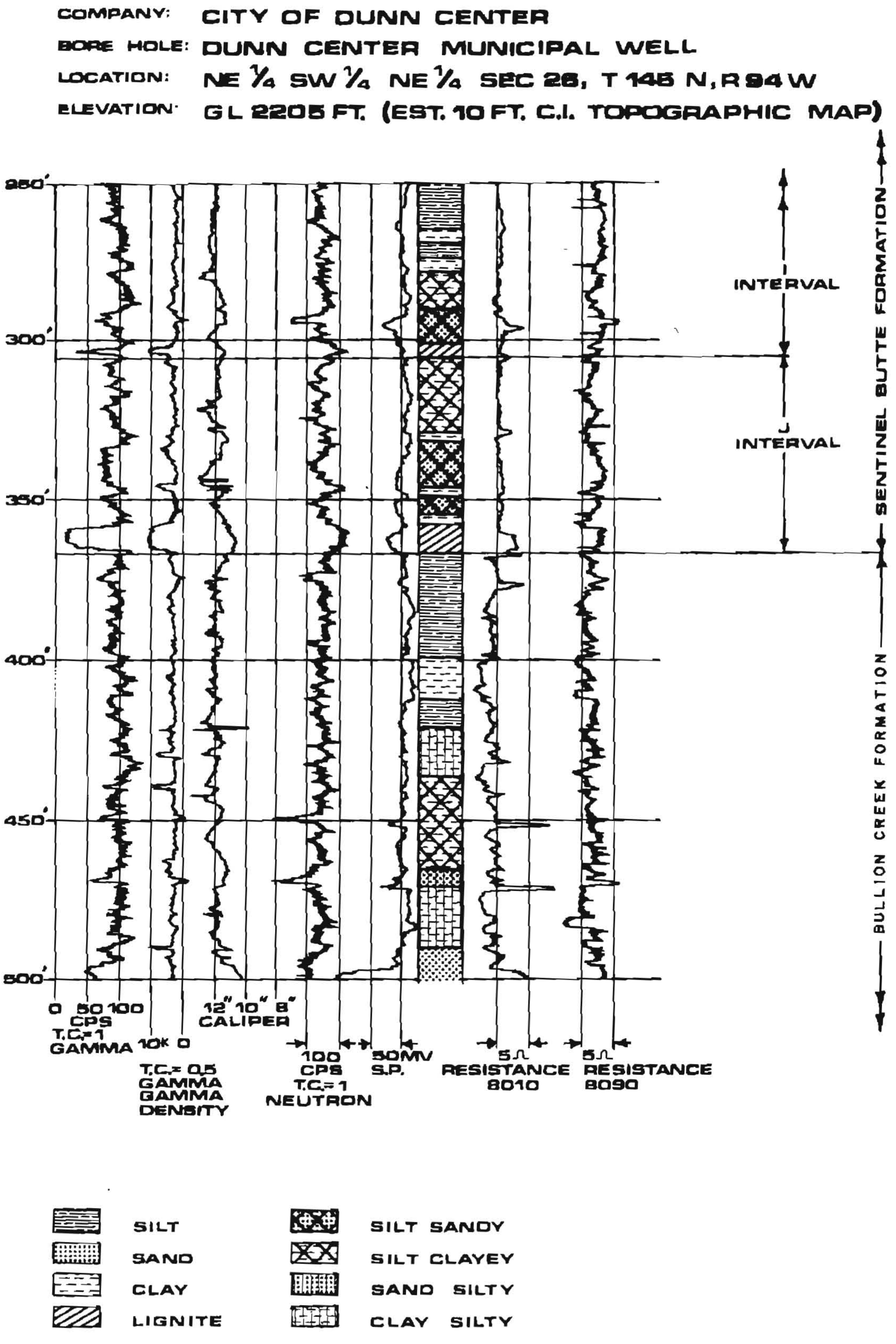

Figure 2.1.7-3 Geophysical log of the upper part of the Bullion Creek Formation.

Formation contains lignite beds that are sufficiently thick that they may be a valuable resource at some time in the future with the development of in situ conversion technology.

More recent work in the Knife River basin indicates that the upper contact of the Bullion Creek Formation is actually lower than that picked in this report (G. H. Groenewold, personal communication). The Bullion Creek Formation, as used in this report, includes the Slope Formation (Clayton and others, 1977). Because of the depth of this contact in the study area, no attempt was made to separate the units.

2.1.8 Sentinel Butte Formation

The Sentinel Butte Formation consists of alternating beds of silt, clay, sand, and lignite (pls. 1, 2, 3, and 4). Individual beds vary in thickness from less than a foot to several tens of feet. Study of cores and outcrops indicates that single beds contain alternating laminae of varying texture that are a few mm thick.

The upper surface of the Sentinel Butte Formation is nearly everywhere eroded. One testhole, which was drilled by the North Dakota Geological Survey about 1¼ miles north of the project area, extended through the lower part of the Golden Valley Formation and the entire Sentinel Butte Formation, which is about 490 feet thick at that site (pl. 2). Using the elevation of the contact between the Golden Valley Formation and the Sentinel Butte Formation and the elevation of the top of the Bullion Creek Formation in nearby testholes, the Sentinel Butte Formation varies in thickness from 525 to 575 feet in the southern part of the area (pl. 1).

Ten major lignite beds are recognized in the Sentinel Butte Formation in the project area. The upper three are very limited in distribution because of erosion of the upper part of the formation. The lower seven have been traced across the entire project area. The characteristics of these major lignite beds and the silt, sand, clay, and minor lignite beds between them are discussed in detail below.

2.1.9 Golden Valley Formation

The Golden Valley Formation caps isolated buttes north of the project area, on the divide between Spring Creek and the Little Missouri River, and in the southern part of the area, along the divide between Spring Creek and the Knife River (fig. 2.1.9-1). It consists of two members. The distinctive, lower member is about 30 feet thick. It consists of a lower unit of gray silt and clay, a middle unit of white or orange kaolinitic clay or silt, and an upper unit of lavender-gray silt and clay (Clayton, 1970). The upper member consists of conspicuously cross-bedded, micaceous sand, sandstone, or silty, fine-grained sand. Silt and bentonitic clay are abundant in the upper part of the member (Clayton, 1970).

2.1.10 Coleharbor Formation

The Coleharbor Formation, as used in this study, contains all of the unconsolidated gravel, sand, silt, clay, and pebble-loam (till) that overlies the Sentinel Butte and Golden Valley Formations. It probably contains some sand and gravel that are, in fact, stratigraphically below the type Coleharbor Formation. It undoubtedly contains sand, silt, and clay which are stratigraphically above the type Coleharbor Formation. The Coleharbor Formation is used in this very broad manner for a number of reasons: (1) The formalized framework for stratigraphic classification of the underlying and overlying units is in a state of flux and unstable. (2) This study has not concentrated sufficient attention on these materials to permit consistent systematic differentiation of the material that is not part of the Coleharbor Formation strictly defined. (3) Very little of the material, herein included in the Coleharbor Formation but not actually part of it, occurs in the project area; and its differentiation is not considered significant to the objectives of this study.

Two principal occurrences of sediment of the Coleharbor Formation have been recognized in the project area: (1) thin, discontinuous patches on the uplands, largely restricted to the northern

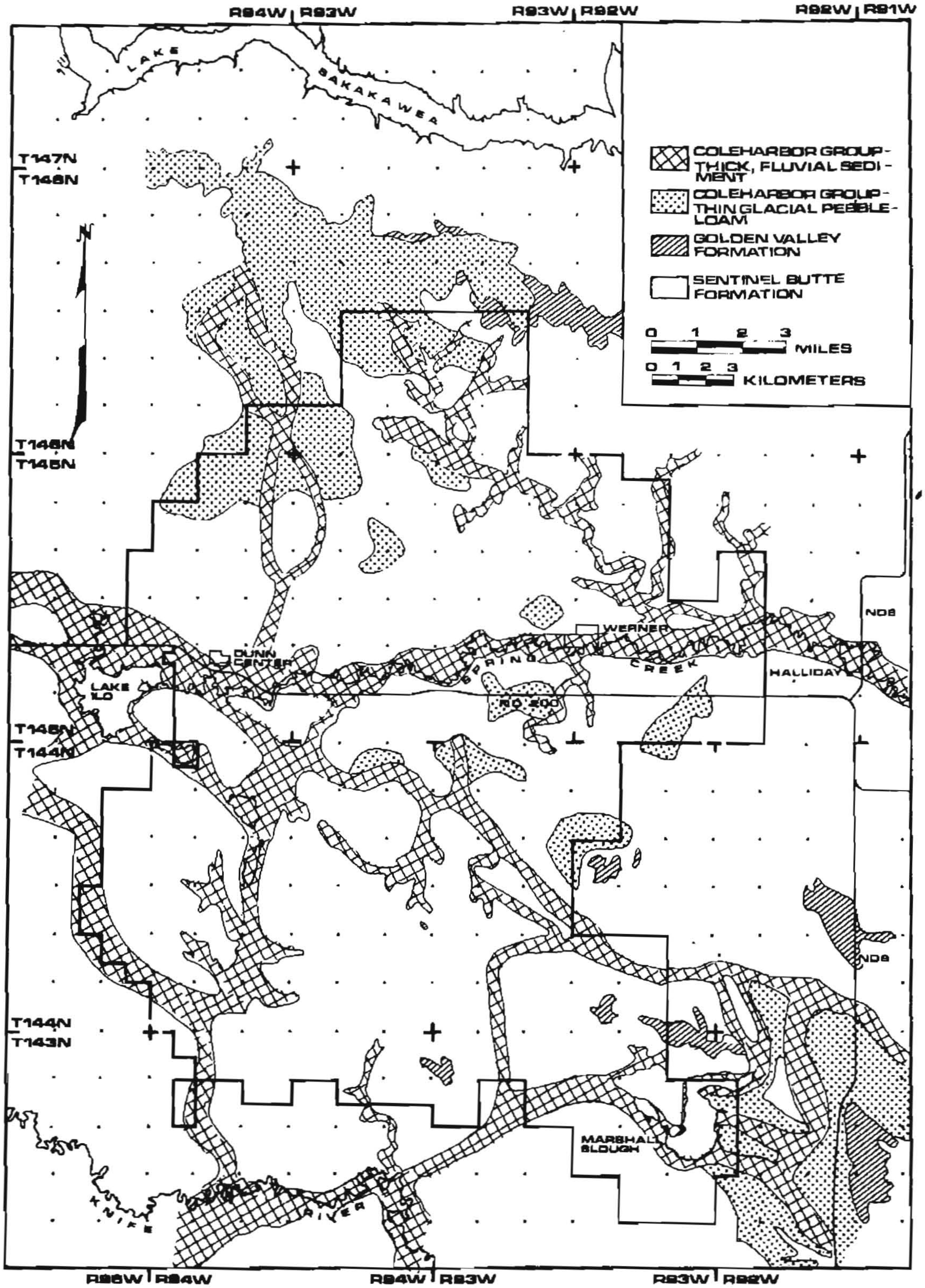

Figure 2.1.9-1 Geological map of the Dunn Center area.

part of the area (fig. 2.1.9-1), and (2) thick, linear bodies filling glacial meltwater channels (fig. 2.1.9-1). The thin patches occurring on the upland are generally clayey to silty pebble-loam (till) that contain scattered boulders. Some sand and gravel occurs in these areas, but it is irregular in distribution and has not been differentiated. In these areas, the sediment of the Coleharbor Formation is thin, generally only a few feet thick and probably nowhere more than 10 to 20 feet thick. Test drilling in the project area, the distribution of boulders throughout the area, and observations in the Indian Head Mine at Zap, North Dakota, which is located in a similar physiographic setting, all indicate that other thin patches of pebble-loam, which range in area from a few hundred square feet to a few acres, will be encountered through the project area. Isolated patches of gravel, from 1 to 3 feet thick, which are too thin and too small to be shown on figure 2.1.9-1, also occur in the area.

The maximum thickness of the meltwater channel fills ranges from about 120 to about 200 feet. Although they are generally complex, indicating a multistage history of deposition, they are characterized by a general pattern of coarse-grained material, sand and gravel, near the base, overlain by finer-grained material, pebble-loam, silt, and clay (fig. 2.1.10-1, -2). In some places, several layers of sand and gravel are separated by layers of pebble-loam or lacustrine clay (fig. 2.1.10-3). In a few places, sand beds were found in the upper, generally fine-grained part of the fill, very near the surface (figs. 2.1.10-1, 2.1.10-4).

2.2 Structure

2.2.1 Regional Structure

The project area is located just east of the center of the Williston basin. Rocks older than the Cannonball Formation dip toward the west indicating that the center of the basin was located west of the project area (figs. 2.1.1-3, 2.1.3-3, 2.1.4-1, 2.1.5-3, 2.1.6-2). The direction of the regional dip in the Bullion Creek and Sentinel Butte Formations is toward the east (fig. 2.2.1-1). It is not clear whether this represents a migration of the center of the Williston basin to the east of the project area or whether the subsidence of the Williston basin had ceased and the basin was filled.

2.2.2 Intermediate Structure

A review of structure maps from the top of the Cannonball Formation (fig. 2.1.6-2) upward (figs. 2.2.1-1, 2.2.2-1, 2.2.2-2) reveals a persistent northeast-trending structural ridge across the center of the project area. This structural ridge is flanked on the southeast and northwest by structural depressions. Two possible explanations for this structural pattern suggest themselves. The first is that the high area reflects a thickening of sediment in the Cannonball Formation (fig. 2.1.6-3) over which the younger rocks were draped. We consider it unlikely that so small a thickening as is present in the Cannonball Formation should persist through such a great stratigraphic interval. The second possible explanation is that differential solution of one of the numerous Paleozoic or Mesozoic salt beds that underlie the project area produced the structure. Extensive salt subsidence has been demonstrated just east of the project area in eastern Dunn County (John Ferguson, NDGS, personal communication). We believe that this structure probably is related to salt-subsidence, but it is outside the scope of this report to establish the exact mode of formation and the time of the subsidence.

2.2.3 Small-Scale Structure

Examination of the structure map of the Dunn Center bed (fig. 2.2.3-1) reveals numerous structural high and low areas that are not accounted for by the regional or intermediate structures outlined above. We believe that these represent one or more of the following processes.

1. Some of the minor structure may result from small-scale salt-subsidence such as is discussed above on a larger scale.

2. Near major valleys such as the Little Missouri and Knife River valleys and along the narrow, steep-sided glacial meltwater trenches, landsliding may result

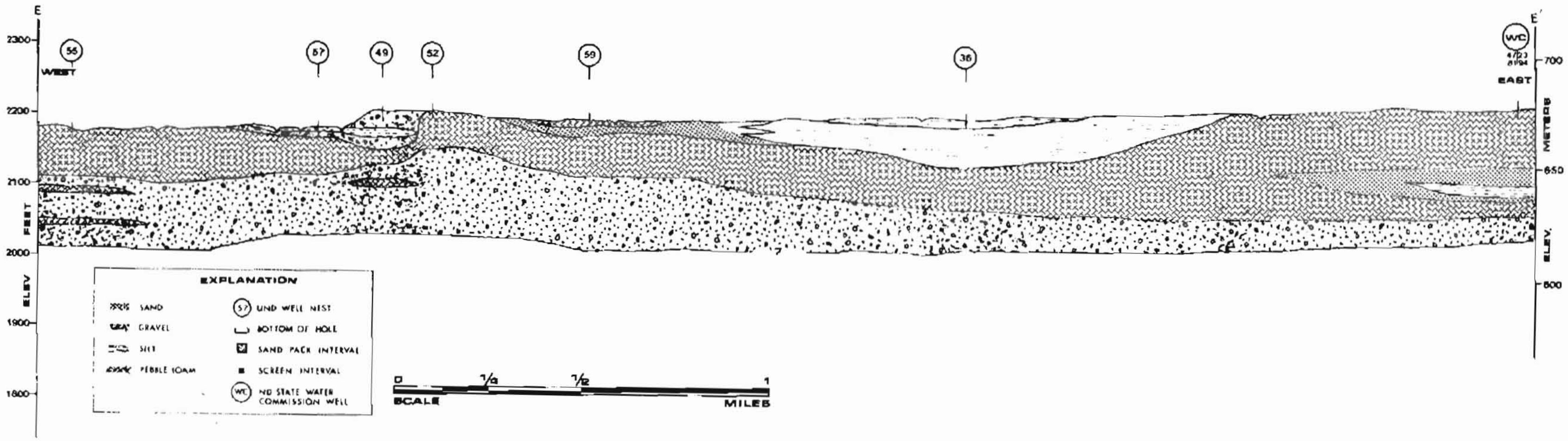

Figure 2.1.10-1 Stratigraphic cross section E-E' along the axis of a partly buried glacial meltwater channel extending from sec 2, T144N, R94W to sec 16, T144N, R93W. See figure 2.1.10-2 for location of the cross section.

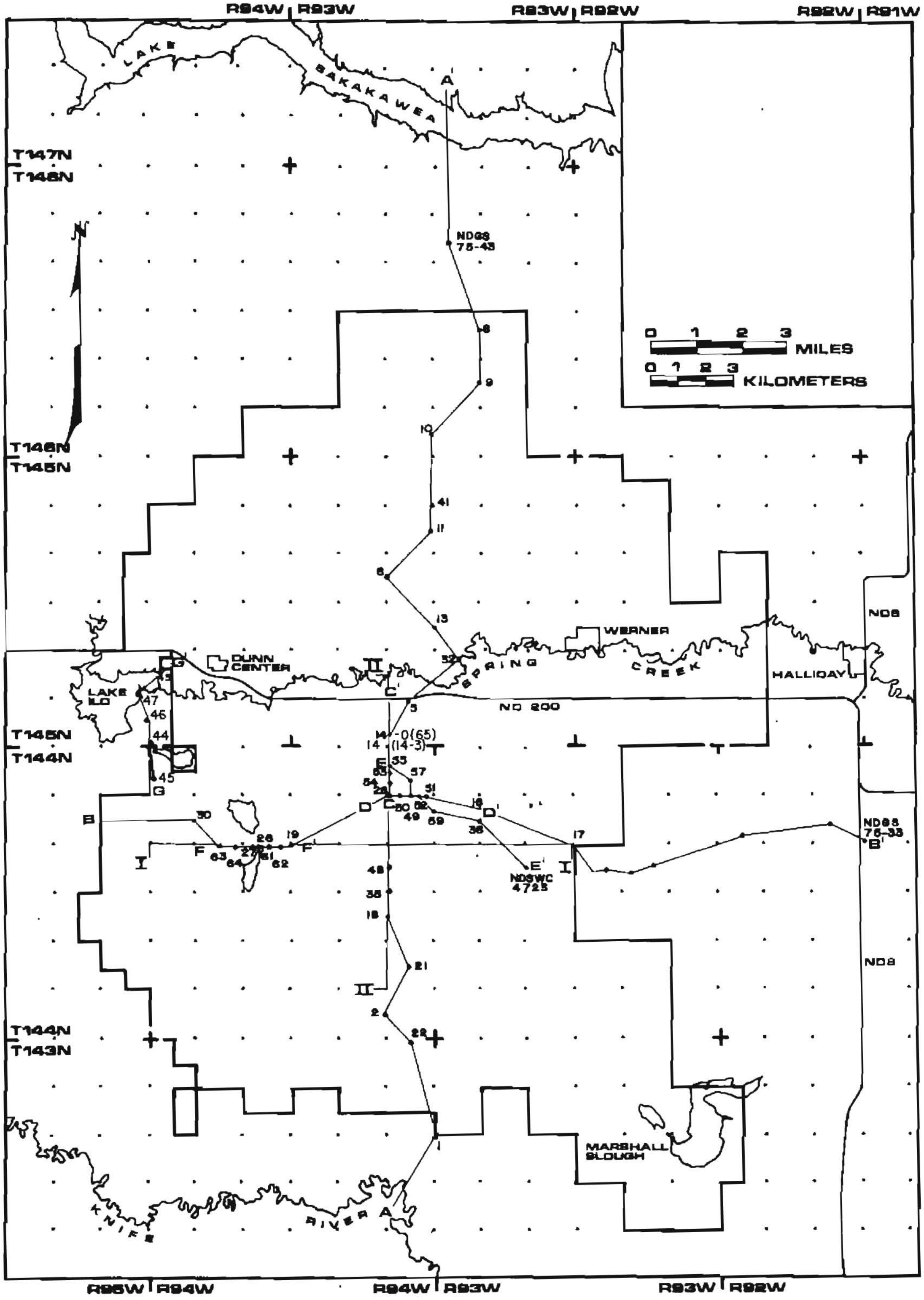

Figure 2.1.10-2 Map showing location of stratigraphic and hydrologic cross sections in the Dunn Center area.

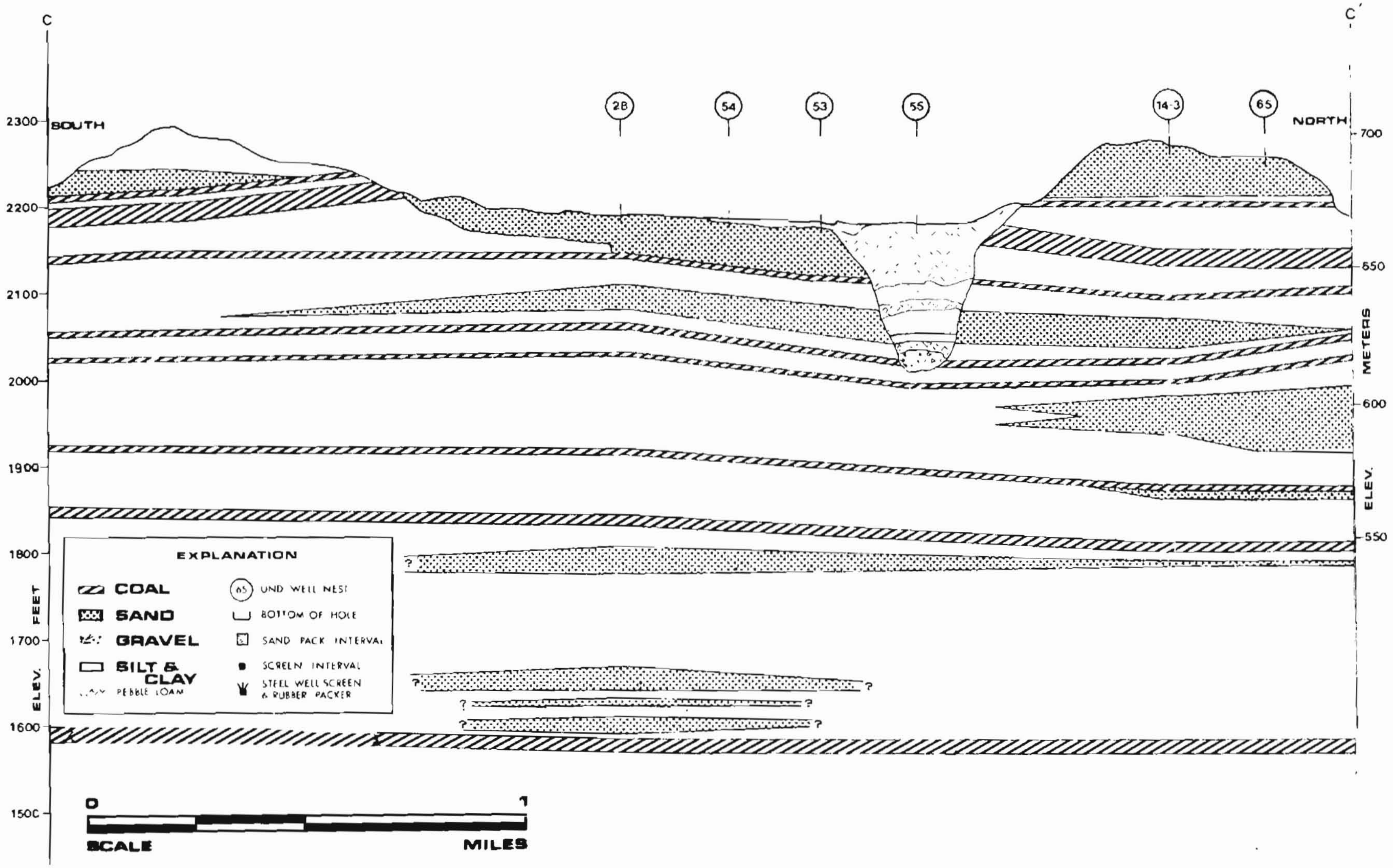

Figure 2.1.10-3 North-south cross section in the proposed plant site area C-C' showing stratigraphy of the valley fill. See figure 2.1.10-2 for location of the cross section.

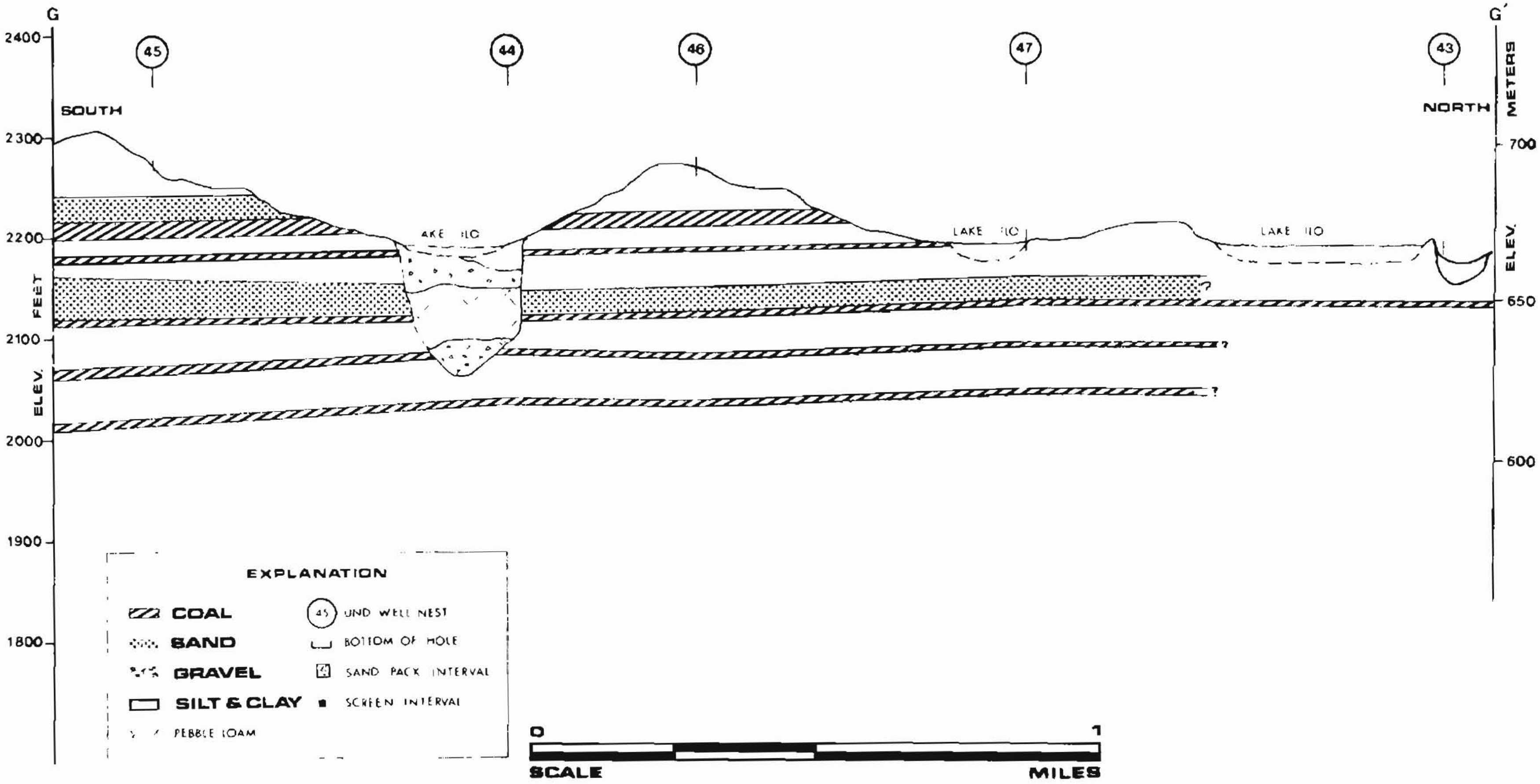

Figure 2.1.10-4 North-south cross section G-G' showing stratigraphy of valley fill at the southeast edge of Lake Ilo. See figure 2.1.10-2 for location of cross section.

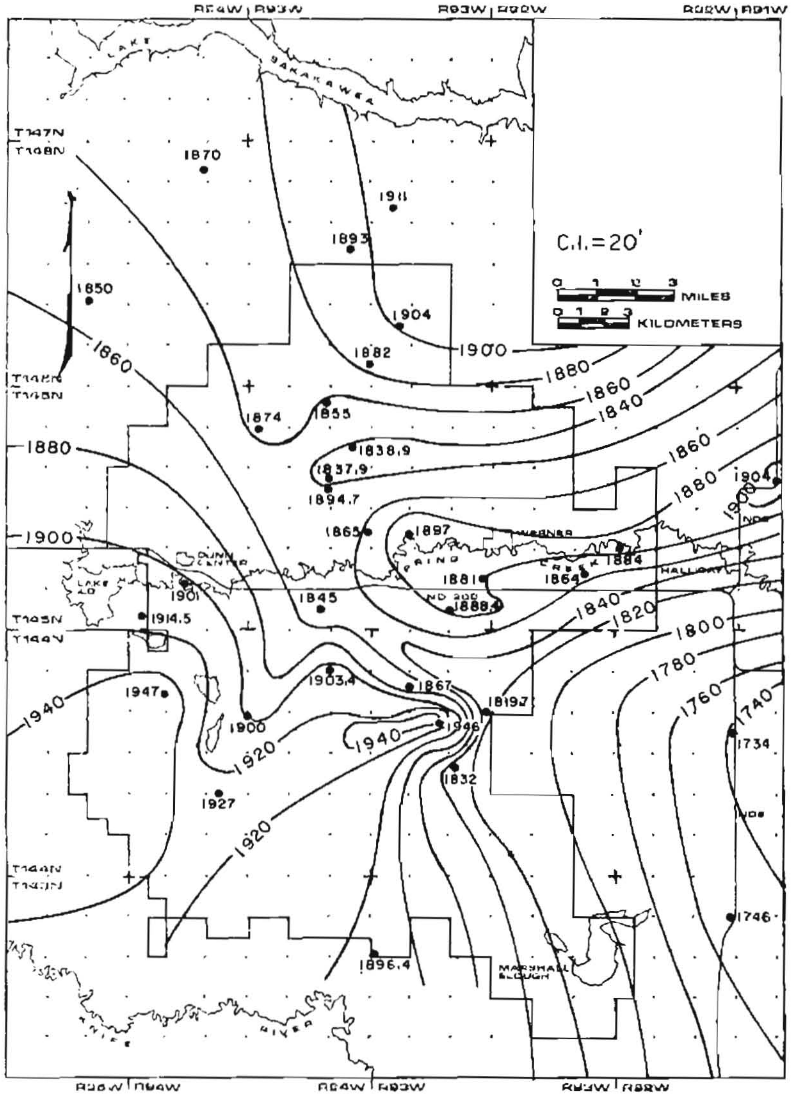

Figure 2.2.1-1 Map of the elevation of the top of the Bullion Creek Formation in the Dunn Center area.

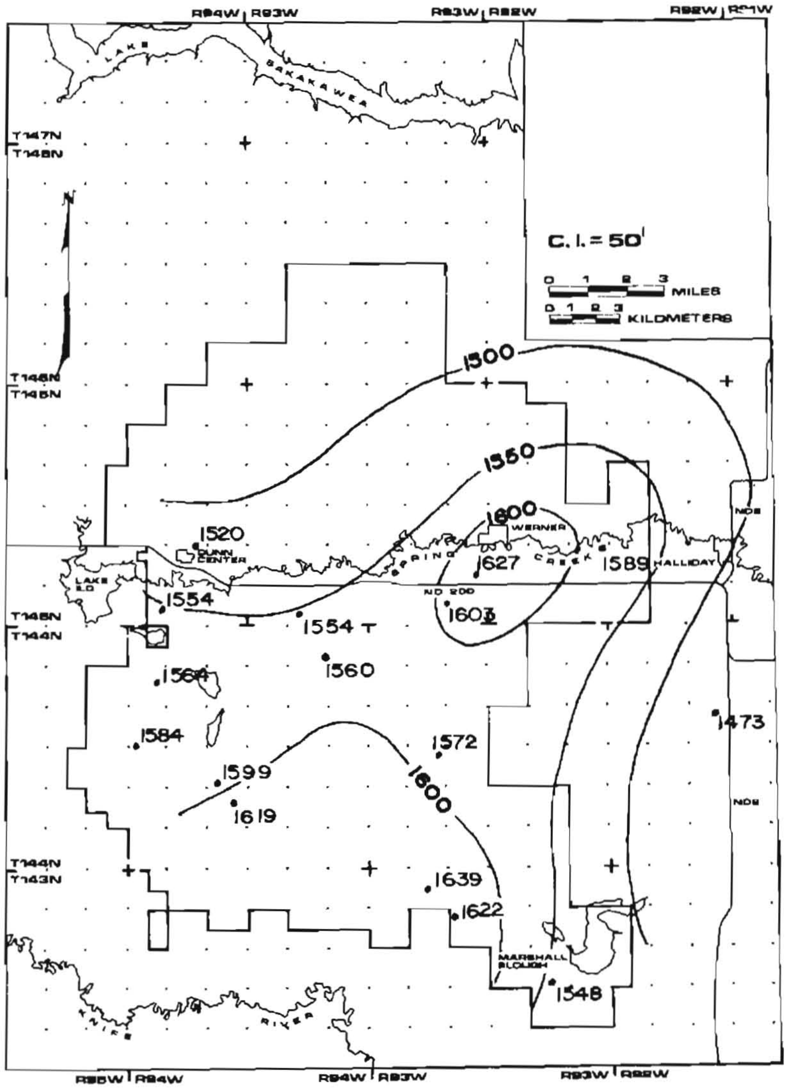

Figure 2.2.2-1 Map of the elevation of the top of the M-lignite in the Dunn Center area.

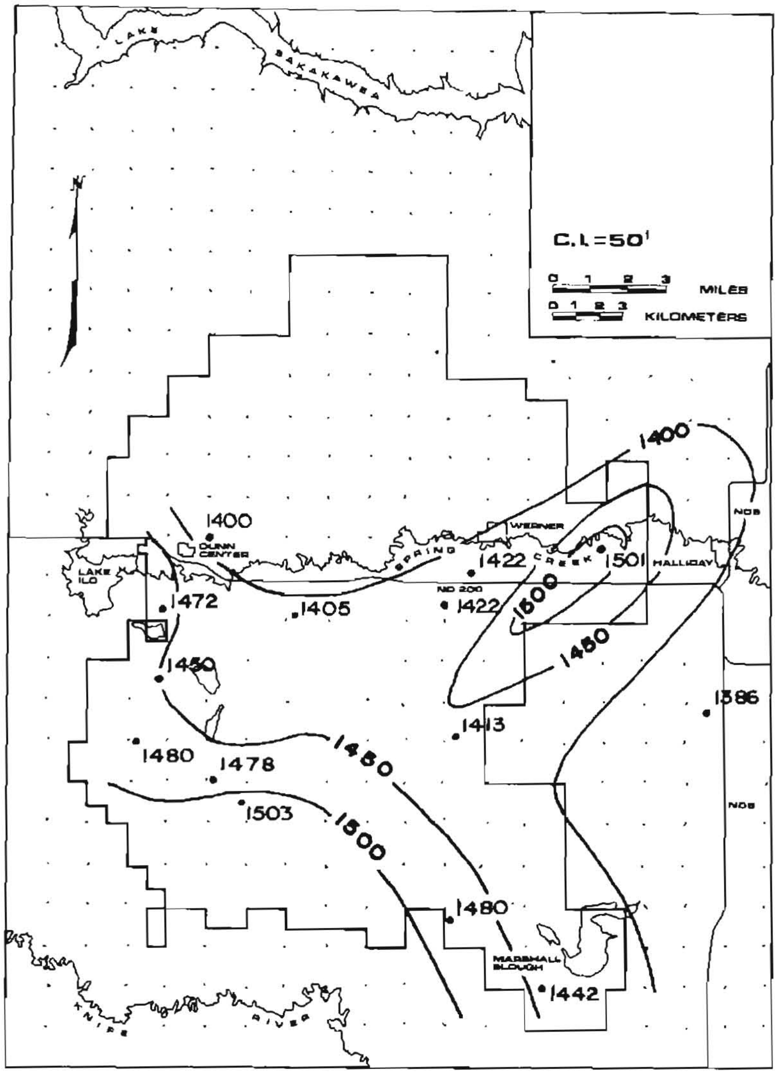

Figure 2.2.2-2 Map of the elevation of the top of the N-lignite in the Dunn Center area.

in an irregular lowering of beds.

3. Original irregularities on the land surface on which the lignite bed was deposited can result in several feet and possibly more of apparent structure. Natural levees on modern flood plains rise several tens of feet above the floors of adjacent flood-basin lakes.

4. Some structure may result from differential subsidence resulting from consolidation of different types of sediment. A thick section of sand may be thinned 10 to 20 percent during consolidation while a section of clay may be thinned as much as 40 to 50 percent.

2.3 Detailed Stratigraphy of the Project Area

2.3.1 Sentinel Butte Formation—Subsurface

Preliminary study of the initial test drilling for this project indicated that the Sentinel Butte Formation was characterized by a series of major lignite beds that could be traced over the entire project area (pls. 1, 2, 3, and 4). It also became increasingly apparent that even lignite beds that are one foot or less thick are traceable over areas of as much as several hundred square miles. The other

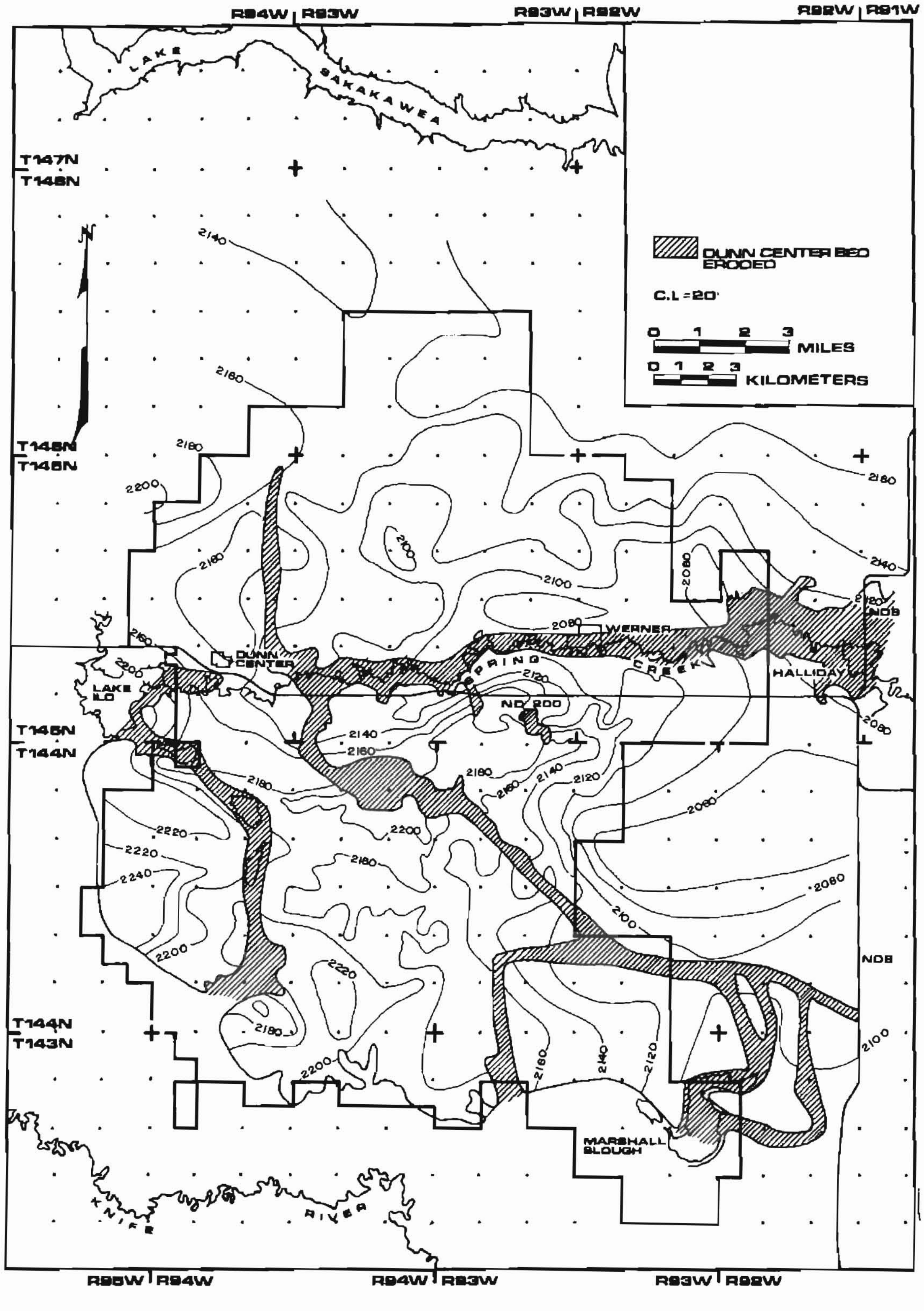

Figure 2.2.3-1 Map of the elevation of the top of the Dunn Center bed in the Dunn Center area.

lithologic types can rarely be traced more than a few miles. Between the laterally continuous lignite beds, abrupt and frequent facies changes are the rule. Accordingly, the Sentinel Butte Formation has been subdivided using a series of key beds, mostly lignites. The major lignites have been given letter designations to serve as informal names for purposes of this project. Too little is known of these units outside the project area to warrant formal treatment.

The sediment between the key beds is named by the lignite lying at the base of the interval, for example, the J-interval. Where a specific bed or lithology is an interval to be named, it is given a name such as I-sand or I-interval sand.

In the project area, the Sentinel Butte Formation is subdivided into ten intervals by named lignite beds. Above the Dunn Center bed the naming convention has followed the practice already established for the project area by the Paul Weir Co. The three main lignites in the overburden are named from the surface down, the C-lignite, B-lignite, and A-lignite. From the Dunn Center bed down, normal alphabetical order was used for the E- through J-lignites.

Each of the intervals above the Dunn Center bed has been subdivided into lithologic units in Mine Area No. 1 (fig. 2.3.1-1 and -2). These units have been extended throughout the project area where feasible. The lignite bed at the base of the interval is named by a number that is an even multiple of 100; the Dunn Center bed is 100; the A-bed is 200; the B-bed is 300; and the C-bed is 400. The units above the basal lignite bed are named in ascending stratigraphic order using a three-digit number related to the basal lignite. For example, unit 110 is clay and silty clay overlying the Dunn Center bed; unit 230 is silt that overlies sand that overlies silt and clay resting on the A-bed.

2.3.1.1 C-Lignite Interval

The C-lignite interval is the highest unit recognized in the Sentinel Butte Formation. It extends from the base of the Golden Valley Formation to the base of the C-lignite (fig. 2.3.1.1-1). The total thickness of the C-interval is not known because the Golden Valley Formation has been removed by erosion over most of the unit. As much as 75 feet of the C-interval is preserved just south of Horse Nose Butte, but the total thickness is probably about 80 to 90 feet.

The C-interval is dominantly silt, but clay and sand are also abundant. The various lithologies making up the C-interval occur in alternating beds from a few feet to about 10 feet thick. Because of the frequent changes in lithology, the thinness of the beds and the small area underlain by the C-interval, we have not attempted to subdivide the C-interval. The C-lignite is as much as 6 feet thick in some places (fig. 2.3.1.1-2).

2.3.1.2 B-Lignite Interval

The B-lignite interval extends from the base of the C-lignite to the base of the B-lignite (fig. 2.3.1.1-1). The B-lignite at the base of the B-interval is overlain by a discontinuous basal unit of sand and silty sand (unit 310) that is overlain by a widespread continuous unit of silt (unit 320) (figs. 2.3.1.2-1 and 2.3.1.2-2). In most places, the C-lignite rests on this silt, but, in some places, a second unit of sand (unit 330) overlies the silt. The B-interval varies in thickness from less than 20 to more than 80 feet (fig. 2.3.1.2-1). Along the cross sections of figures 2.3.1-1 and -2, the B-interval has a mean thickness of 31 feet, of which 9.4 feet is the B-lignite. The B-lignite is generally 10 feet or less thick, but in the eastern part of Mine Area No. 1, where it is split by a bed of silt, it is greater than 20 feet thick (fig. 2.3.1.2-2).

2.3.1.3 A-Lignite Interval

The A-lignite interval extends from the base of the B-lignite to the base of the A-lignite (fig. 2.3.1.1-1). It forms the surface material over much of the project area. In Mine Area No. 1, the A-interval has been subdivided into seven lithologic units. The lowest unit (unit 210) which everywhere rests on the A-lignite, is silt. A discontinuous unit of sand and silty sand (unit 220) overlies the silt and the A-lignite. In some places this sand is as much as 60 feet thick. A unit of silt (unit

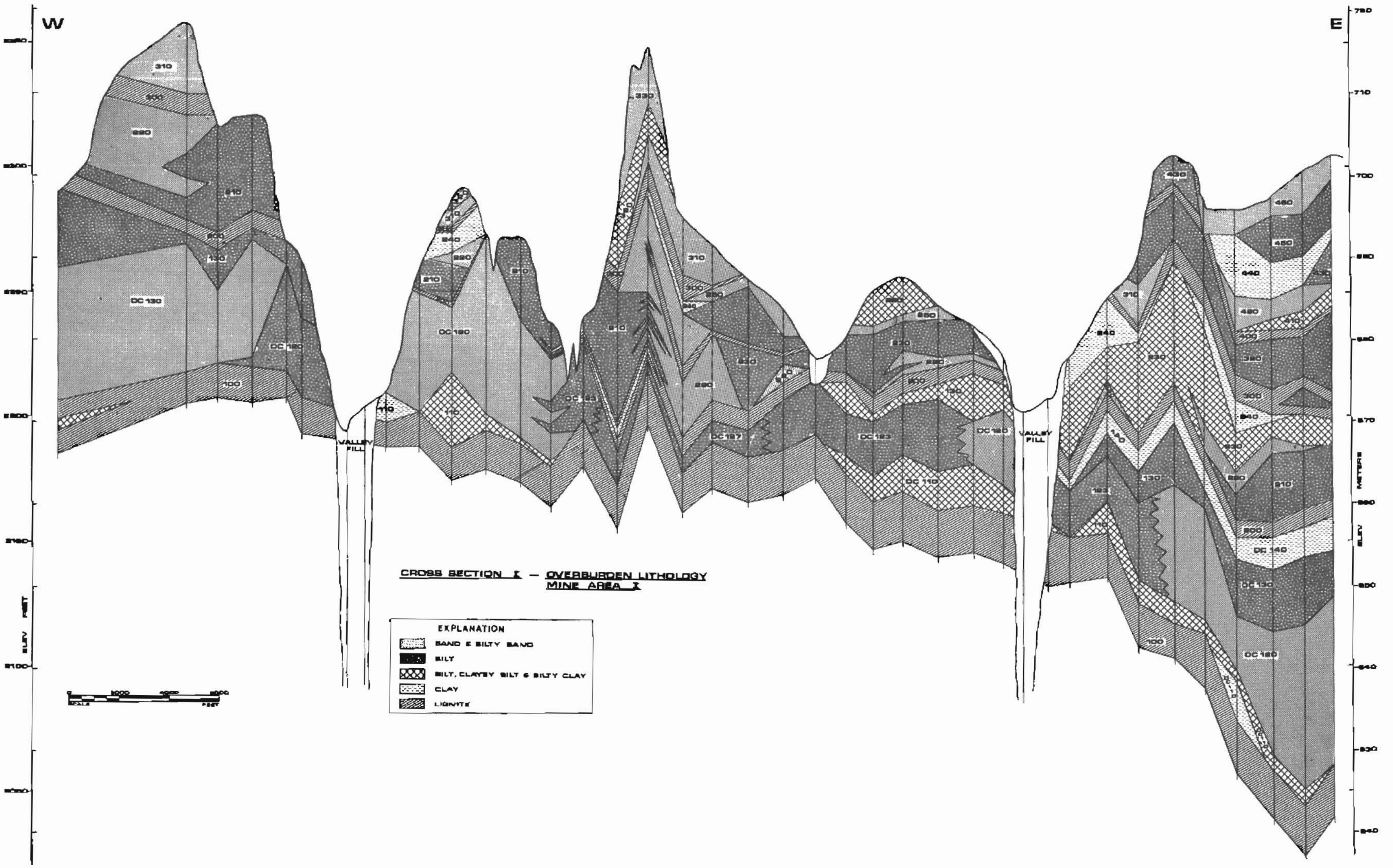

Figure 2.3.1-1 East-west stratigraphic cross section of the Sentinel Butte Formation above the Dunn Center bed in proposed mine area No. 1. See figure 2.1.10-2 for location of the cross section.

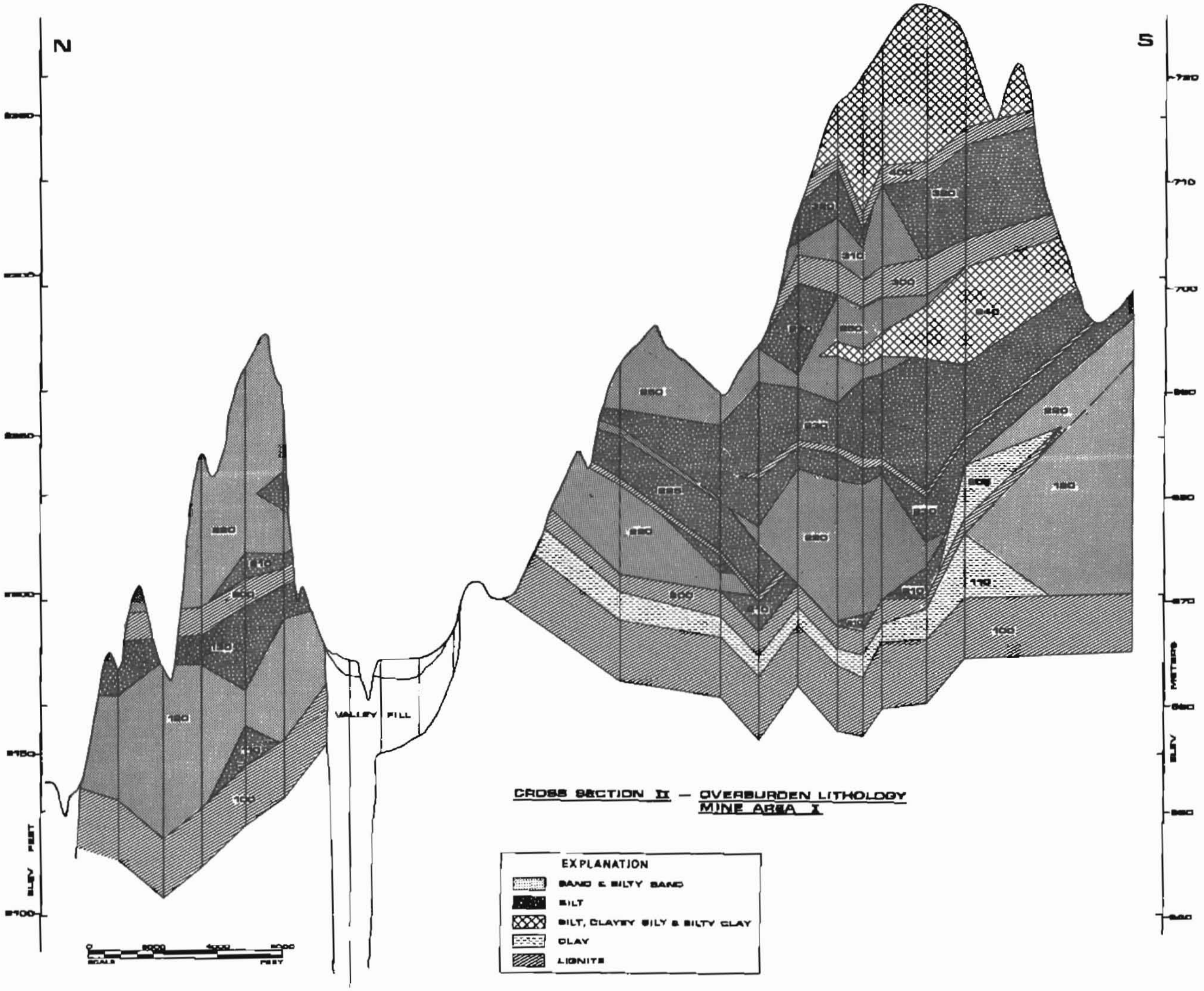

Figure 2.3.1-2 North-south stratigraphic cross section of the Sentinel Butte Formation above the Dunn Center bed in proposed mine area No. 1. See figure 2.1.10-2 for location of the cross section.

COMPANY: UND ENGINEERING EXPERIMENT STATION

BORE HOLE: 75-17-2

LOCATION: SE ¼ SE ¼ SE ¼ SEC 9, T144N, R93W

ELEVATION: G.L. 2286.3 FEET

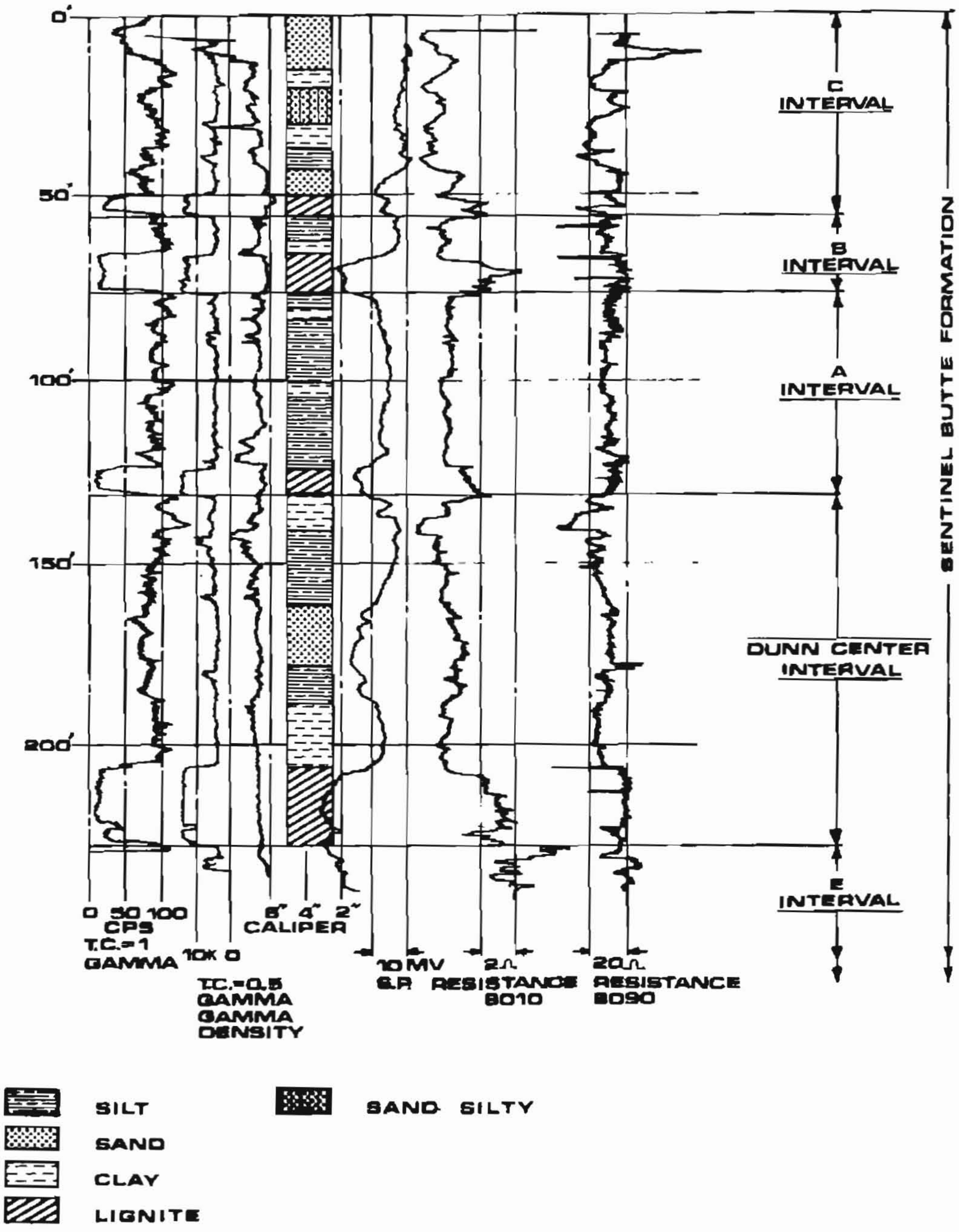

Figure 2.3.1.1-1 Geophysical log of the upper part of the Sentinel Butte Formation.

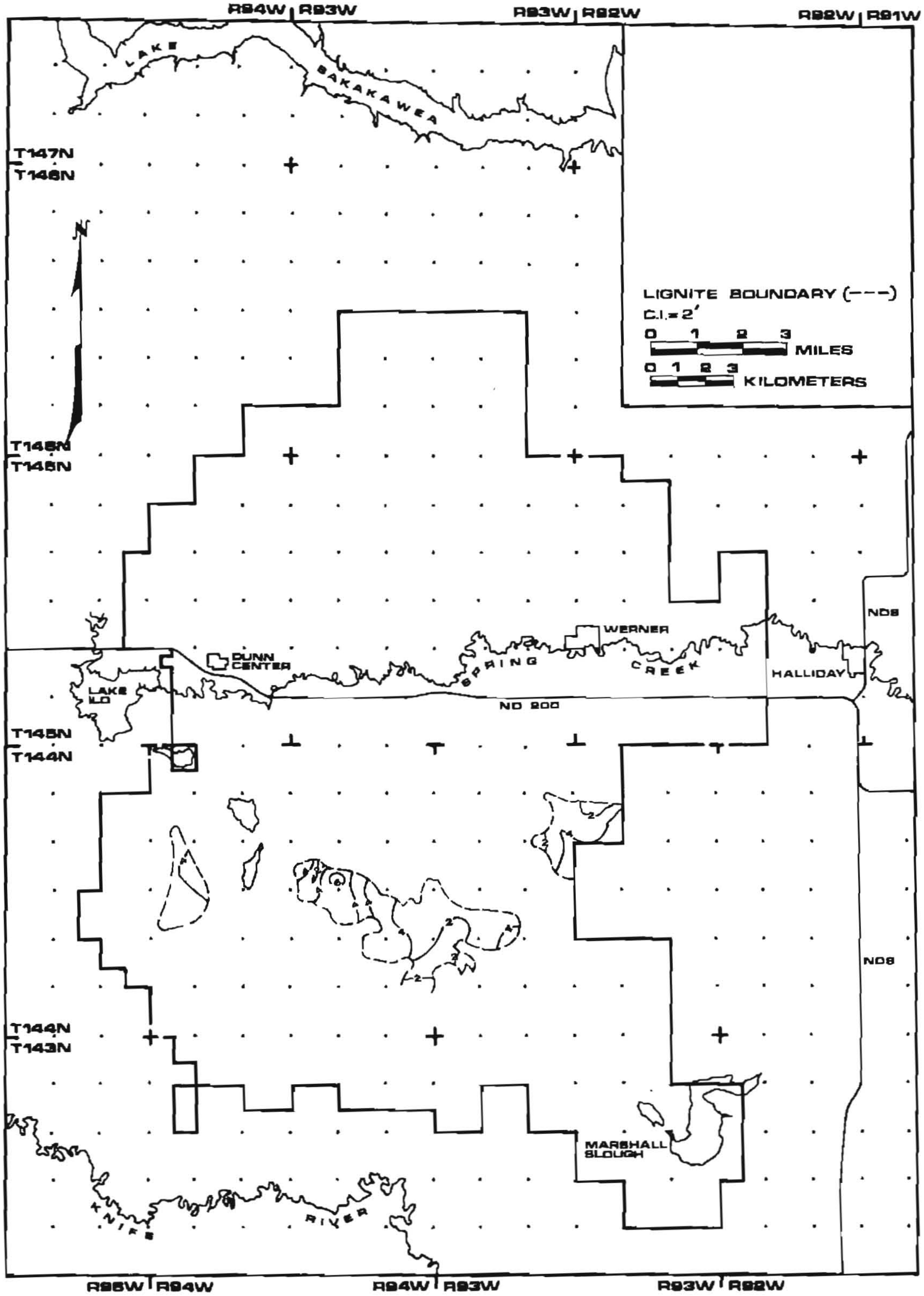

Figure 2.3.1.1-2 Map of the thickness of the C-lignite in proposed mine area No. 1.

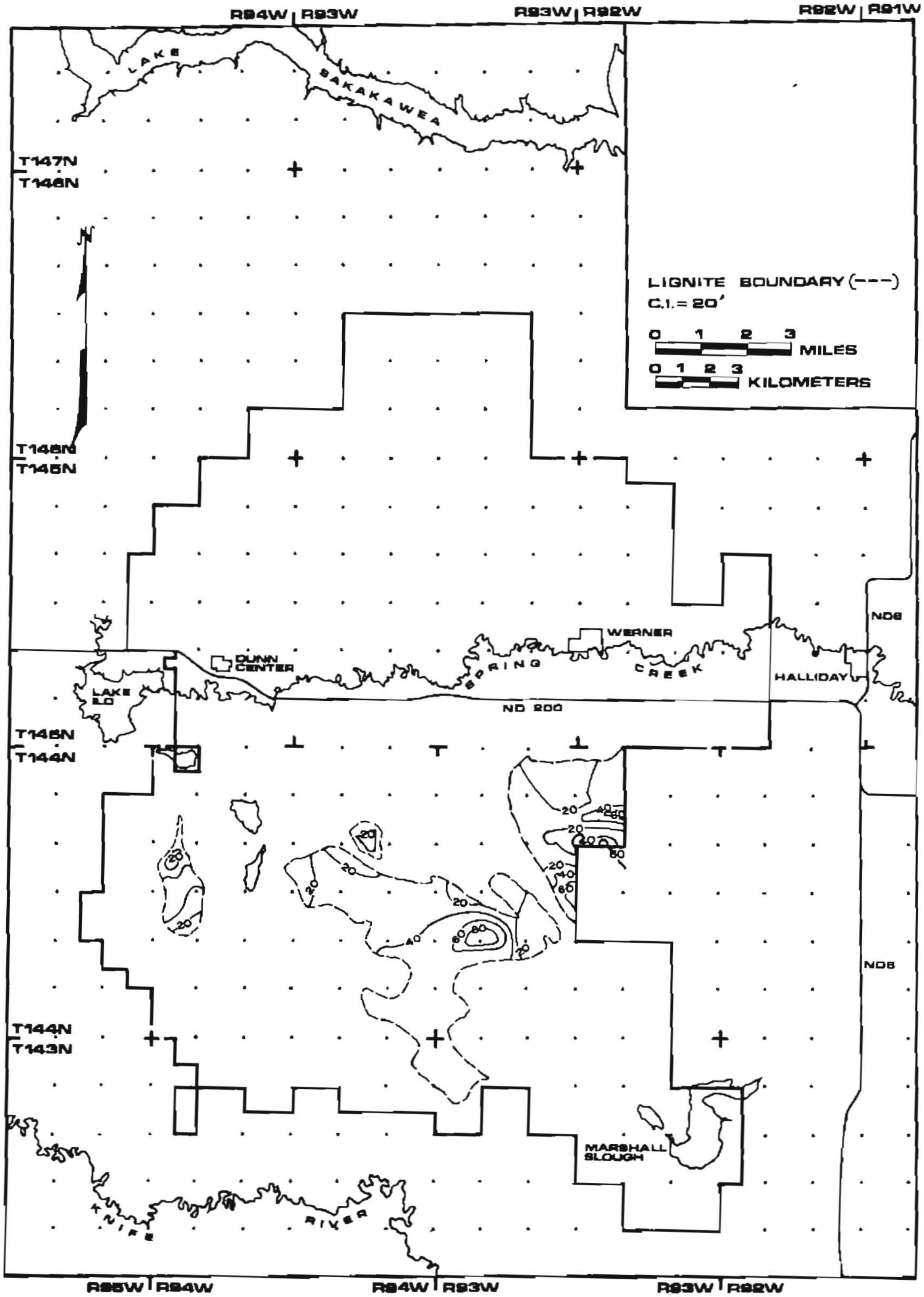

Figure 2.3.1.2-1 Map of the thickness of the B-Interval in the Dunn Center area.

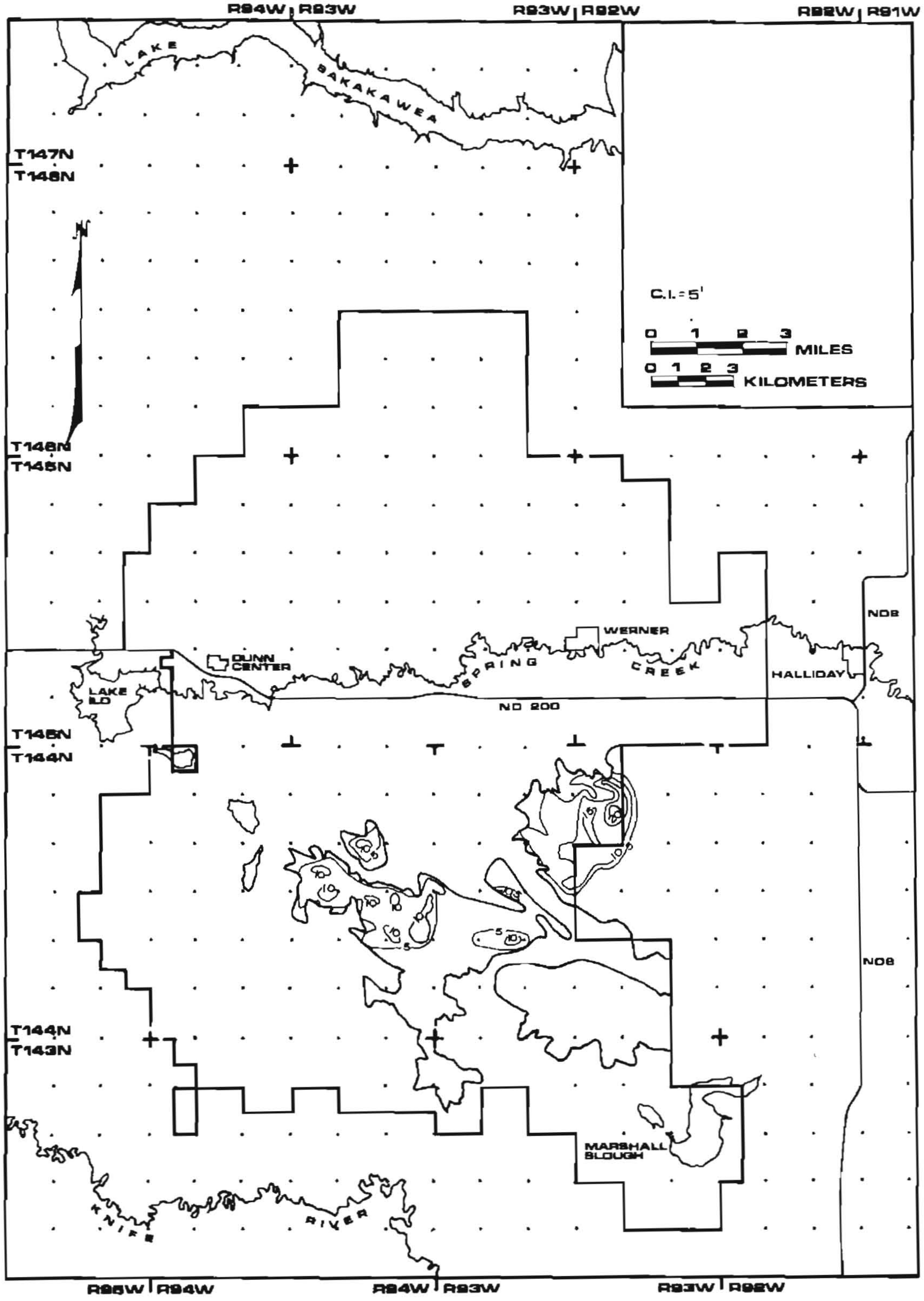

Figure 2.3.1.2-2 Map of the thickness of the B-lignite in the Dunn Center area.

225) that, in some places, contains a minor lignite bed a few feet thick grades laterally into the sand. The sand is overlain by a nearly continuous bed of silt, which contains a minor lignite bed (unit 230). A discontinuous unit of clay (unit 240), which has a very limited distribution, overlies unit 230. It is overlain by a thin sand unit (unit 250) which is overlain by silt of unit 260. At various places the B-lignite rests on units 220, 230, 240, 250, and 260 (figs. 2.3.1-1, 2.3.1-2).

In Mine Area No. 1, the A-interval varies in thickness from about 40 to about 110 feet (fig. 2.3.1.3-1). The mean thickness is about 70 feet. The A-lignite varies in thickness from 4 feet to 10 feet, with a mean thickness of 7.1 feet in Mine Area No. 1 (fig. 2.3.1.3-2). North of Spring Creek it is thicker. In some places, the A-lignite grades laterally into unit 130 and is replaced by sand (figs. 2.3.1-1, 2.3.1-2).

2.3.1.4 Dunn Center Interval

The Dunn Center interval extends from the base of the A-lignite to the base of the Dunn Center bed (fig. 2.3.1-1). The uneroded thickness of the Dunn Center interval is extremely variable, ranging from about 5 feet to about 140 feet (fig. 2.3.1.4-1).

The Dunn Center bed is nearly everywhere overlain by unit 110, a layer of clay, silty clay, and clayey silt that ranges in thickness from about 5 feet to about 20 feet. A discontinuous but extensive sand and silty sandy body, unit 120, overlies the Dunn Center bed or unit 110. In places, it is as much as 70 feet thick. Unit 120 grades laterally into silt of unit 123, which in turn grades into silt, silty clay, and clayey silt of unit 127. Unit 130 overlies units 120, 123, and 127 in most places. It consists of silt, or silt, silty clay, and clayey silt (figs. 2.3.1-1, 2.3.1-2).

The Dunn Center bed varies in thickness from less than 10 to more than 20 feet (fig. 2.3.1.4-2). In the western part of the Dunn Center area, a wedge of silt splits the Dunn Center bed into two beds 8 to 10 feet thick. This parting, which in places is as much as 30 feet thick, accounts for the great thickness of the Dunn Center bed in the western part of the project area (fig. 2.3.1.4-2). The structure of the Dunn Center bed is complex, but generally the bed dips eastward (fig. 2.2.3.1).

2.3.1.5 E-Lignite Interval

The E-lignite interval extends from the base of the Dunn Center bed to the base of the E-lignite (fig. 2.3.1.5-1). The E-interval is dominantly silt, although clay is an important constituent in some areas. Sand is limited to thin beds in the extreme northern and southern parts of the project area and a thick body that trends roughly east-west, just south of the plant site (pls. 1, 2, and 3). A minor lignite occurs just below the Dunn Center bed near the top of the interval throughout most of the area. The thickness of the E-interval varies from 10 to 50 feet; it is generally about 25 to 30 feet thick (fig. 2.3.1.5-2). The E-lignite underlies the entire area; it is split in the northern part of the area. The E-lignite has a mean thickness of about 5 feet (fig. 2.3.1.5-3).

2.3.1.6 F-Lignite Interval and G-Lignite Interval

These two intervals are treated together because the G-lignite and F-lignite appear to be splits of the same bed. Only a single bed is present over most of the area, the F-lignite. In the northern and western parts of the area, a wedge of silt splits the bed and both the F-lignite and G-lignite are present (fig. 2.3.1.5-1). In those areas, the G-interval is present. In the rest of the area, there is no G-interval.

The F-lignite interval extends from the base of the E-lignite to the base of the F-lignite. It ranges in thickness from 60 to 95 feet and has a mean thickness of about 80 feet (fig. 2.3.1.6-1). The F-interval is generally silt. Sand makes up most of the interval in the northern 3 or 4 miles of the project area and is a significant constituent in the area of the plant site. Clay is a minor constituent of the interval. The F-interval includes an interval of 5 to 30 feet of white, highly calcareous silt, silty sand, clay, and limestone. This interval is readily recognizable in most of the project area by its white color and geophysical log characteristics (fig. 2.3.1.5-1); it served as a useful field marker bed during drilling

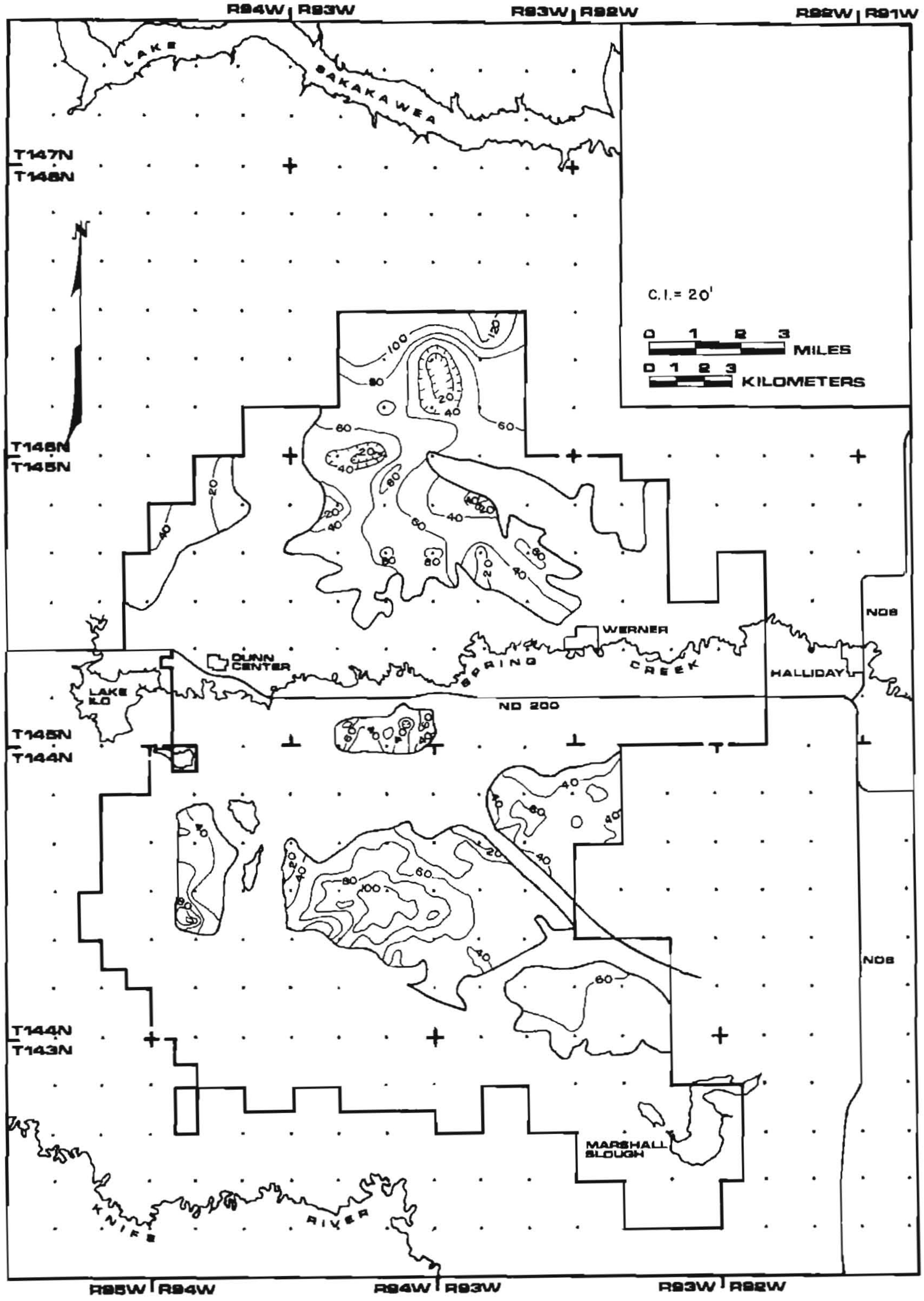

Figure 2.3.1.3-1 Map of the thickness of the A-interval in the Dunn Center area.

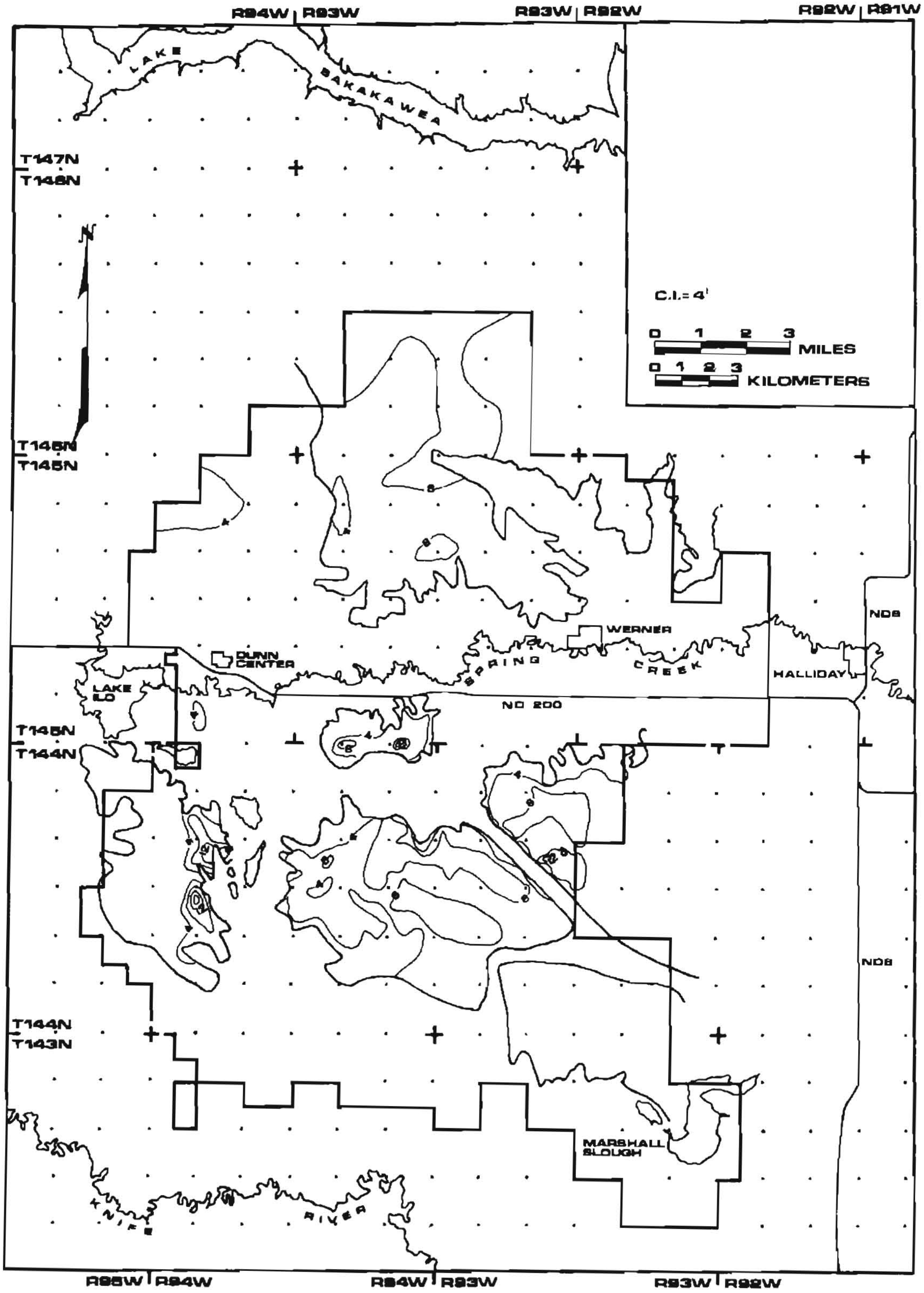

Figure 2.3.1.3-2 Map of the thickness of the A-lignite in the Dunn Center area.

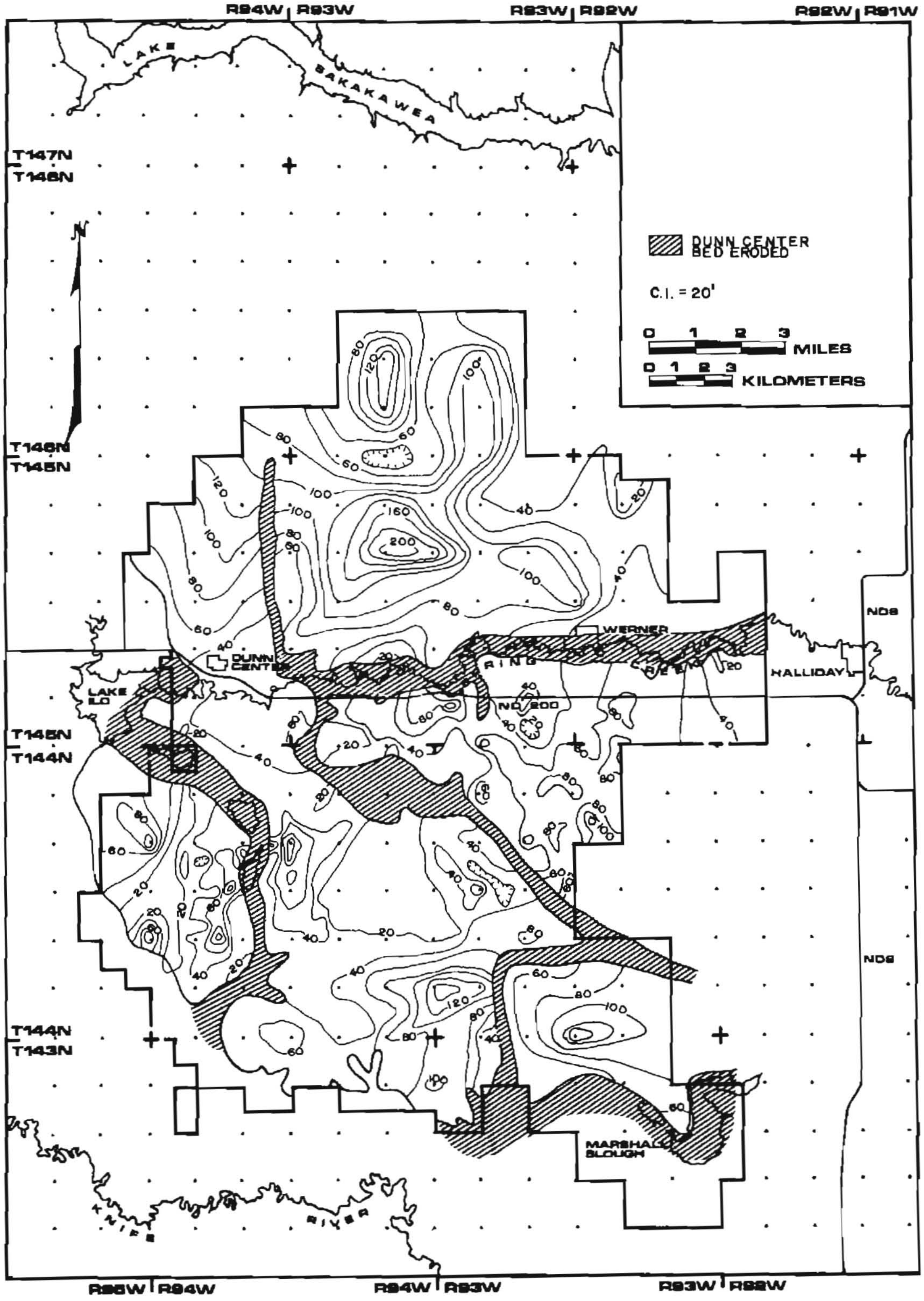

Figure 2.3.1.4-1 Map of the thickness of the Dunn Center interval in the Dunn Center area.

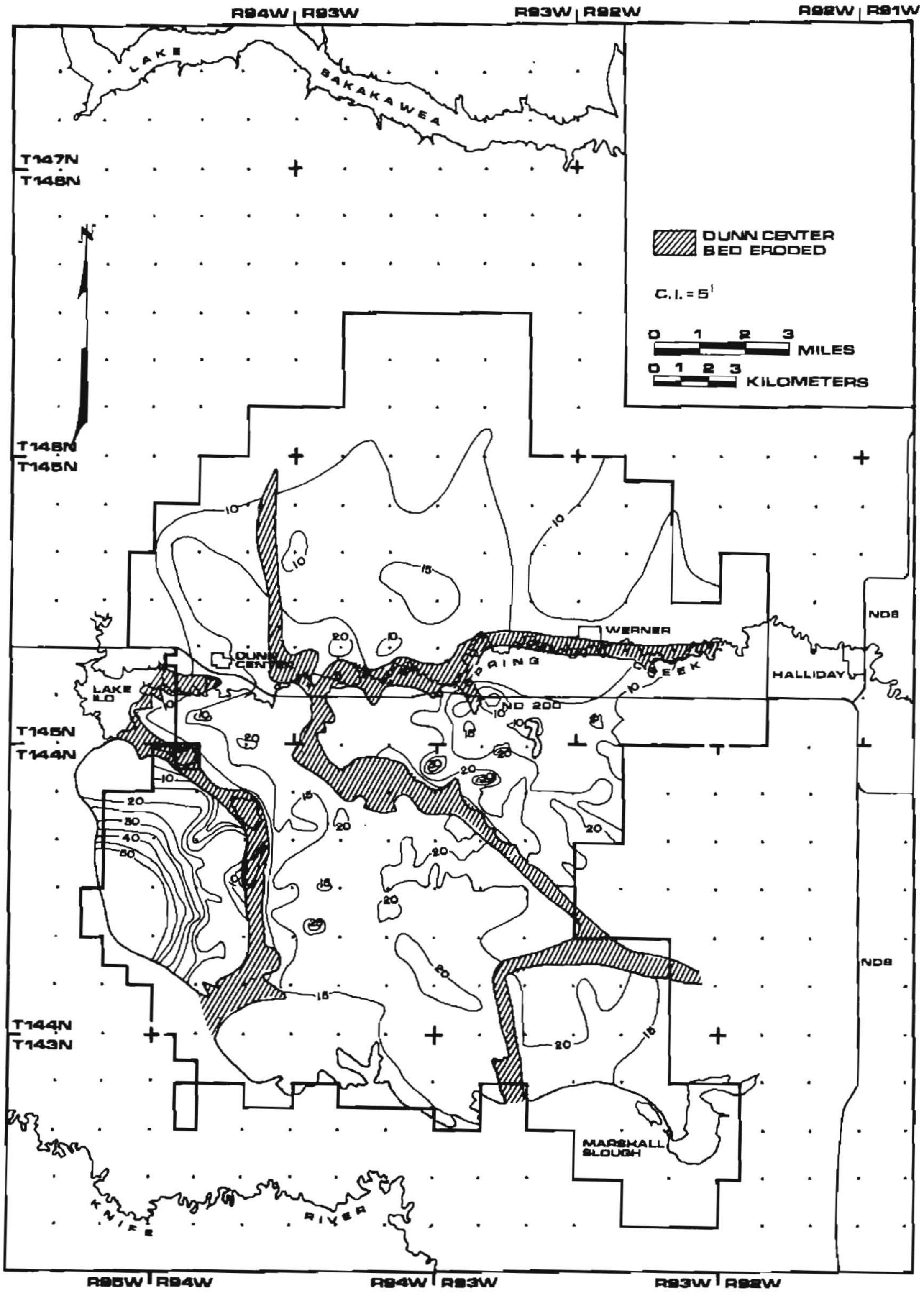

Figure 2.3.1.4-2 Map of the thickness of the Dunn Center bed in the Dunn Center area.

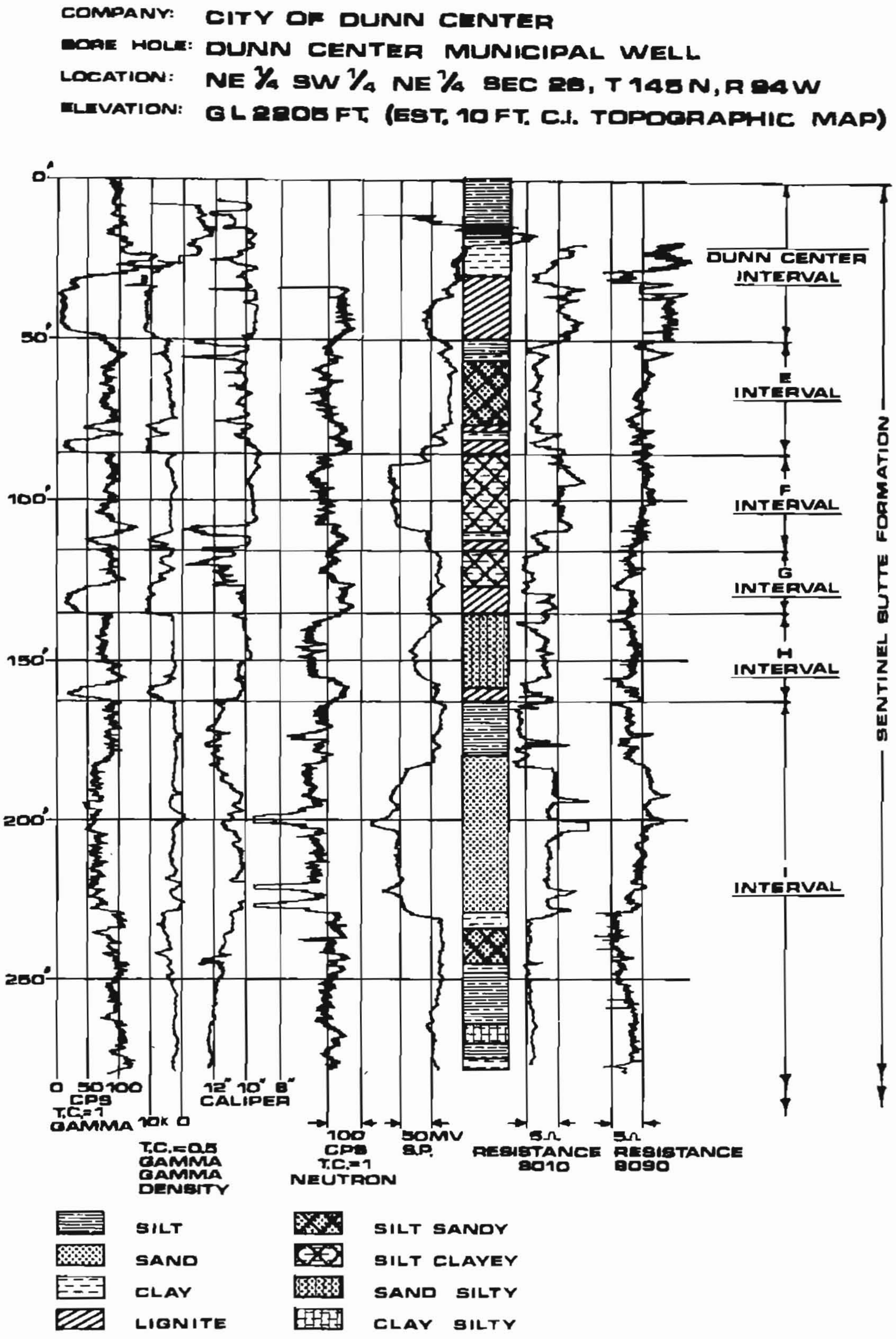

Figure 2.3.1.5-1 Geophysical log of the middle and lower part of the Sentinel Butte Formation.

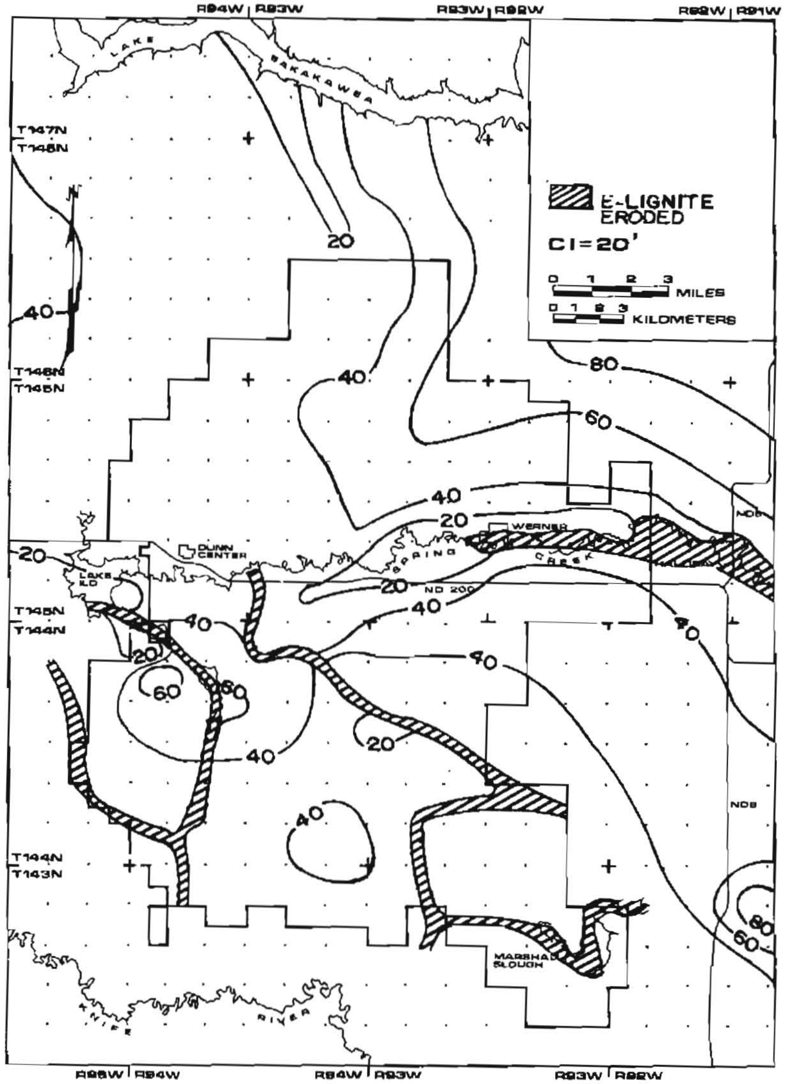

Figure 2.3.1.5-2 Map of the thickness of the E-interval in the Dunn Center area.

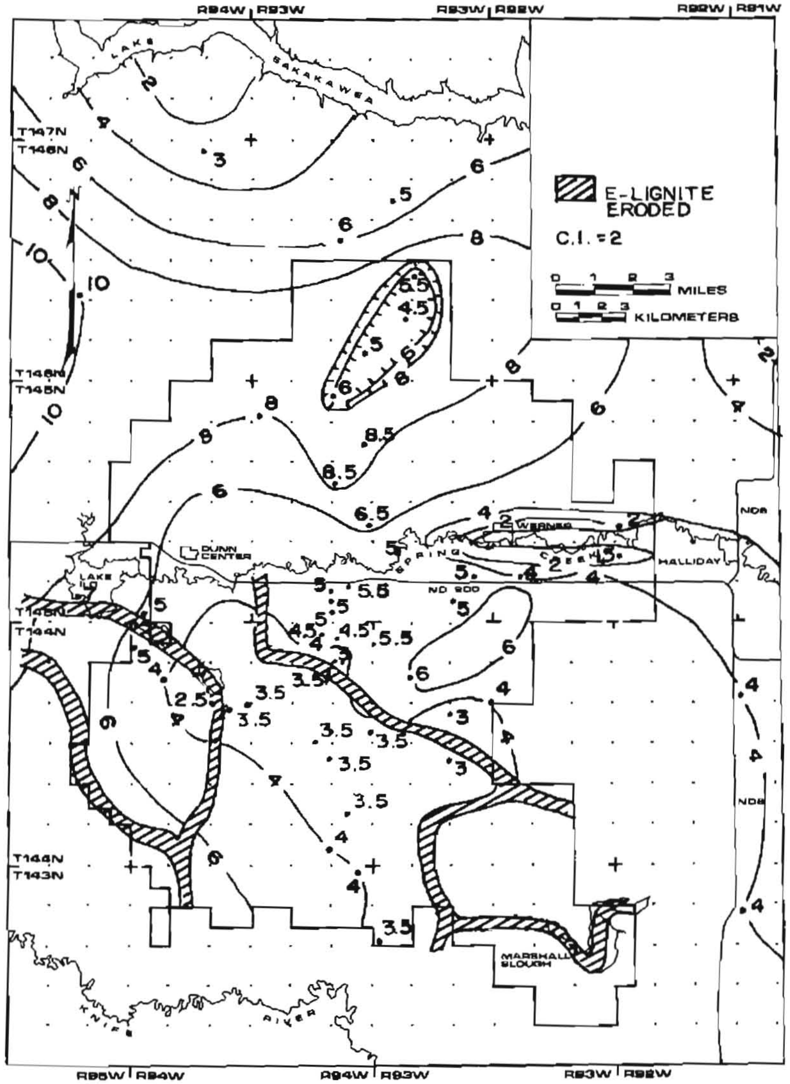

Figure 2.3.1.5-3 Map of the thickness of the E-lignite in the Dunn Center area.

operations. This unit, informally called "the white bed," is believed to correlate with the "lower yellow bed" of the outcrop section north of the project area (see sec. 2.3.2). A minor lignite occurs in the southern part of the project area in about the middle of the F-interval. This lignite seems to be laterally equivalent to a sandy body just south of the plant site (pls. 1 and 3).

The unsplit F-lignite ranges in thickness from 2 feet, in the southern part of the project area, to about 10 feet in the north (fig. 2.3.1.6-2). Where it is split, the F-lignite is 1 to 3 feet thick in the north and 3 to 5 feet in the west. The G-lignite is 1 to 10 feet thick (fig. 2.3.1.6-3).

2.3.1.7 H-Lignite Interval

The H-lignite interval is generally about 20 feet thick (fig. 2.3.1.5-1). It consists almost entirely of silt and clay. The H-lignite ranges in thickness from 3 to 9 feet; it has a mean thickness of about 4 feet (fig. 2.3.1.7-1). The relatively major, closely spaced F and H-lignites form a prominent geophysical log marker throughout the project area, informally called "the double coal" (pls. 1, 2, and 3).

2.3.1.8 I-Lignite Interval

The I-lignite interval is generally composed of silt, but clay is also an abundant constituent (fig. 2.3.1.5-1; pls. 1, 2, and 3). Sand occurs in two types of deposits. In the northern part of the area, several beds that range in thickness from about 10 feet to 20 feet are traceable for 2 to 3 miles (pl. 2). Two thick, narrow, linear bodies occur near the top of the interval in the southern part of the project area; one extends from Dunn Center to just north of the plant site and a second lies at the extreme southern end of the project area (fig. 2.3.1.5-1, pl. 1). The I-interval varies in thickness from 60 to 150 feet (fig. 2.3.1.8-1). The mean thickness is about 100 feet. Four or five minor lignite beds occur approximately evenly spaced in the interval throughout the project area. The I-lignite is thickest in the northern part of the project area, where it is 6 to 10 feet thick (fig. 2.3.1.8-2). In the southern part of the project area, it is as thin as 2 feet.

2.3.1.9 J-Lignite Interval

The J-lignite interval consists dominantly of silt (fig. 2.3.1.5-1, pls. 1, 2, and 3). It contains significant amounts of clay and minor sand. The sand is limited to beds about 10 feet thick except in the extreme southern part of the area and north of the project area where sand beds as thick as 50 feet make up the entire interval (pls. 1 and 2). The J-interval contains two widespread minor lignite beds. The thickness of the interval varies from 40 to 60 feet. It has a mean thickness of about 50 feet. The J-lignite, the arbitrarily defined basal unit of the Sentinel Butte Formation, has a mean thickness of 8 feet throughout the project area (fig. 2.3.1.9-1). It splits into two and possibly three minor beds at the northern edge of the project area.

2.3.2 Sentinel Butte Formation—Little Missouri Badlands Outcrop Area

During the summer of 1975, Stancel studied the stratigraphy of the Sentinel Butte Formation in badlands exposures along the Little Missouri River north of the project area. He mapped the entire section from the reservoir to the upland surface along about 20 miles of exposure on both sides of the valley (pl. 4).

The mapping was begun by sketching, from a distance, all of the readily visible characteristics of each outcrop. Observation points were located overlooking exposures on south-facing bluffs. The bluff was studied through binoculars and sketched on a plane-table sheet. A topographic map at a scale of 1:24 000 and contour interval of 20 feet was used to locate and estimate the height of the section. The cross sections that were drawn in the field and depicted on plate 4 are projections into two dimensions of exposures that, in some cases, extend as much as a mile in the third dimension. Only rarely do the cross sections represent one continuous exposure. After sketching the exposure, sections were measured in each outcrop and correlated with the sketch. In this way, a series of cross sections were constructed across the entire area (pl. 4).

Several units served as marker beds

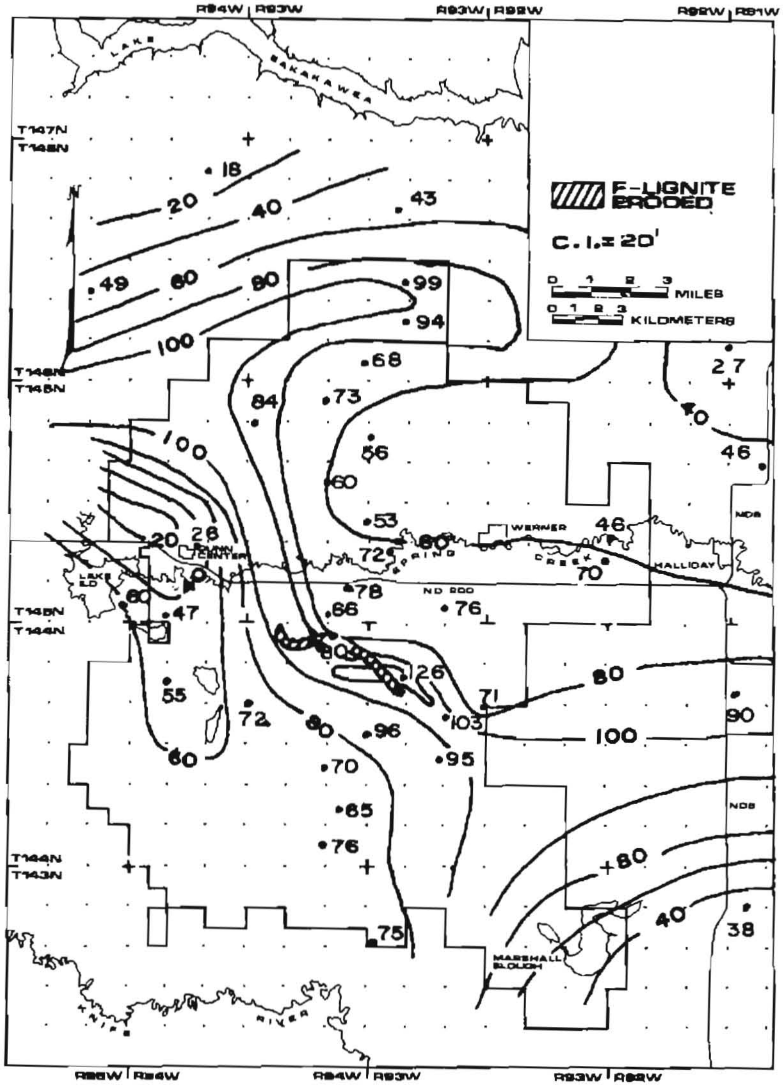

Figure 2.3.1.6-1 Map of the thickness of the F-interval in the Dunn Center area.

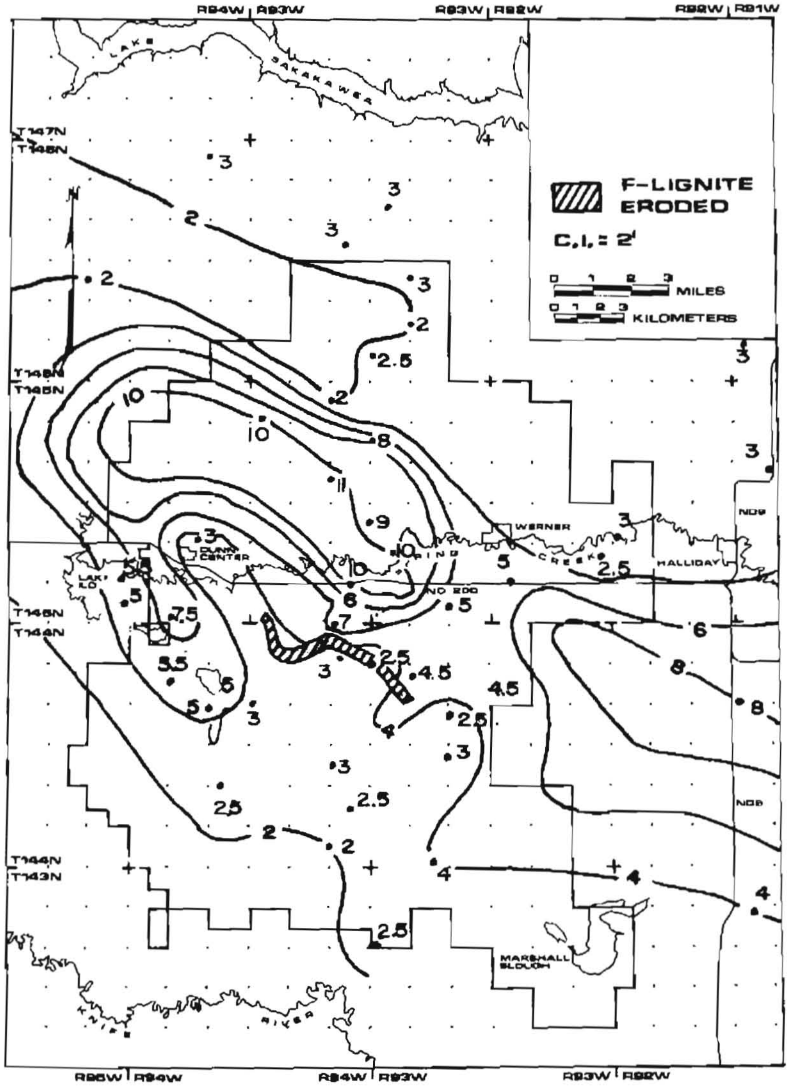

Figure 2.3.1.6-2 Map of the thickness of the F-lignite in the Dunn Center area.

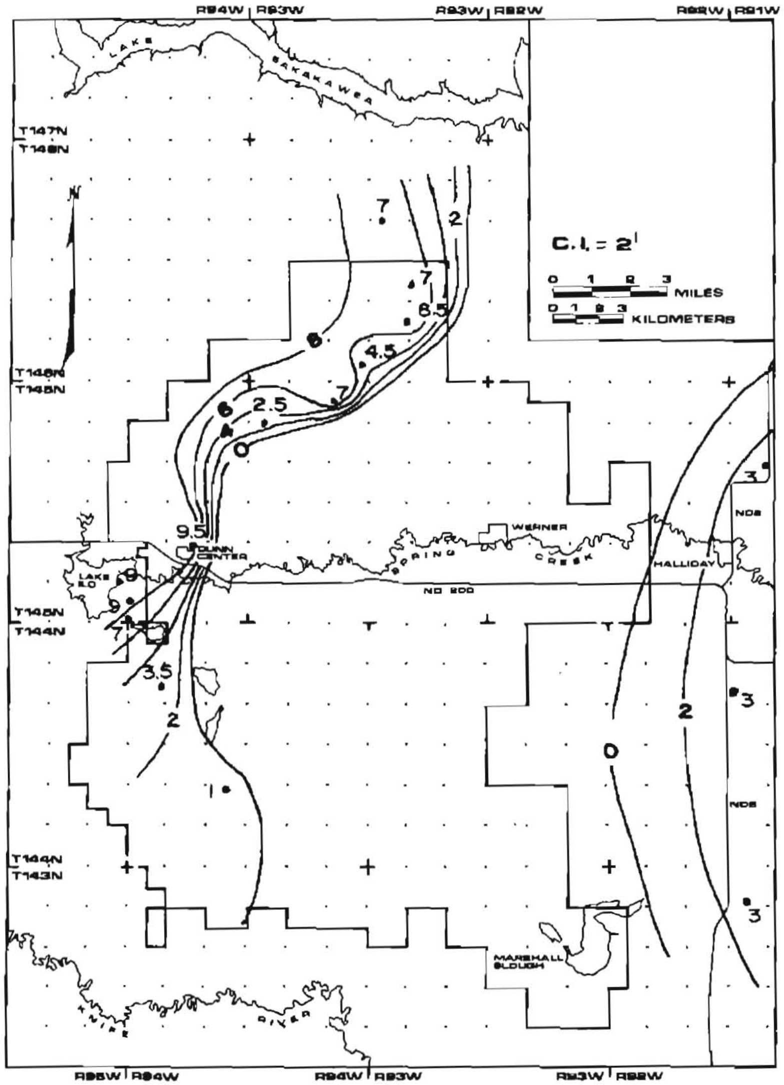

Figure 2.3.1.6-3 Map of the thickness of the G-lignite in the Dunn Center area.

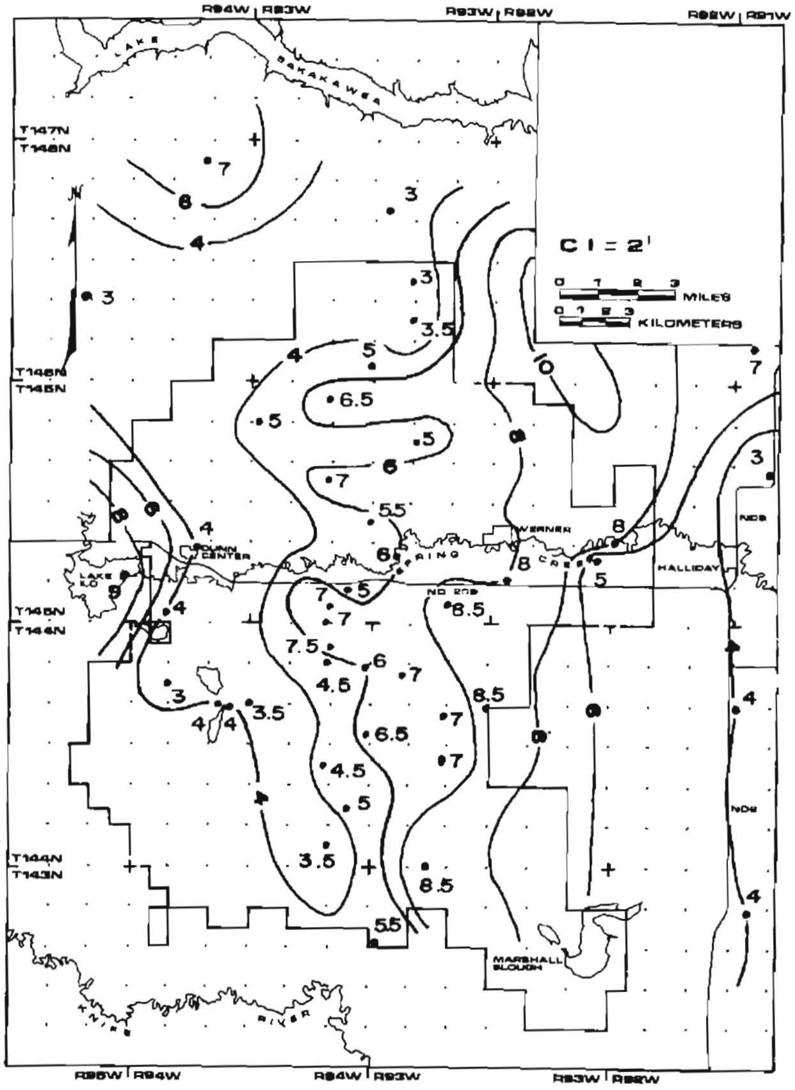

Figure 2.3.1.7-1 Map of the thickness of the H-lignite in the Dunn Center area.

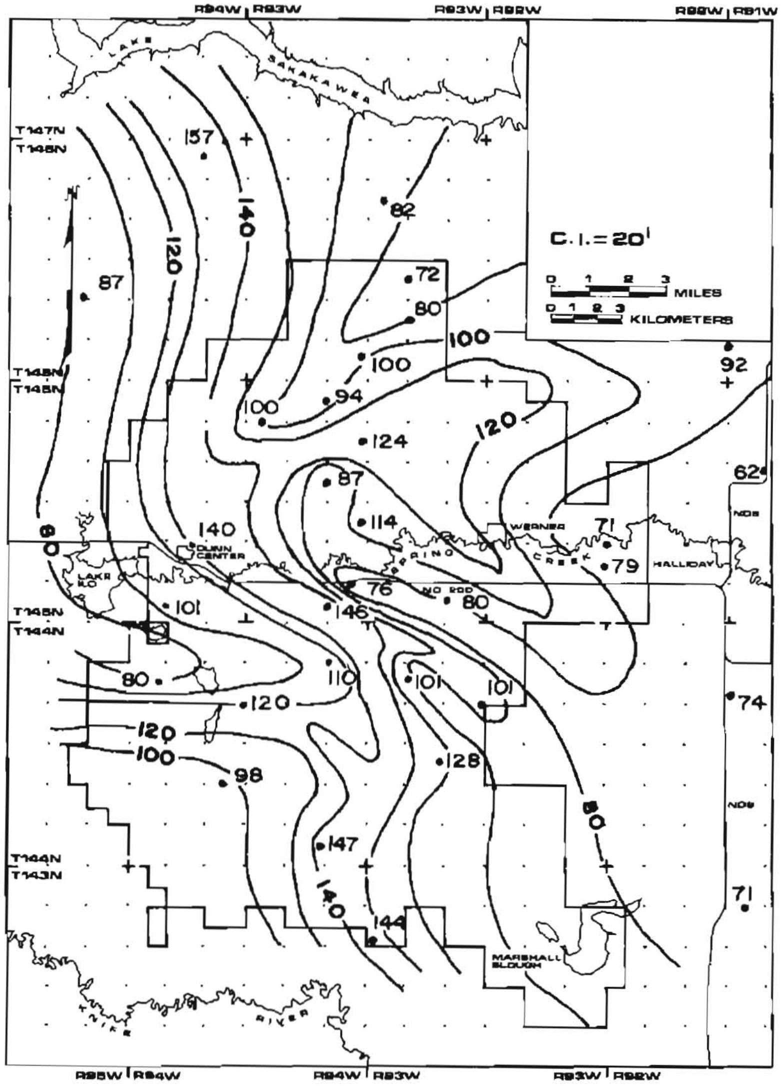

Figure 2.3.1.8-1 Map of the thickness of the I-interval in the Dunn Center area.

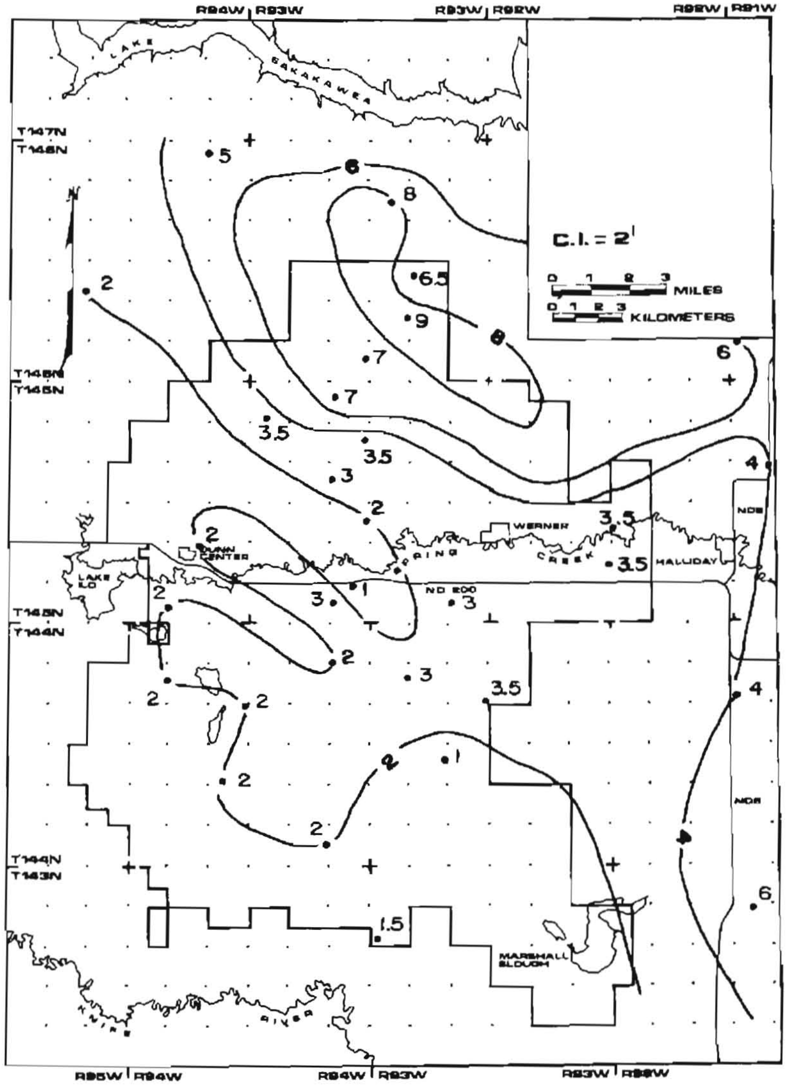

Figure 2.3.1.8-2 Map of the thickness of the I-lignite in the Dunn Center area.

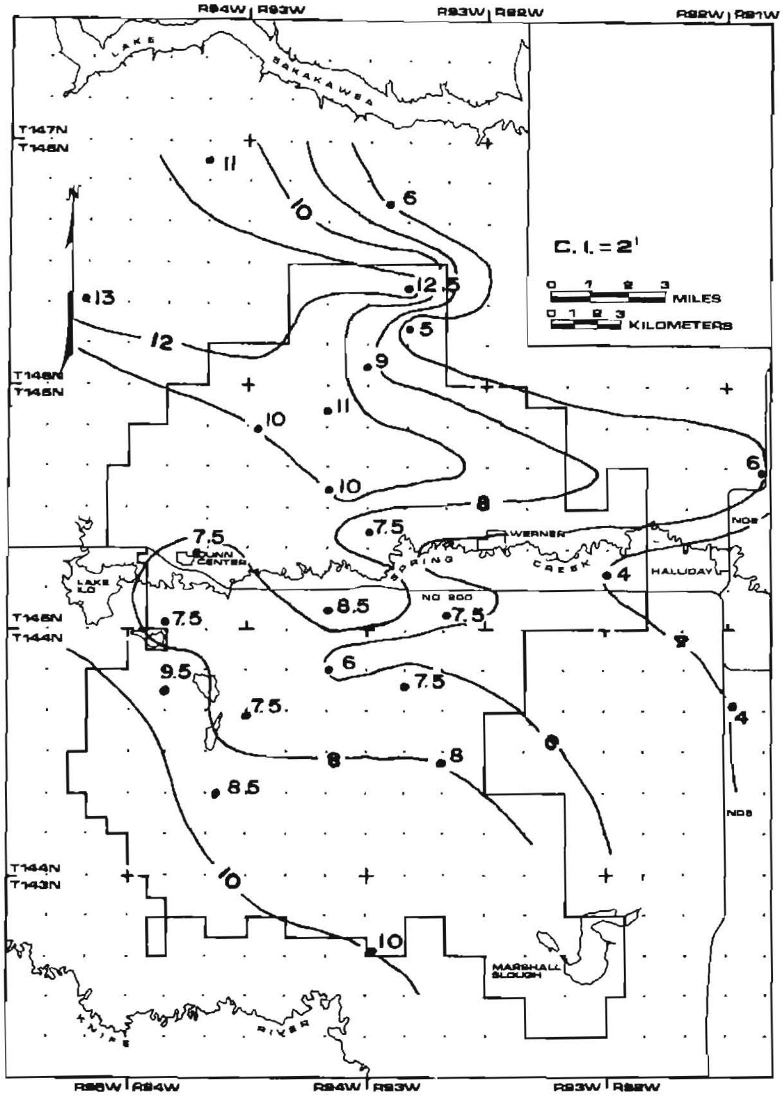

Figure 2.3.1.9-1 Map of the thickness of the J-lignite in the Dunn Center area.

through part or all of the study area. The most extensive are the lower yellow bed and the Dunn Center bed. The upper yellow bed–A-lignite combination was also useful but harder to follow. Other marker beds are labeled on plate 4.

Coal beds were used as boundaries for most of the descriptive units. They are laterally extensive and appeared to be the most logical break between units. Where coal beds thinned laterally, the units they defined could not be differentiated and were combined. Boundaries of descriptive units defined on the basis of coal beds also gave fair, but not complete, correspondence to interpreted environmental units. The interpreted environmental units were determined by close inspection of outcrop along the line of measured sections and to a lesser extent from observation points. Relationships between the measured sections are inferential though supported by observational data where possible. The criteria for definition of interpreted environmental units is given in the explanation for plate 4. Solid contacts between these units implies confidence in the position of the boundary; lack of a contact or a dashed contact implies less confidence in the position of the boundary.

In this area, the Sentinel Butte Formation can be subdivided into two thick units on the basis of gross lithologic characteristics. The lower unit consists of thin cyclic units. Individual beds are generally 3 feet or less thick; cycles are approximately 18 to 30 feet thick. Although silt is the dominant lithology, clay is abundant. Lignite beds are common and generally less than 3 feet thick. Each cycle generally begins with a thick, oxidized, brownish sand or silt unit that comprises the bulk of the cycle. This unit grades upward into unoxidized silt and clay that is generally grayish. The clay is generally overlain by a thin lignite bed or a "smutty" organic clay. The top of the cycle is generally a sharp contact with the overlying oxidized silt or sand. The lower unit of the Sentinel Butte Formation is drab colored but variegated; colors alternate between various shades of gray, blue, green, brown, and yellow.

The upper unit consists of thicker bedded, less clearly cyclic units. Individual beds are commonly about 10 feet thick. The sediment is generally coarser, with sand and silt the dominant lithology; clay occurs only rarely. Lignite beds are few and thick, generally from 9 to 15 feet thick. The color of the upper unit is much more uniform than the lower unit. It is somber, drab brown and gray.

The position of the contact between the upper and lower units of the Sentinel Butte Formation is not clearly defined. It is either at the position of the Dunn Center bed or the lower yellow bed which corresponds to the white bed in the F-interval. The subsurface data indicate a general change from thicker bedded units in the C-, B-, A-, Dunn Center, and E-intervals to thinner bedded units in the F-, H-, I-, and J-intervals.

Only one unit, the Dunn Center bed, is continuous, without break, in the badlands area. Most of the major sand bodies either overlie or are overlain by this lignite bed (pl. 4).

The lower yellow bed is nearly continuous throughout the badlands area and is the main stratigraphic marker bed used in surface mapping. It is generally calcareous silt, although, in some places, it is sandy or clayey. It is buff yellow in color, highly calcareous, and forms smooth, soft, vegetated slopes. The lower yellow bed is generally bounded by lignite beds, the E-lignite above, and the F-lignite, below. The lower yellow bed varies in thickness from 6 to 30 feet.

The upper yellow bed is similar in appearance and character to the lower yellow bed but can be identified only in the western third of the badlands area. The A-lignite at the base of the upper yellow bed is generally burned out in the eastern part of the area forming a conspicuous "scoria." The upper yellow bed is less than 15 feet thick in the badlands area but thickens markedly to the west of Lost Bridge.

Many of the beds in the badlands outcrop area have been correlated with beds in the subsurface to the south. Plate 2 shows this correlation through sections 9 and 10 of the surface section (pl. 4). On the basis of these correlations, the stratigraphic terminology of the subsurface section has been extended into the surface exposures. Eastward from the Little Missouri Public Use Area (Voight Bay), the I-lignite occurs at a 6- to 10-foot bed that outcrops just at reservoir level (1850 feet) to about 30 feet above the reservoir. The lower yellow bed, which lies at an elevation of about 2000 feet along the entire length of the outcrop area, about 150 feet above the reservoir (pl. 4), is correlated with the white bed in the F-interval. The Dunn Center bed, which is generally burned out, lies between 2100 and 2200 feet. The A-, E-, F-, and H-lignites were also recognized in the outcrop area (pl. 4).

2.4 Relation of Geology to Projected Activities

2.4.1 Possible Geologic Hazards

Potential geologic hazards associated with the project include surface subsidence, landsliding, and erosion. None of these potential hazards is considered serious.

2.4.1.1 Surface Subsidence

In certain limited areas, especially along Spring Creek, underground mining of lignite has produced undermined areas. Many of these areas are known and pose no threat. It, however, has been shown by experience in other areas in North Dakota, such as the Indian Head Mine at Zap, that the actual extent of such underground workings is in some cases greater than the known extent. Where construction or traffic over such areas of undermined land occurs, subsidence may cause damage to structure or equipment and may pose some threat of injury.

The possibility exists that surface subsidence might occur as a result of solution of deeply buried beds of salt. We believe that the probability of such subsidence is extremely low, but we do not know how to actually assess the probability. An examination of all the structure maps and maps of thickness of the various intervals above the Pierre Formation indicates a pattern of continued subsidence and sedimentation along an east-northeast-trending belt extending across the center of Mine Area No. 1. An area of extremely abrupt change in elevation of the Dunn Center in secs 35 and 36, T145N, R93W located along this trend is believed to be the result of such subsidence (fig. 2.2.3-1). The timing of this subsidence is unknown. It post-dates the deposition of the Dunn Center bed, but there is no stratigraphic evidence to indicate a more recent time marker. It is clear from stratigraphic evidence and geomorphic evidence in Saskatchewan that similar solution subsidence has occurred within the last 10,000 years (Christiansen, 1967, 1971). The presence of minor seismic activity along the solutional edge of the Prairie Formation in north-central North Dakota indicates that solution subsidence is actively occurring in North Dakota at the present time (S. B. Anderson, personal communication).

In summary, there exists, in small areas, a probability of surface subsidence as a result of collapse of abandoned subsurface mines and an extremely low probability of subsidence from salt solutions.

2.4.1.2 Landsliding

Under existing climatic conditions, natural slopes within the project area are stable. It seems probable that natural slopes should remain stable under the range of climatic conditions foreseeable in the project area. North of the project area in the Little Missouri badlands, landslides are active on many of the slopes. The sliding is generally associated with groundwater discharge at the base of slopes where coal beds or sand beds outcrop. Slumping is not occurring on the slopes south of the project area along the Knife River valley. Slopes of less than about 30 percent are stable under present climatic conditions; active landsliding is occurring on slopes greater than about 30 percent. Slope stability appears to be greater on the drier south-facing slopes than on the wetter north-facing slopes.

Two types of potential problems caused by instability of slopes are anticipated as a consequence of project activities. The first involves creation of new slopes or altering existing slopes by removing material at the base of the slope or by loading the top of the slope. This type of slope failure will be a potential problem primarily in areas of mining activity. As such, it should pose problems which will be met by routine engineering procedures of the mining operation.

The second type of slope stability problem will occur if construction of housing is undertaken in the badlands north of the project area. The topographic setting, wooded slopes, and scenic overlook of the badlands should make this area a very attractive location for residential development. Much of this area is undergoing active landsliding at present. During extended periods of greater precipitation associated with cyclic changes in climate, landsliding activity will be increased. Any cutting and filling to increase the area of flat land on which to construct houses and roads on badlands slopes will create steeper slopes and increased slope loading. Both of these changes will tend to increase instability of slopes and increase the probability of failure. The inherent instability of slopes in the badlands must be considered in any proposed construction in this setting. Failure to consider slope stability can result in serious loss of property and threat to safety.

2.4.1.3 Erosion

Under present climatic conditions, most of the project area is stable. In some small areas of loose sand such as the NW¼sec 25, T144N, R94W, active wind erosion is occurring. Stream erosion is generally limited to very steep gulleys in the badlands north and south of the project area. Very local, extremely heavy rainfall events such as the storm in the north end of the project area on the morning of June 30, 1975, when 4 inches of rain fell in one hour, can produce considerable sheet flow erosion on plowed fields and gulleying along watercourses that are normally stable.

It has been shown that a decrease in precipitation produces an increase in erosion on hill slopes in western North Dakota (Hamilton, 1967; Clayton, Moran, and Bickley, 1976). It appears that the decreased precipitation results in a decrease in the degree of vegetative cover so that the runoff, although decreased, is far more effective at eroding sediment. The diminished vegetative cover of mine spoils and newly reclaimed lands will make them susceptible to erosion and will require the application of engineering procedures to prevent erosion. This increased susceptibility to erosion will be even further increased in the event of an extended period of low rainfall.

2.4.2 Reclamation

The overburden has been subdivided into large stratigraphic units that are bounded by the major coals, the A-, B-, and C-lignites. Each of these intervals has been further subdivided into lithologically defined units that have been mapped throughout Mine Area No. 1 and extended into the remainder of the project area where feasible (figs. 2.3.1-1, 2.3.1-2). These units are briefly described in the discussion of stratigraphy of the Sentinel Butte Formation (sec. 2.3). Core sample analyses from the overburden are summarized by Moran and others (1976) on a unit by unit basis. The capability of each unit that was sampled to meet the requirements of suitable plant growth material as set forth in the Rules and Regulations for Reclamation of Surface Mined Lands of the North Dakota Public Service Commission was discussed (Moran and others, 1976, p. 115-126). The suitability of the various units are here summarized in figure 2.4.2-1. The factors affecting the capability of material to meet the criteria of suitable plant growth material are briefly discussed. For a more comprehensive treatment the reader is referred to Moran and others (1976) and especially Moran, Groenewold, and Cherry (1977).

Five variables that affect the chemical properties of the overburden material have been isolated. (1) The first is the composition of the material. The higher the clay content of the sediment, the greater the tendency for the material to be sodic. The higher the sand content, the less likely for it to be sodic. It is not clear whether there is a relationship between clay content and salinity. (2) The second factor is variation in the geochemical environment at the time of deposition. Although the effects of this variation have not been recognized in the overburden, it seems reasonable that clay deposited in one setting should have different chemical characteristics from clay deposited in another setting. (3) The third variable is proximity to the land surface. This factor interacts complexly with the fourth variable and is by no means an independent variable. The primary result of proximity to the land surface is the release of ionic species from the sediment by weathering. In the absence of water movement,proximity to the land surface would result in an increase in salinity (ECE) and probably a change in SAR, either an increase or a decrease depending on the composition of the material. (4) The fourth variable, the direction of water movement in the subsoil and soil, interacts with the second to modify the original composition of the material. In areas of infiltration, where water is moving downward to recharge the groundwater, the result of weathering and water movement is to create a flushed zone from which ions have been removed. This generally results in low salinity and SAR. In areas of exfiltration, where water is moving upward from groundwater

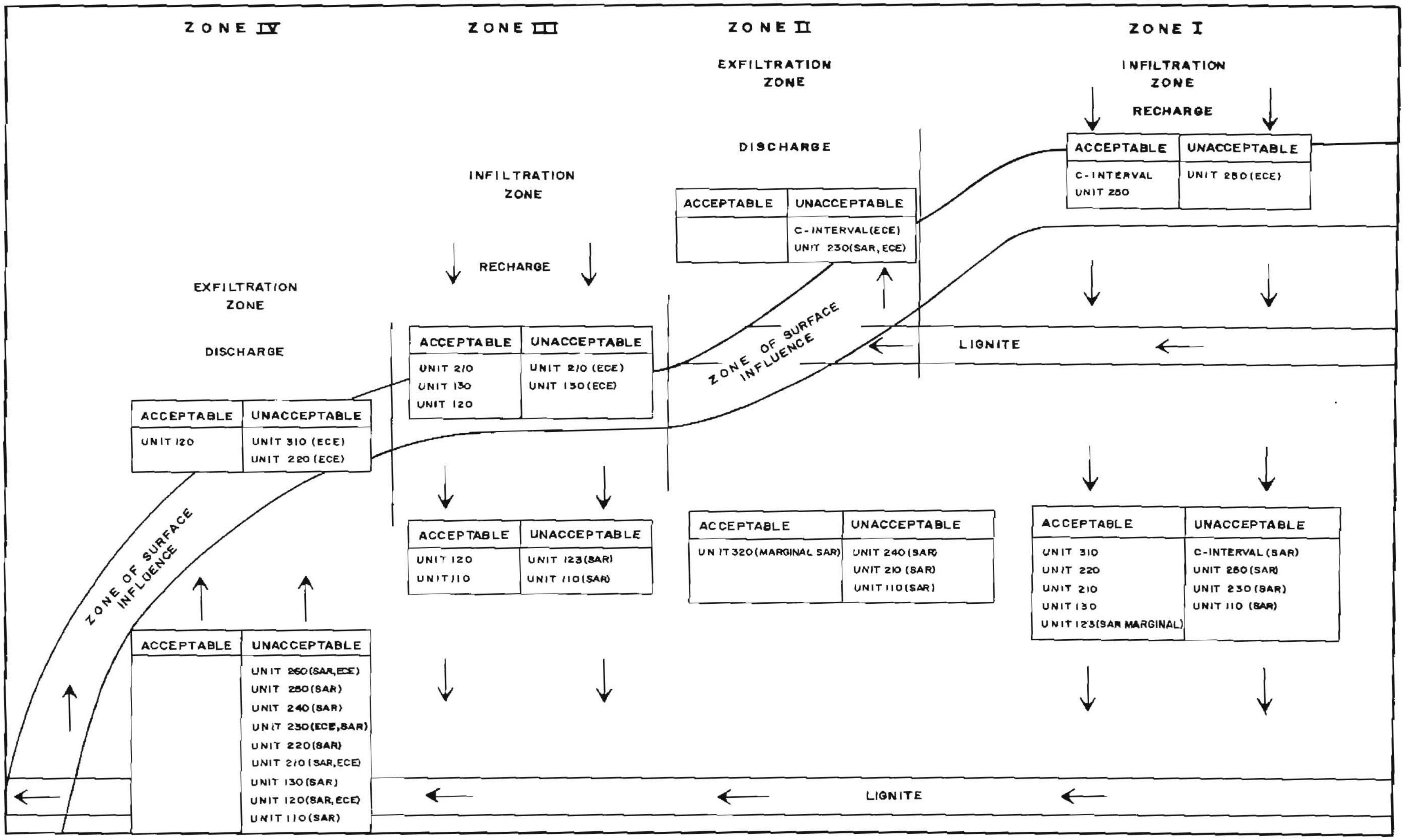

Figure 2.4.2-1 Generalized diagram summarizing the acceptability of overburden materials as suitable plant-growth material in the various stratigraphic, hydrologic, and topographic settings in the Dunn Center area.

discharge and then evaporating, a zone of concentration, in which salinity and SAR tend to be high, is created. (5) The fifth variable is the position of the material in the groundwater-flow system. It has been long recognized that the chemistry of water changes as it moves through a groundwater flow system. The salinity increases and the relative amount of sodium increases with distance and time of travel. This same relationship appears to hold in the chemistry of overburden materials. Materials near the input end of groundwater-flow systems appear to retain low salinity and SAR to considerable depths. On the other hand, materials farther down gradient in flow systems have generally high salinity and SAR.

3.0 SUBSURFACE HYDROLOGICAL AND GEOCHEMICAL SYSTEMS

3.1 General Conditions

Of the various types of geologic materials that occur in the project area and elsewhere in the region, only bedrock units of lignite or relatively clean sand, and Quaternary units of sand or gravel have potential of being significant aquifers. All other units, composed of materials such as silt and clay or relatively silty or clayey sands or gravels are aquitards. In the aquifers, the velocities of groundwater flow are normally expected to be in the order of feet per year to feet per day. In the aquitards, the groundwater velocities are expected to be in the order of feet per decade to feet per million years.

The major regional aquitard in the project area is the Pierre Formation, which has an extremely low hydraulic conductivity as a result of its high content of montmorillonitic clay. The rate of groundwater flow through this formation has been estimated to be less than a few feet in a million years (Fletcher, 1974). We consider the top of the Pierre Formation, at a depth of about 1800 feet below ground surface in the project area, to be the maximum theoretical depth of significant locally-influenced groundwater movement in this area. In a later section of this report, field data are presented which indicates that the actual maximum depth of locally influenced groundwater movement is less than 500 feet.

Except for shallower aquifers in the Sentinel Butte Formation, generally at depths less than 500 feet below ground surface, there is only one major regional aquifer that extends beneath the Dunn Center area. This aquifer is referred to as the Fox Hills-Hell Creek aquifer. It is composed of relatively clean sand, with thicknesses in the Dunn Center area ranging from about 190 to 300 feet. The top of this aquifer occurs at depths of 1218 to 1752 feet below ground surface. Croft (1973), in a study of Mercer and Oliver counties located east of Dunn County, presents a map of the potentiometric surface of the aquifer in this area, which indicates that the main direction of groundwater flow in this aquifer is from west to east. Based on evidence presented later in this report, we estimate that the age of the groundwater in the Fox Hills-Hell Creek aquifer beneath the project area is many thousands or possibly tens of thousands of years old. The water in the aquifer probably enters the system in the outcrop areas in the extreme southwestern part of North Dakota. The aquifer is generally capable of yielding several tens of gallons per minute to properly constructed individual wells.

Little is known specifically about the aquifer occurrences and groundwater conditions between the Fox Hills-Hell Creek aquifer and the base of the Sentinel Butte Formation. Although most of this interval is composed of silt and clay beds, there are several sand units many tens of feet thick and some coal beds as much as 20 feet thick. In the project area there are no farm or municipal wells in this interval. During the fall of 1975, an attempt was made by a well driller to obtain water supply for the town of Dunn Center at depths below the Dunn Center bed. The hole was eventually extended to the Fox Hills-Hell Creek aquifer, because none of the shallower potential aquifers below the Dunn Center bed showed potential yields in the order of several tens of gallons per minute. This well is the only water supply well in the entire project area at a depth below 400 feet.

Data available indicated that the general groundwater conditions in the project area were characterized by (1) primarily horizontal groundwater flow in the sand and lignite aquifers in the bedrock and in the sand and gravel aquifers in the Quaternary valley fill, and (2) by primarily vertical groundwater flow through the silt, clay, and dirty sand aquitards that extend as relatively horizontal layers in the bedrock and as aquifer confining beds or interbeds in the valley fill.

3.2 Methods of Investigation

Since delineation of the stratigraphy is the crucial prerequisite step in the study of the groundwater-flow system and groundwater chemistry, it was necessary to insure that adequate field data for stratigraphic interpretations were obtained. For this purpose, down-hole geophysical probes for measurement of electrical, nuclear, and physical borehole parameters were used on a routine basis at all major test sites. To provide relatively large borehole samples so that the physical and chemical properties of the various stratigraphic units could be obtained from laboratory tests, core samples were collected from representative zones in selected boreholes.

To determine the hydraulic conductivities of the main aquifers and aquitards, four types of tests were used: (1) single-well response tests (Hvorslev, 1951), (2) pumping tests, (3) permeameter tests on core samples, and (4) injection tests in packer-isolated intervals in uncased boreholes. Each of these four techniques has its strengths and weaknesses, and each deals with hydraulic conductivity on a different scale. More reliable estimates of the representative conductivities for the various stratigraphic units can be obtained by combining data from the four tests.

The configuration of the main water table and the distribution of hydraulic head in the Sentinel Butte Formation and in parts of the valley fill systems were determined using an observation well network consisting of clusters of wells, referred to as nests, at numerous observation sites. Each nest consisted of between 2 and 7 individual wells in separate boreholes at different depths. At each nest the vertical distribution of hydraulic head was monitored. From the areal network of nests, the three-dimensional patterns of hydraulic head were determined.

The observation wells were installed so that water could flow into the well screens only from relatively narrow specified stratigraphic intervals. The borehole segments above the well screens were sealed to prevent leakage from other sources. For simplicity these installations will be referred to as wells rather than as piezometers.

The chemistry of the groundwater was determined by making field measurements of the pH and specific conductance of water samples collected from the observation well network, from North Dakota Water Commission wells, and from farm wells. In the water quality laboratory at UND, samples were analyzed for total dissolved solids, major ions, and nitrate. Minor constituent and trace element analyses were made on a much smaller number of samples. The purpose of the well water analyses was threefold: (1) to define the general water quality of the significant aquifers in the Sentinel Butte Formation, (2) to obtain information on the water chemistry produced from natural leaching of infiltration water that has passed through various types of overburden materials, and (3) to define water chemistry patterns that can be used as an aid in groundwater source area and flow pattern interpretations.

To obtain estimates of the source areas and ages of groundwater in some of the aquifers, samples from observation wells and farm wells were analyzed for their natural concentrations of oxygen isotopes, tritium, carbon-14, and carbon-13. These isotopes have been used as tools in subsurface hydrological studies in many parts of the world and have often been found to be very useful.

The methods used in the subsurface

Table 3.3.1-1. *Comparison of values of hydraulic conductivity of lignite.*

Well	Single-Well Response Test	Pump Test	K (Pump Test)^{b} K (Single-Well Response)	Packer Test
NDSWC 4794-e	2.16x10^{-3}	2.65x10^{-2}	12.27	
NDSWC 4794-f	9.90x10^{-4}	2.64x10^{-2}	26.67	
NDSWC 4794-g	7.21x10^{-4}	2.54x10^{-2}	35.23	
NDSWC 4794 (e, f, g)	1.32x10^{-3a}	2.61x10^{-2}	19.77	
NDSWC 4794 (a, b, d)	1.45x10^{-2a}	6.08x10^{-1}	41.19	
UND 75-2-4	7.2 x10^{-4a}	2.52x10^{-4}	0.35	
UND 75-17-2-3	1.29x10^{-3}			3.14x10^{-3}

[a] Value estimated from regression analysis of relationship between hydraulic conductivity and depth.

[b] Ratio of hydraulic conductivity determined by pumping test to the hydraulic conductivity determined by single-well response test.

hydrologic investigation are briefly outlined in chapter 5 of this report. For a more complete discussion the reader is referred to Moran and others (1976). The location of wells utilized to obtain hydrologic data is given in figure 3.2-1.

3.3 Hydraulic Conductivity Measurements

3.3.1 Lignite

The hydraulic conductivity of lignite aquifers was determined by 78 single-well response tests and 3 pump tests. The single-well response test values ranged from 1.8 x 10^{-2} to 1.4 x 10^{-6} cm/sec; the pump test values ranged from 6.2 x 10^{-1} to 2.5 x 10^{-4} cm/sec; and a single packer test value was 3.14 x 10^{-3} cm/sec.

Table 3.3.1-1 shows the comparison of values of hydraulic conductivity for lignite determined by single-well response test and pump testing. Some of the values were determined on the same well by both methods. Others are estimated using the relationship between hydraulic conductivity and depth that is discussed below. From these data, it is evident that in five of six cases the pump test value is from 1 to 1.5 orders of magnitude greater than the single-well response-test value. Since long-term pumping tests are generally considered to give accurate values of hydraulic conductivity and because the values of hydraulic conductivity determined by single-well response tests are probably minimal for reasons discussed by Moran and others (1976, p. 154-160), the values of hydraulic conductivity used in calculations have been corrected to corresponding pump-test values by multiplying 1.2 x 10^{1}.

On the basis of data both from the pump testing (fig. 3.3.1-1) and single-well response testing (fig. 3.3.1-2), there appears to be an inverse relationship between depth and hydraulic conductivity. Although only three pump-test values are available, they strongly suggest that the log of the hydraulic conductivity of lignite decreases by 2.47 per 100 feet of depth. This is a decrease in hydraulic conductivity of nearly 2.5 orders of magnitude every 100 feet. The coefficient of determination, r^2, which expresses the degree to which a set of observations fits the calculated regression line, has a value of 0.996. This coefficient varies from 0 for no fit to 1.0 for a perfect fit. Although the slope of the regression line that describes the relation is steeper and the fit of the 78 data points not nearly so tight (r^2=0.263), the data for the single-well recovery tests (fig. 3.3.1-2) also strongly suggest a depth control on hydraulic conductivity. The log of the hydraulic conductivity decreases by 0.37 per 100 feet. This is a decrease of 1 order of magnitude every 300 feet of depth.

These conclusions are consistent with the fact that permeability in lignite is entirely fracture permeability. These relationships result from an increase in the number and size of joints and bedding partings in the lignite as the thickness of

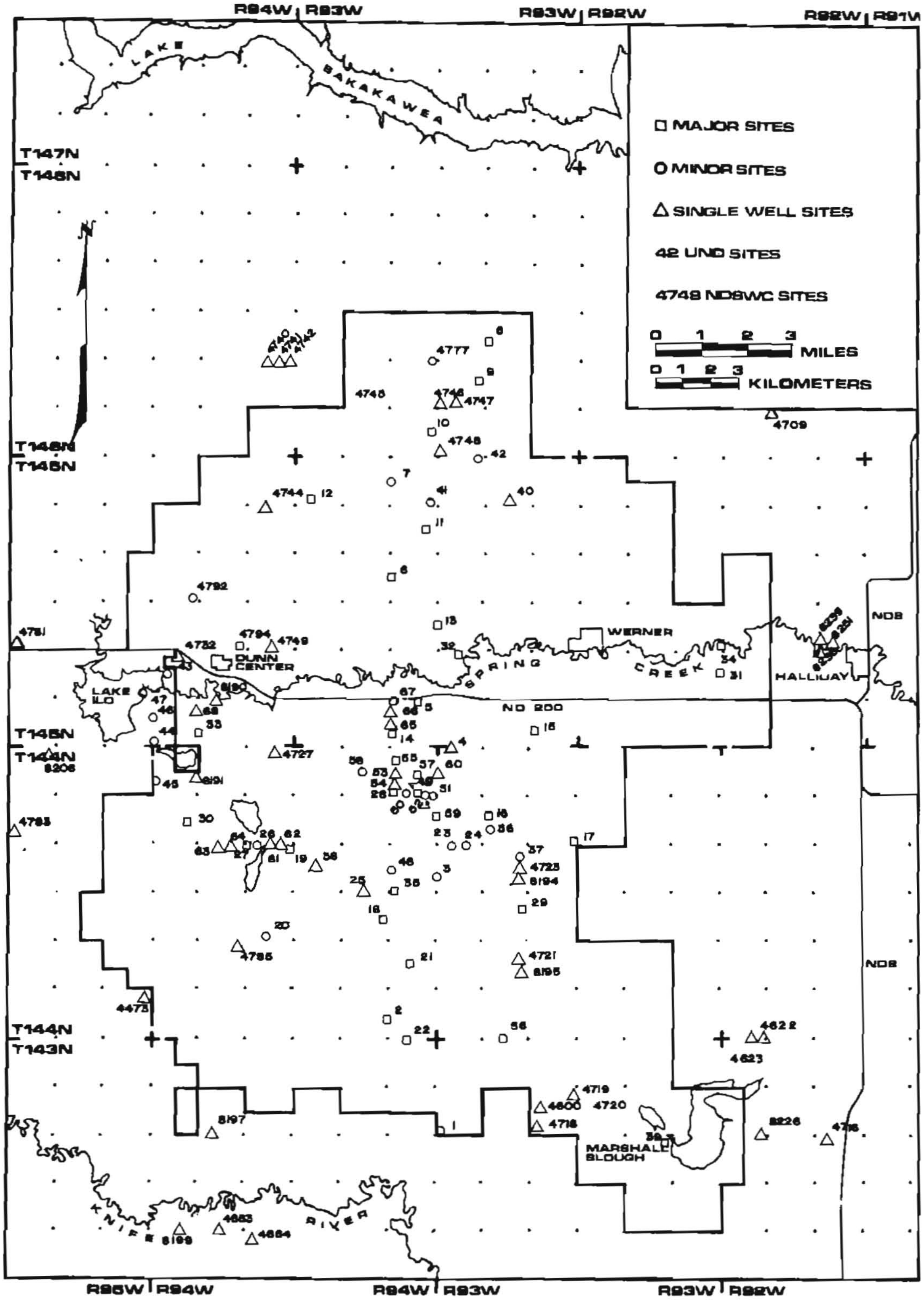

Figure 3.2-1 Map of the location of hydrological sites in the Dunn Center area.

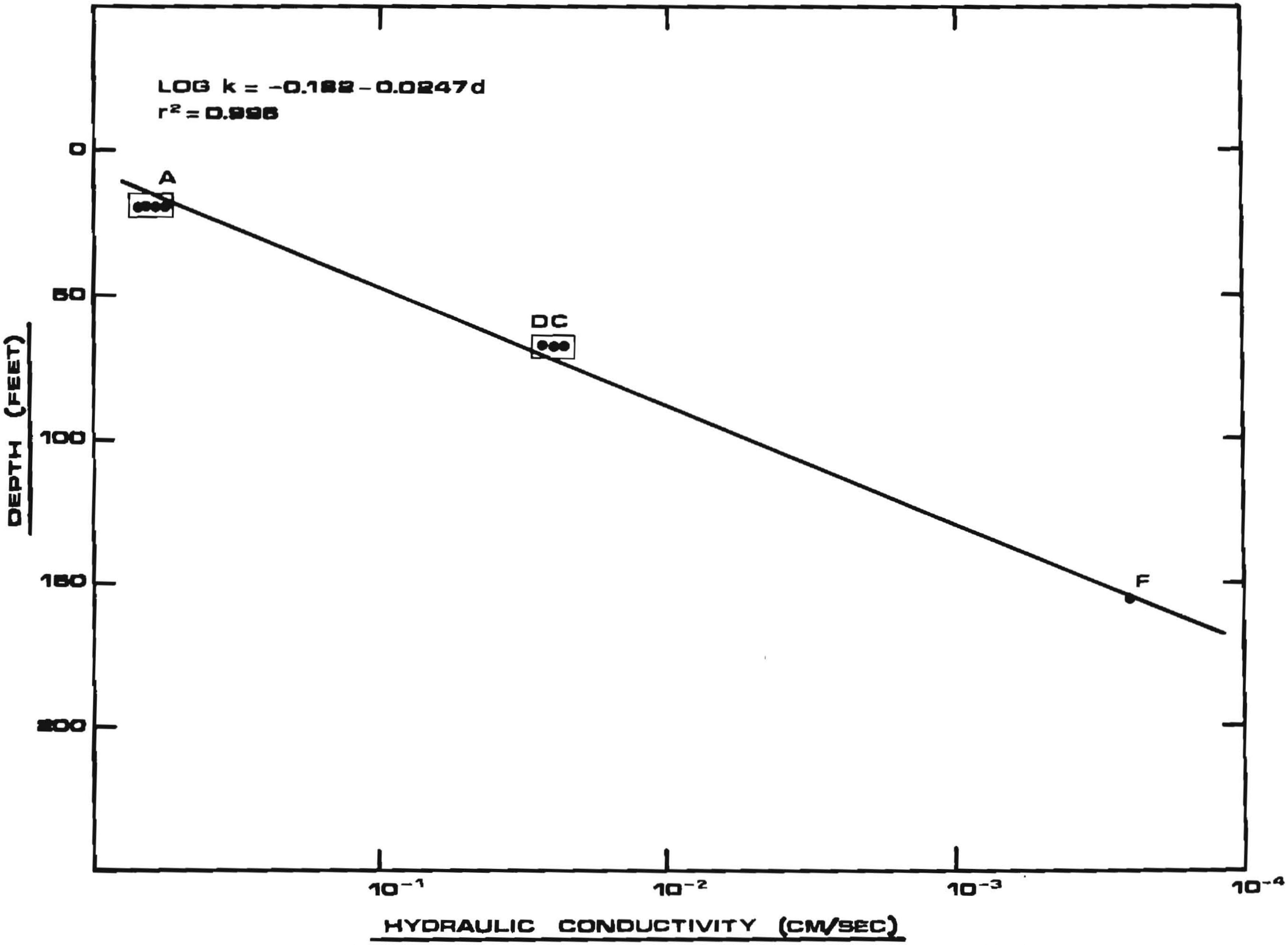

Figure 3.3.1-1 Relationship between hydraulic conductivity of lignite determined by pump tests and depth.

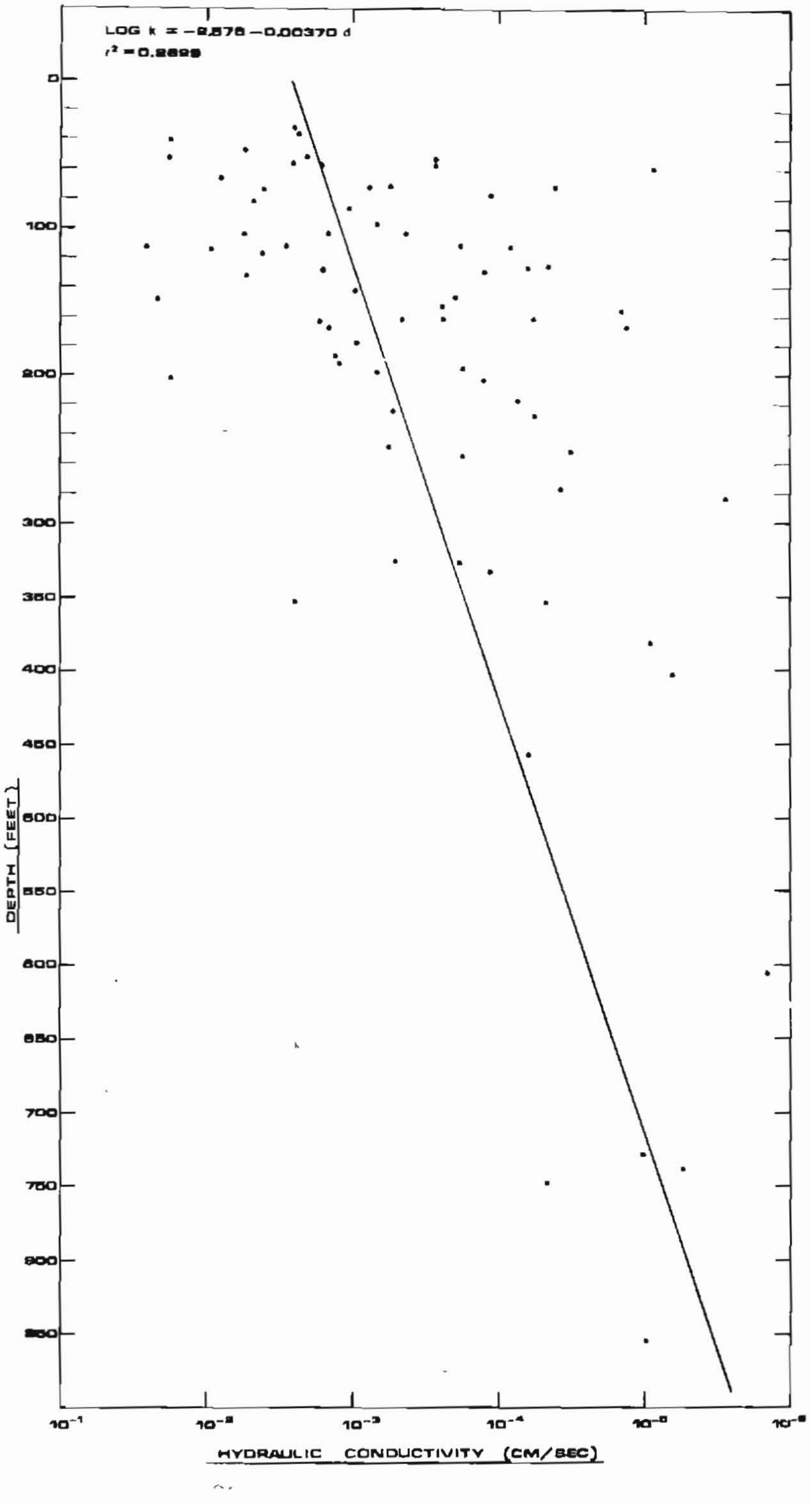

Figure 3.3.1-2 Relation between hydraulic conductivity of lignite determined by single-well response tests and depth.

cover over the lignite decreases. Further analyses are needed to determine whether the permeability is controlled by depth of burial, thickness of cover removed by erosion, thickness of glacial cover, or some other factor that has affected the loading history of the region during the geologic past.

3.3.2 Sand Aquifers in the Sentinel Butte Formation

The hydraulic conductivity of sand beds in the Sentinel Butte and Bullion Creek Formations was estimated with 24 single-well response tests, 1 pump test, and 3 permeameter tests. The hydraulic conductivity of sand beds ranges from about 2×10^{-2} to 5×10^{-6} cm/sec with most values falling in the range from about 2×10^{-3} to 2×10^{-5} cm/sec. There seems to be a decrease in hydraulic conductivity with depth, although this trend is weaker than for the lignite aquifers. The one pump test value from the E-interval is above the mean of the single-well response-test values for sand in the same interval. The permeameter-test values are all low.

3.3.3 Confining Beds in the Sentinel Butte Formation

The hydraulic conductivity of silt and clay beds in the Sentinel Butte and Bullion Creek Formations was assessed by four single-well response tests and 10 permeameter tests. The values ranged from 10^{-6} to 10^{-8} cm/sec, with most values lying between 5×10^{-7} and 10^{-8} cm/sec. Two of the single-well response test values are in the range 5×10^{-7} to 10^{-6}. At least one of these wells, UND 75-55-1, has not yet reached static level, so the draw-down figures used to calculate the hydraulic conductivity are too small. As a result, the actual hydraulic conductivity is smaller than the presently calculated value.

3.4 Porosity

Porosity is defined as the ratio of the volume of the voids to the total sample volume. There are in general two types of effective porosities that can occur in geologic materials: (1) intergranular porosity, and (2) fracture porosity. Intergranular porosity is a measure of the volume of the voids that occur between the grains that comprise sediments such as gravel, sand, silt, or clay. Fracture porosity is a measure of the voids that occur because of fractures, joints, bedding planes, or solution channels. The term "effective" porosity refers to the porosity that involves voids that are effective in transmitting fluids. In other words, it includes only the voids that are interconnected as part of the permeability network. Effective intergranular porosities for gravel, sand, silt, or clay sediments that are nonindurated are normally in the range of 0.2 to 0.4. Effective fracture porosities of fractured or jointed rock are normally in the range 10^{-2} to 10^{-5}.

Data on the effective porosities of deposits in the Dunn Center area were obtained from laboratory tests on relatively undisturbed core samples and from pumping tests in the field. The laboratory data for samples of sand, silt, and clay are reported by Moran and others (1976, app. C-X). Except for one sample with a porosity of 0.24, the values are within the narrow range of 0.30 to 0.43 and are probably representative of the non-lignite beds in the Sentinel Butte Formation.

In terms of hydraulic properties, the porosity of interest for the lignite beds is the fracture porosity, since it is this porosity that relates to the effective storage of drainable groundwater from these beds. The porosity of the lignite beds in the Dunn Center area is assumed to be about the same as the storage coefficient, from 10^{-2} to 5×10^{-5}.

3.5 Aquifers and Aquitards

3.5.1 Coleharbor Formation

The sediments of the Coleharbor Formation constitute important aquifers and aquitards in the project area. The areas of thin deposits of pebble-loam that cap uplands (fig. 2.1.10-1) are generally aquitards. The low hydraulic conductivity of the sediment prevents rapid movement of water. In addition, these areas are generally high enough in the landscape that they are in the unsaturated zone and contain no water even where hydraulic conductivity is higher.

The sediments filling the valleys constitute both aquitards and aquifers. Sand and gravel, which generally constitute less than half the thickness of the valley fill, are aquifers. Silt, clay, and pebble-loam are aquitards.

The distribution of thick deposits of Coleharbor Formation that contain aquifer material is shown in figure 3.5.1-1. In most of the area, the distribution of these materials is clearly limited by conspicuous surface valleys. However, in an area immediately southeast of Dunn Center, in secs 3 and 4 of T144N, R94W, sec 31 of T145N, R93W, and sec 36 of T145N, R94W, the location of the deep valley poses a problem. We traced a narrow, deep valley from the southeast, through secs 12, 1, and 2 of T144N, R94W (fig. 3.5.1-1), but lost it in sec 3. The deep valley continues north or west by three possible routes. One meanders north out of section 3 into section 31; the second trends more or less straight northwest from section 3 into section 36 and then on toward Dunn Center; the third trends southwestward from section 3 into section 4. The first route is a narrow meandering valley with dissected margins that is currently occupied by the ephemeral stream that drains the large flat area in secs 1, 2, 11, and 12 of T144N, R94W. The second and third possible routes are low sags in the topography that are floored by sand. No drainage presently occupies these sags. The test drilling that would have indicated the location of the extension of the valley was precluded by problems of access to the appropriate locations. For several reasons we believe that the valley extends northward from section 3 into section 31 through the narrow dissected valley. The meander geometry of the valley is consistent with the pattern of this outlet and its extension across the valley of Spring Creek. On the other hand, the northwestern route is very straight; the southwestward route through section 4 is not ruled out on this basis. The steep gradient of the potentiometric surface in the Coleharbor Formation (fig. 3.5.1-2) through the possible southwestern route suggests that only fine-grained material is present in the sag, which is inconsistent with the nature of the valley fill. The northern route is also favored by the buried valley that enters the Spring Creek valley immediately east of Dunn Center, which can best be continued as the northward extension of the same valley.

The fill within the buried valleys is complex. The basal unit in the valley fill is sand and gravel (figs. 3.5.1-3, 3.5.1-4, 3.5.1-5, 3.5.1-6, 3.5.1-7). A layer of clayey pebble-loam overlies this, and in some places, is overlain by lacustrine clay (fig. 3.5.1-6). One or more layers or lenses of sand and gravel occur within the pebble-loam. In many places, the pebble-loam extends to the land surface (figs. 3.5.1-3, -4, -5); in others, the pebble-loam is overlain by another unit of sand or sand and gravel (figs. 3.5.1-4, -5, -6, -7). This upper unit of permeable material is generally discontinuous (fig. 3.5.1-5). In some places, it is overlain by silt and clay that probably consists of lake sediment and sediment of alluvial fans washed into the valley from adjacent slopes (figs. 3.5.1-5, -6, -7).

The hydraulic conductivity of the sand and gravel unit at the base of the valley fill was determined at nine wells using the single-well response test method. The values ranged from 2.30×10^{-4} cm/sec to 2.95×10^{-2} cm/sec with a mean value of 6.59×10^{-3} cm/sec (fig. 3.5.1-2). These values are considered representative only of the finer-grained portions of the permeable valley fill and are believed to be too low for much of the material for three reasons. (1) In several wells, water level recovery was so rapid that either no drawdown was possible during pumping (Moran and others, 1976, p. 154-160) or recovery was complete before measurement was possible (approximately 15 to 30 seconds following cessation of pumping). In either case, the hydraulic conductivity at these wells is much greater than any values measured. (2) The upper limit of hydraulic conductivity that can be measured using the well installation procedure that was employed for this project is about 5.5×10^{-2} cm/sec because of the size of the sand pack used (Moran and others, 1976, p. 151-154). The procedure was designed for the lignite and

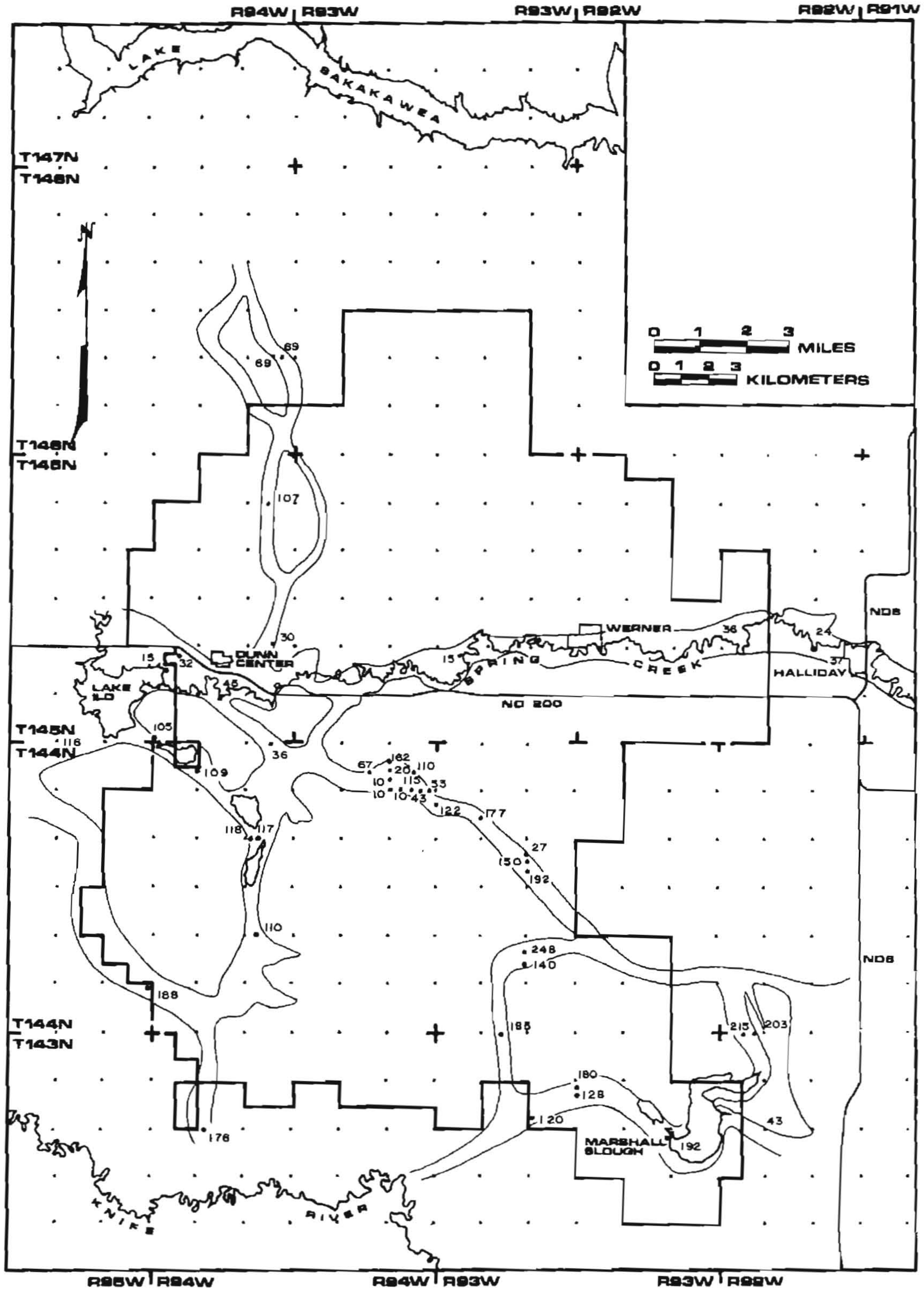

Figure 3.5.1-1 Map of the thickness, in feet, of valley fill sediment in the Coleharbor Formation, Dunn Center area.

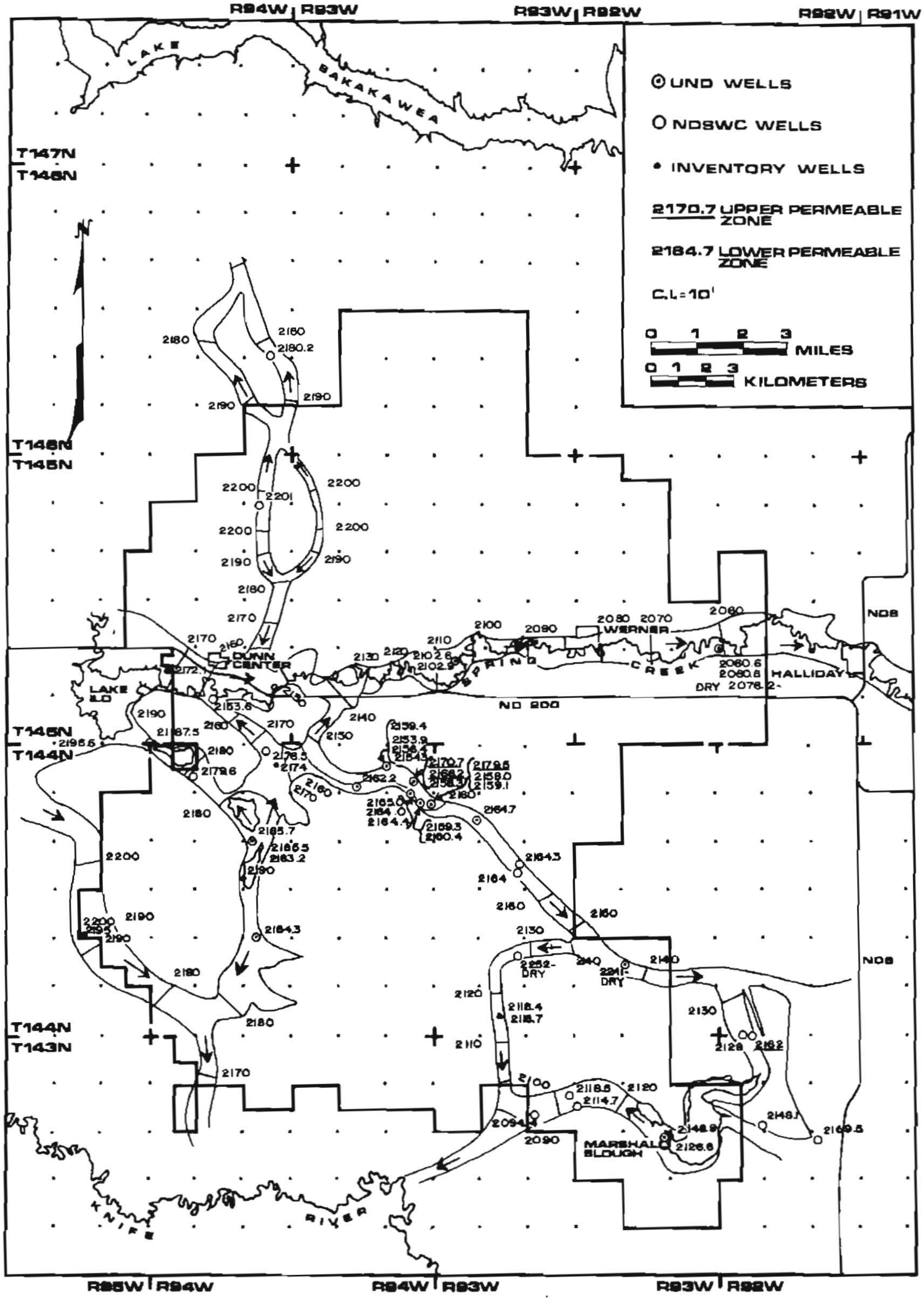

Figure 3.5.1-2 Map of the elevation of the potentiometric surface in the Coleharbor Formation, Dunn Center area.

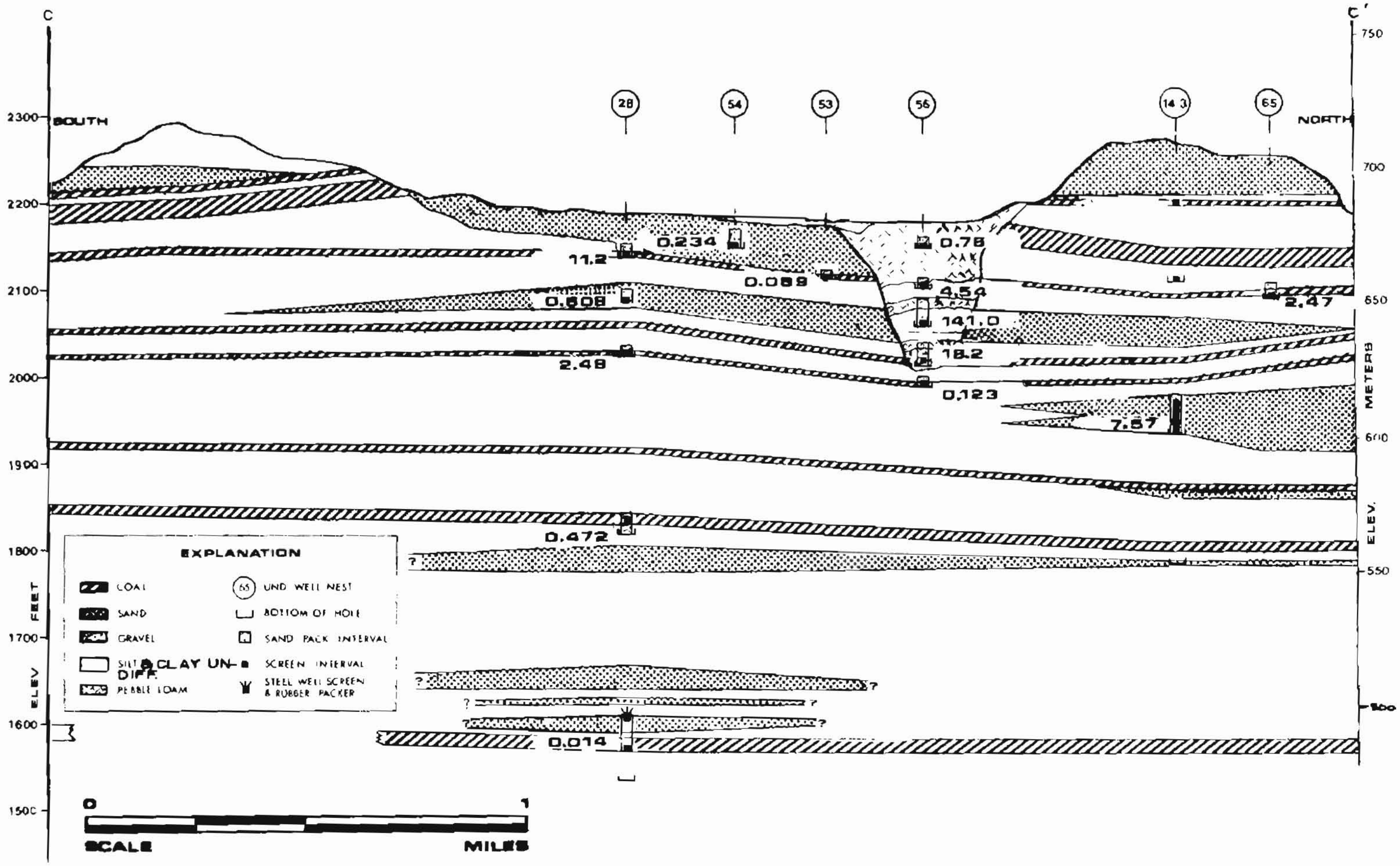

Figure 3.5.1-3 North-south hydrologic cross section C-C' through the plant site area. Values of hydraulic conductivity times 10^{-4} cm/sec. Location of the cross section shown in figure 2.1.10-2.

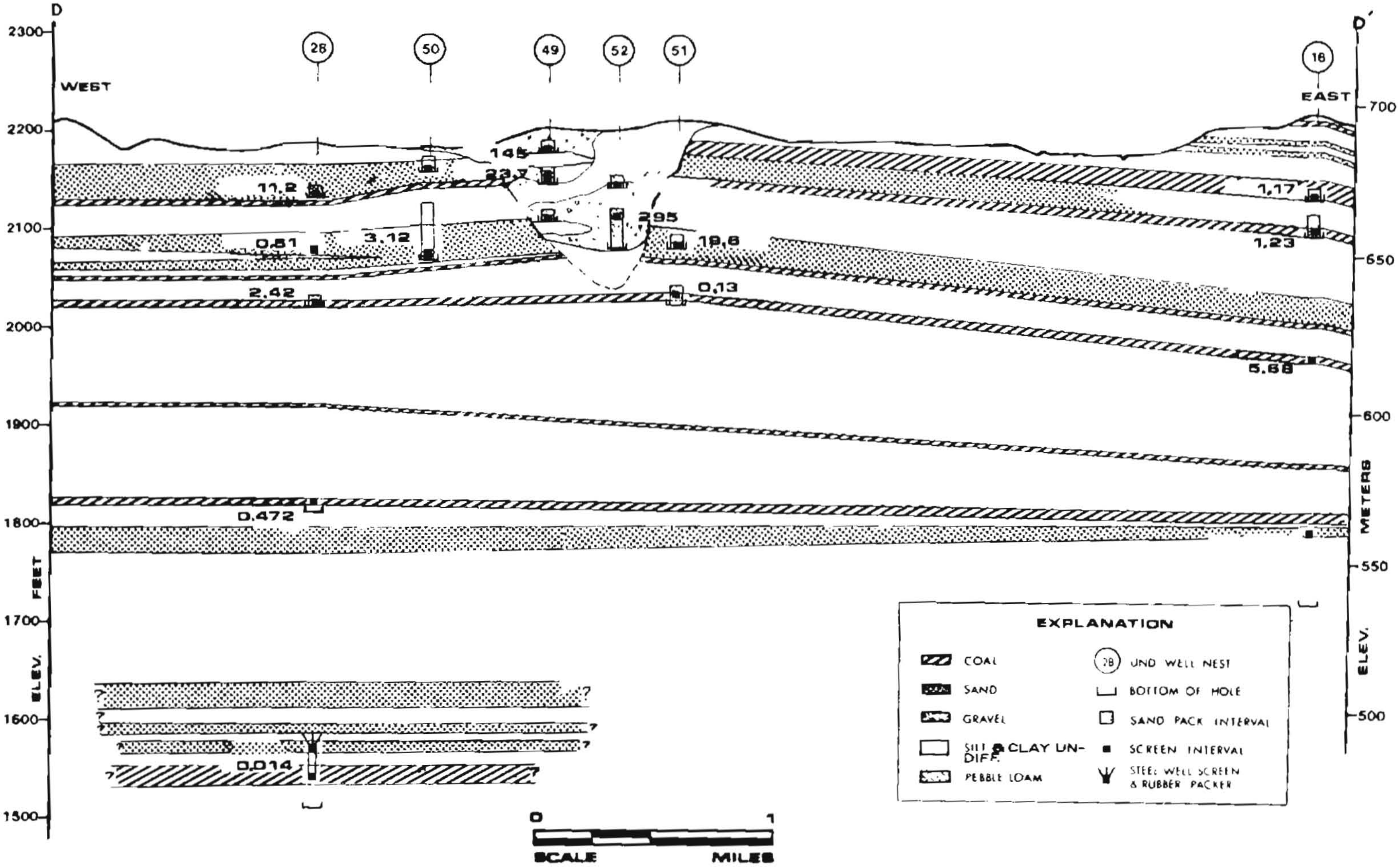

Figure 3.5.1-4 East-west hydrologic cross section D-D' through the plant site area. Values of hydraulic conductivity times 10^{-4} cm/sec. Location of the cross section shown in figure 2.1.10-2.

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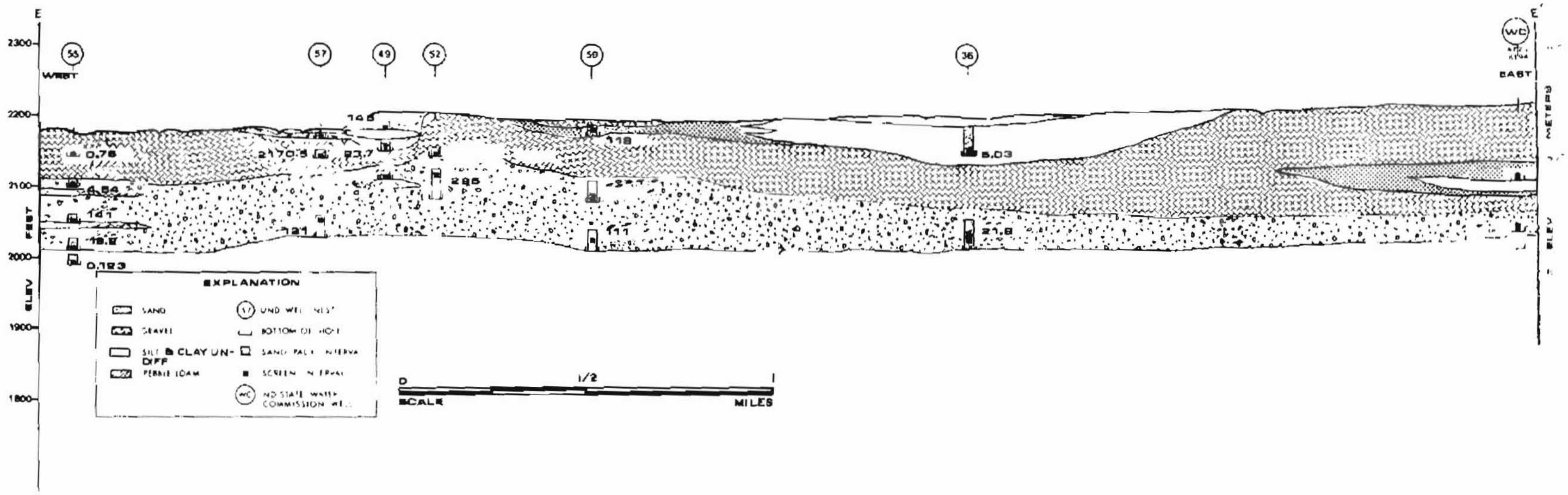


Figure 3.5.1-5 Hydrologic cross section E-E' along the axis of the partly buried glacial meltwater channel extending from sec 2, T144N, R94W to sec 16, T144N, R93W. Hydraulic conductivity times 10^{-4} cm/sec. Location of the cross section shown on figure 2.1.10-2.

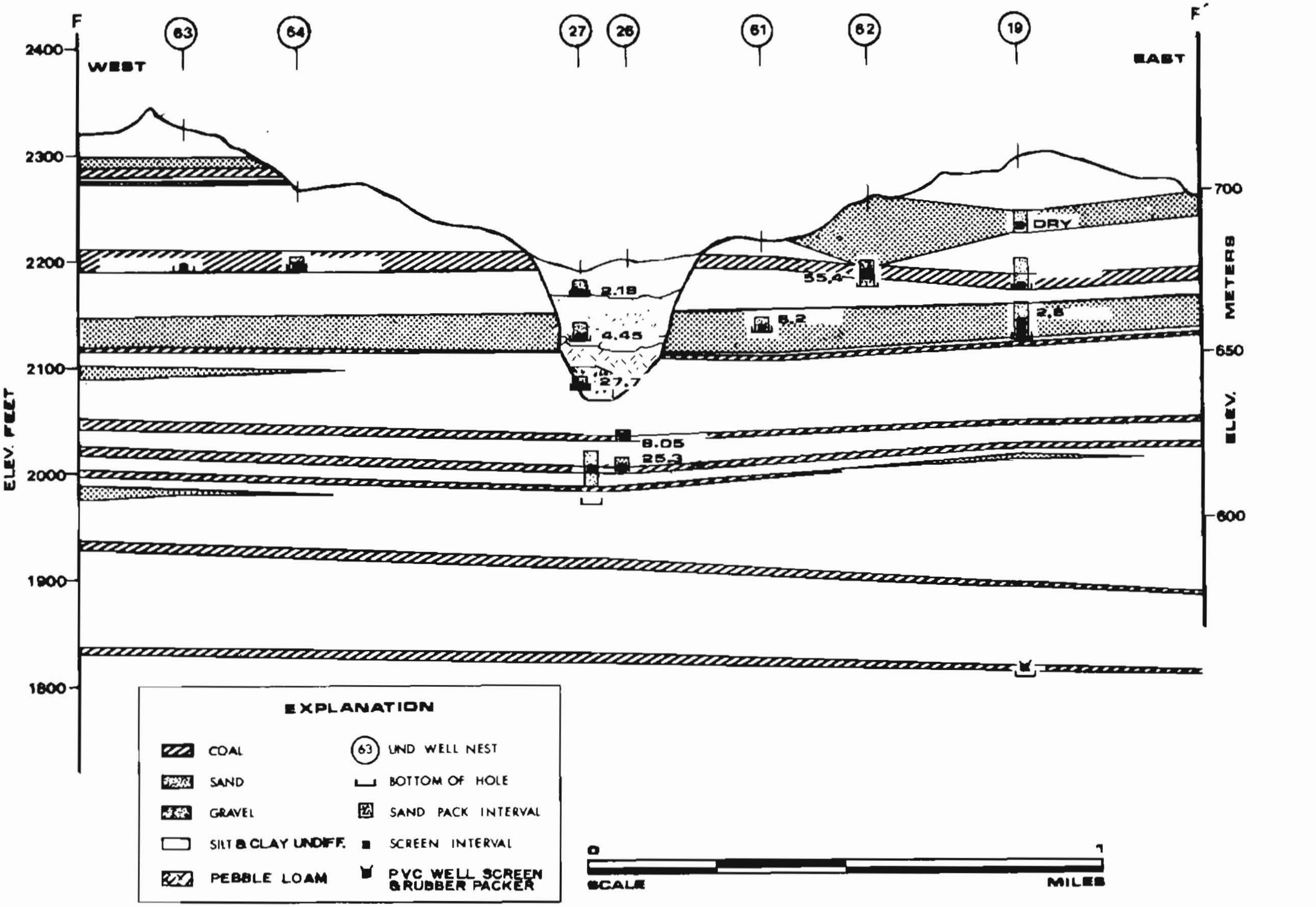


Figure 3.5.1-6 Hydrologic cross section F-F' across the partly buried glacial meltwater channel in secs 16 and 17, T144N, R94W. Hydraulic conductivity times 10^{-4} cm/sec. Location of the cross section shown on figure 2.1.10-2.

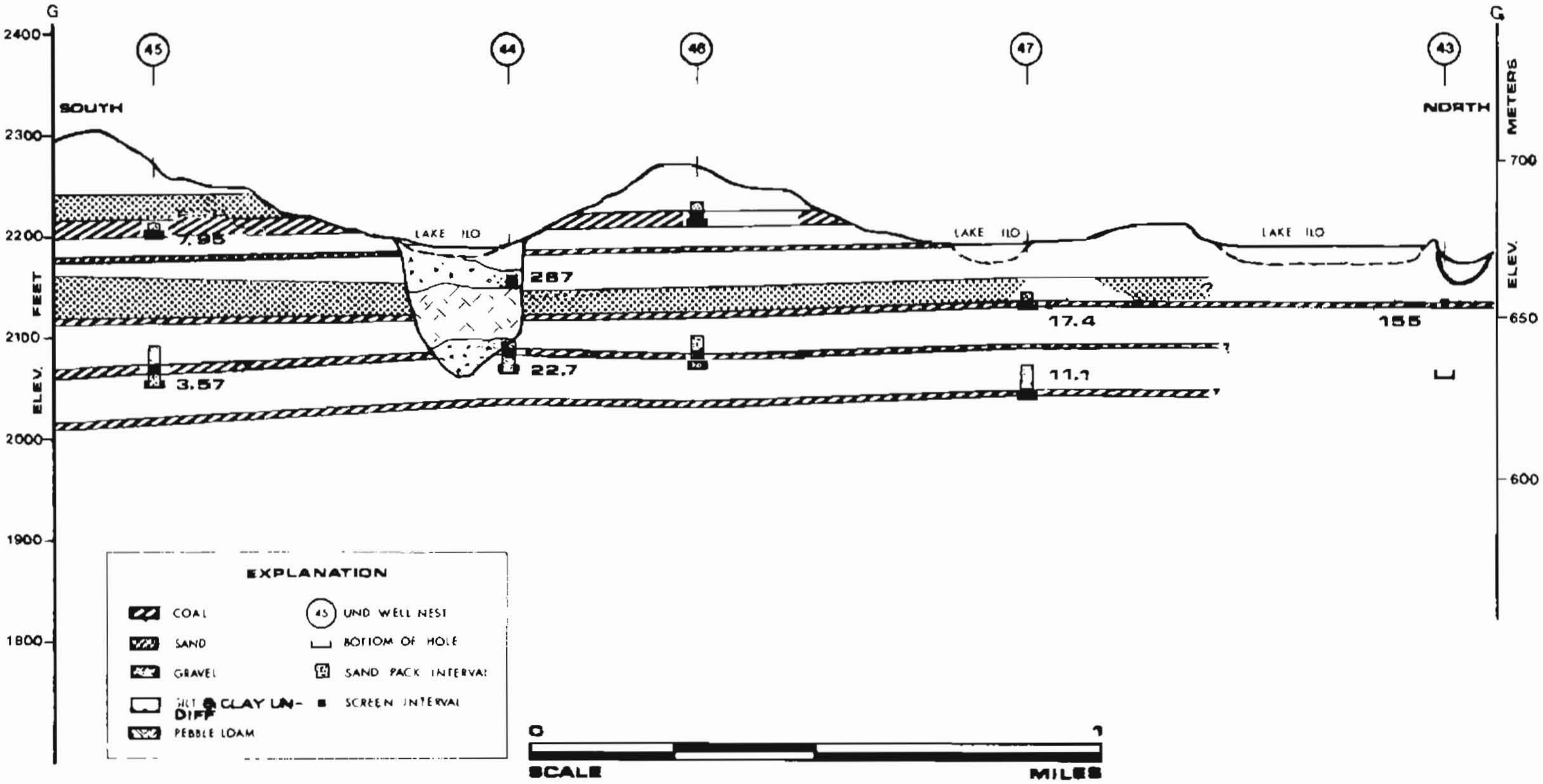


Figure 3.5.1-7 Hydrologic cross section G-G' across the partly buried glacial meltwater channel at the southeast edge of Lake Ilo. Hydraulic conductivity times 10^{-4} cm/sec. Location of the cross section shown on figure 2.1.10-2.

fine-sand aquifers of the Sentinel Butte Formation rather than for the more permeable valley-fill sediments. (3) Long-term pumping tests in valley-fill deposits in Mercer County, east of the project area, indicate hydraulic conductivity values of 3.0 x 10^{-1} cm/sec (Croft, 1973, p. 57, 61). There is no reason to believe that these values are not representative of the more permeable portions of the valley-fill deposits in the project area.

Hydraulic conductivity of the upper permeable unit of the valley fill was determined at eight sites using the single-well response test method. The values ranged from 2.37 x 10^{-3} cm/sec to 2.67 x 10^{-2} cm/sec with a mean value of 6.54 x 10^{-3} cm/sec (fig. 3.5.1-8). For the reasons outlined in the previous paragraph, these values are believed to represent minimum values for the unit.

Hydraulic conductivity of confining beds in the valley fill was determined at six sites, two sites in pebble-loam and four sites in silt, using the single-well response test method. The values ranged from 7.49 x 10^{-5} cm/sec to 7.60 x 10^{-5} cm/sec for the pebble loam and from 2.28 x 10^{-4} cm/sec to 5.03 x 10^{-4} cm/sec for the silt (fig. 3.5.1-8).

The distribution of values of potentiometric head in the lower-permeable unit of the valley fill is contoured in figure 3.5.1-2. Values in the confining beds and in the upper-permeable unit are also shown. The marked separation in values of potentiometric head between the upper and lower units (fig. 3.5.1-2) indicates that the two units of permeable material are effectively isolated from one another by the intervening layer of pebble loam and clay.

3.5.2 Overburden Aquifer-Aquitard System

The hydraulic characteristics of the C-, B-, and A-intervals and lignites and the Dunn Center interval are considered here. The distribution and thickness of each of these intervals are shown in figures 2.3.1.2-1, 2.3.3-1, 2.3.4-1.

The C-interval is apparently unsaturated in the western outcrop area, in Mine Area No. 1, and is not an aquifer. In the eastern outcrop area around Horse Nose Butte, the C-lignite and possibly sand in the lower part of the C-interval are saturated and do yield water to wells. The hydraulic conductivity of the C-lignite was determined to be 1.29 x 10^{-3} cm/sec at well 17-2-3 using a single-well response test (fig. 3.5.2-1). Much of the C-interval is fine-grained silt and clay and may serve as an aquitard. However, because much of the interval is unsaturated, fracturing of the fine-grained material is probably common. Core samples revealed fracturing in only a few cases. In the Underwood-Falkirk area, about 80 miles east of the project area, however, fracturing was commonly observed (Moran) in cores cut in similar settings. If fracturing of the fine-grained material is common, as we assume, then the C-interval probably readily passes water downward to lower aquifers.

The B-interval and lignite are saturated and yield water to wells in the eastern outcrop area around Horse Nose Butte. The B-lignite and therefore, presumably, the B-interval appear to be unsaturated in the western outcrop area. The hydrologic properties of this unit are probably similar to the C-interval and lignite. A single value of 1.2 x 10^{-5} cm/sec for the hydraulic conductivity of a core of fine sand from the B-interval (fig. 3.5.1-8) was determined by the permeameter method.

The A-interval and lignite are saturated and provide water to wells throughout the project area. The hydraulic conductivity of sand in the A-interval was determined at three sites using the single-well response test method. The values ranged from 1.76 x 10^{-4} cm/sec to 1.19 x 10^{-2} cm/sec (fig. 3.5.1-2). The hydraulic conductivity of the A-lignite was determined at ten sites using the single-well response test method and by four observation wells at the site of a single long-term pumping test conducted by the North Dakota State Water Commission (Moran and others, 1976, app. C-VIII). The values from the single-well response test ranged from 1.09 x 10^{-4} cm/sec to 1.82 x 10^{-2} cm/sec with a mean of 9.98 x 10^{-3} cm/sec (fig. 3.5.2-1). The values from the pump test ranged from 5.79 x 10^{-1} to 6.25

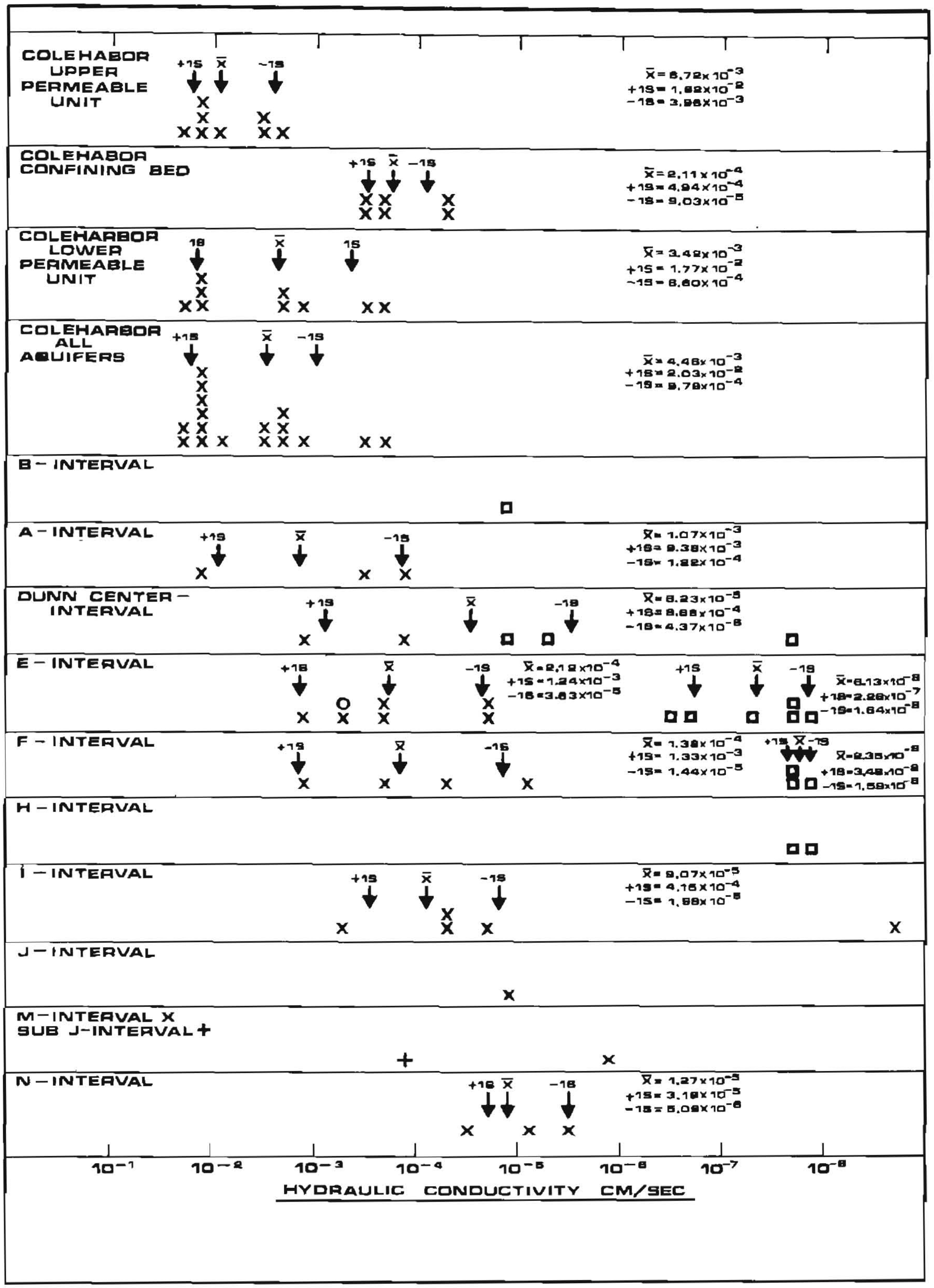


Figure 3.5.1-8 Frequency distribution of hydraulic conductivity data for non-lignite aquifers in the Dunn Center area. The logarithmic mean $\bar{X}$ and standard deviations, s, are shown for each unit; +1s and −1s refer to values one standard deviation above and below the mean. Values determined by pump test are shown by 0; values determined by permeameter test are shown by □.

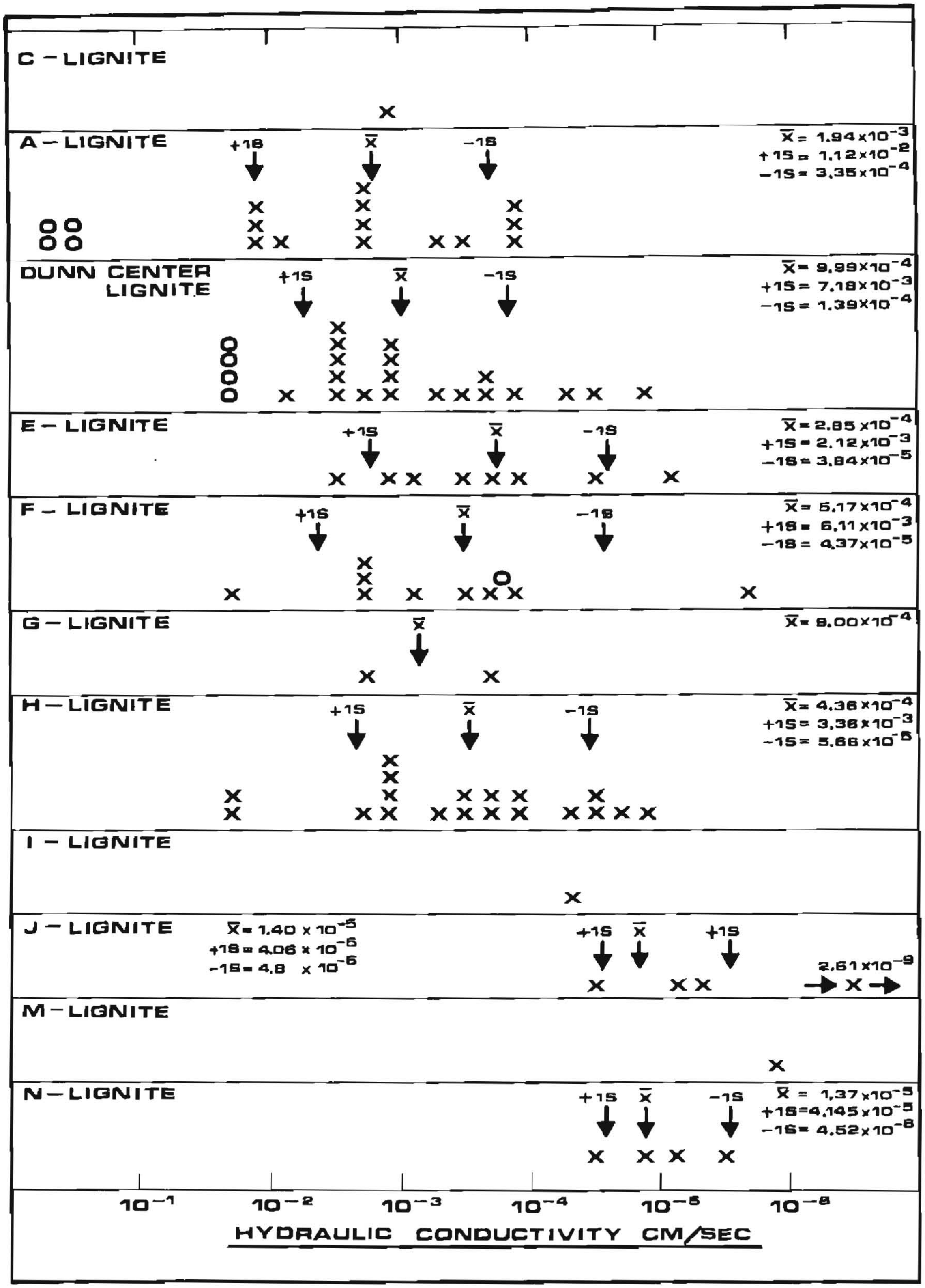


Figure 3.5.2-1 Frequency distribution of hydraulic conductivity data for lignite aquifers in the Dunn Center area. Logarithmic mean X̄, and standard deviation, s, shown for each unit; +1s and −1s indicates values one standard deviation greater and less than the mean. Values determined by single-well response test shown by X. Values from pumping tests shown by 0.

x 10^{-1} cm/sec (fig. 3.5.2-1).

Figure 3.5.2-2 is a map showing the distribution of values of hydraulic conductivity in the A-lignite.

Although much of the A-interval is sand and therefore acts as an aquifer, parts of the A-interval contain fine-grained material in some areas. Where saturated, the fine-grained material of the A-interval serves as an aquitard. The hydraulic properties of this part of the A-interval is probably similar to the underlying Dunn Center interval.

The Dunn Center interval is generally saturated and yields water to wells especially in the northern part of the project area where it is thick and contains considerable sand (pl. 2). In other areas, especially through the center of the project area, in Mine Area No. 1 where it is thin and fine-grained, the Dunn Center interval serves as an aquitard (pl. 1). Five values of hydraulic conductivity have been determined, two by the single-well response test method and three by the permeameter method. Values of hydraulic conductivity range from 1.7 x 10^{-5} to 1.86 x 10^{-3} for very fine sand, to 4 x 10^{-6} for silty sand and 2.4 x 10^{-8} for clayey silt (fig. 3.5.1-8).

3.5.3 Dunn Center Bed

The Dunn Center bed is an aquifer

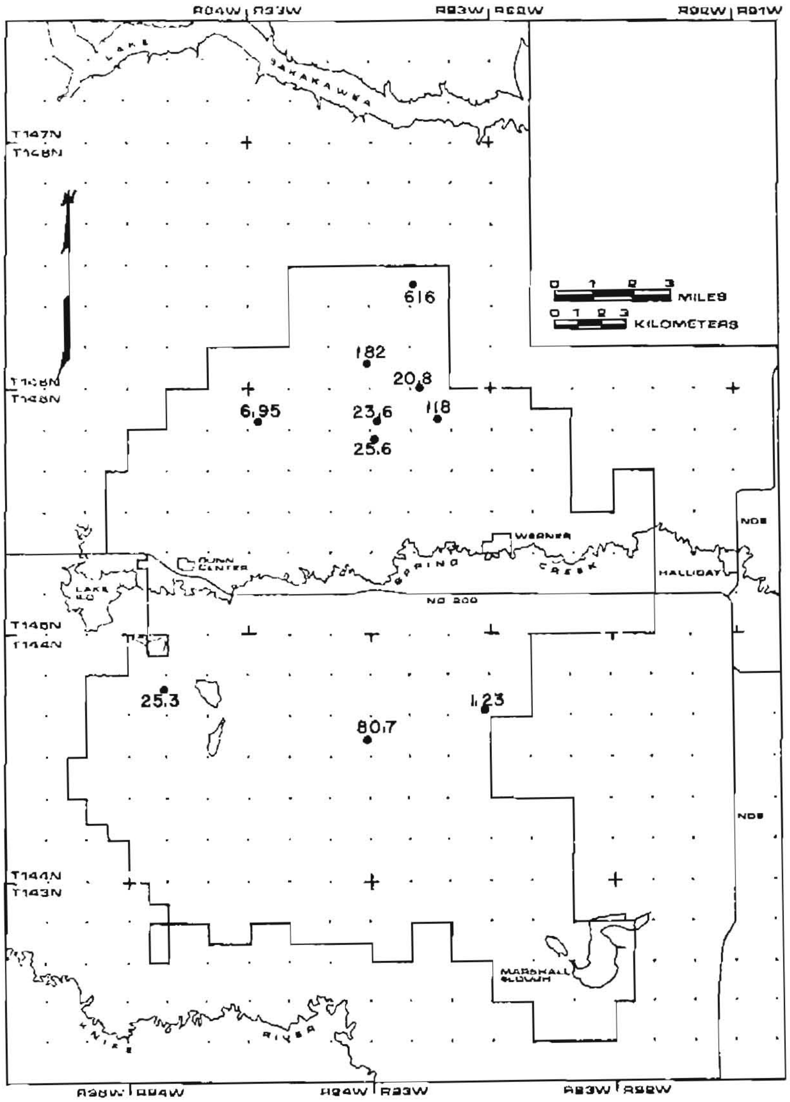


Figure 3.5.2-2 Map of the distribution of values of hydraulic conductivity, in cm/sec (x10^4), in the A-lignite, in the Dunn Center area.

throughout the project area and many wells are completed in it. The hydraulic conductivity of the Dunn Center bed, as determined in 19 single-well response tests, ranges from 1.49 x 10^{-5} cm/sec to 8.07 x 10^{-3} cm/sec with a mean of 1.38 x 10^{-3} cm/sec (fig. 3.5.2-1). Four determinations of the hydraulic conductivity were made in a long-term pumping test conducted by the North Dakota State Water Commission (Moran and others, 1976, app. C-VIII). These values ranged from 2.47 x 10^{-2} to 2.65 x 10^{-2} cm/sec. Figure 3.5.3-1 is a map of hydraulic conductivity in the Dunn Center bed.

3.5.4 Lower Part of Sentinel Butte Formation

The interval from the base of the Dunn Center bed to the top of the Bullion Creek Formation is treated here together because of the general similarity of both the hydrologic characteristics and the similar interbedding of aquifers and aquitards.

The principal aquifers in the lower part of the Sentinel Butte Formation are lignite beds. In some places, sand beds in various intervals are capable of applying small quantities of water to wells. A sand body in the E-interval in the middle of Mine Area No. 1 appears to be such an aquifer. This body trends east-northeast from site 19 through site 28 (fig. 3.2-1, pl. 3). A similar sand body is recognized trending east-southeast through the Dunn Center Municipal well and site 14 at the top of the I-interval (fig. 2.3.1.5-1, 3.2-1, pl. 3). This sand body is about 0.5 mile wide and as much as 60 feet thick. Throughout most of the project area, however, the intervals of clastic sediment between the lignite beds are composed of fine-grained sediment that serves as an aquitard.

The hydraulic conductivity values of lignite and sand aquifers as well as aquitards in the lower part of the Sentinel Butte Formation are summarized in figures 3.5.1-8 and 3.5.2-1. As was discussed above, the hydraulic conductivity generally decreases with increasing depth. Figures 3.5.4-1, -2, and -3 summarize the hydraulic conductivity values of the major, potential lignite aquifers in the lower part of the Sentinel Butte Formation.

3.5.5 Bullion Creek Formation—Upper Part

No wells are completed in this interval in the project area, and very little is known of its hydrologic properties. It consists of thin beds of fine-grained to very fine-grained sand and lignite interbedded with silt and clay.

The hydraulic conductivity of both sand and lignite beds is probably low, although a value of 1.74 x 10^{-4} cm/sec was determined for one sand bed in the interval by the single-well response method (fig. 3.5.1-8).

3.5.6 Bullion Creek Formation—Middle and Lower Part

This interval is similar to the upper part of the formation with the addition of several thick sand units throughout the interval and two thick lignite beds, the M- and N-lignites, at the top of the interval. No producing wells are completed in this interval in the project area. A single-well response test on an observation well completed in the M-lignite and a thick sand immediately overlying it gave a hydraulic conductivity of 1.42 x 10^{-6} cm/sec (figs. 3.5.1-8, 3.5.2-1). This value, which must be considered the maximum for the two beds, suggests that little water could be produced from this well. Three similar completions in the underlying N-lignite and a thick sand overlying it indicate the same conclusion. Hydraulic conductivity values on these wells ranged from 5.48 x 10^{-6} cm/sec to 4.69 x 10^{-5} cm/sec. A fourth well completed in the N-lignite gave a value of 1.02 x 10^{-5} cm/sec (fig. 3.5.2-1).

3.5.7 Cannonball Formation

No hydrological data are available on the Cannonball Formation. However, on the basis of the data presented above, inferences about these properties can be drawn with considerable confidence. The dominant lithology of the Cannonball Formation in the project area is clay or silty clay. On the basis of permeameter tests presented above the hydraulic conductivity of these materials is no greater than 10^{-8} cm/sec and it may be less. The

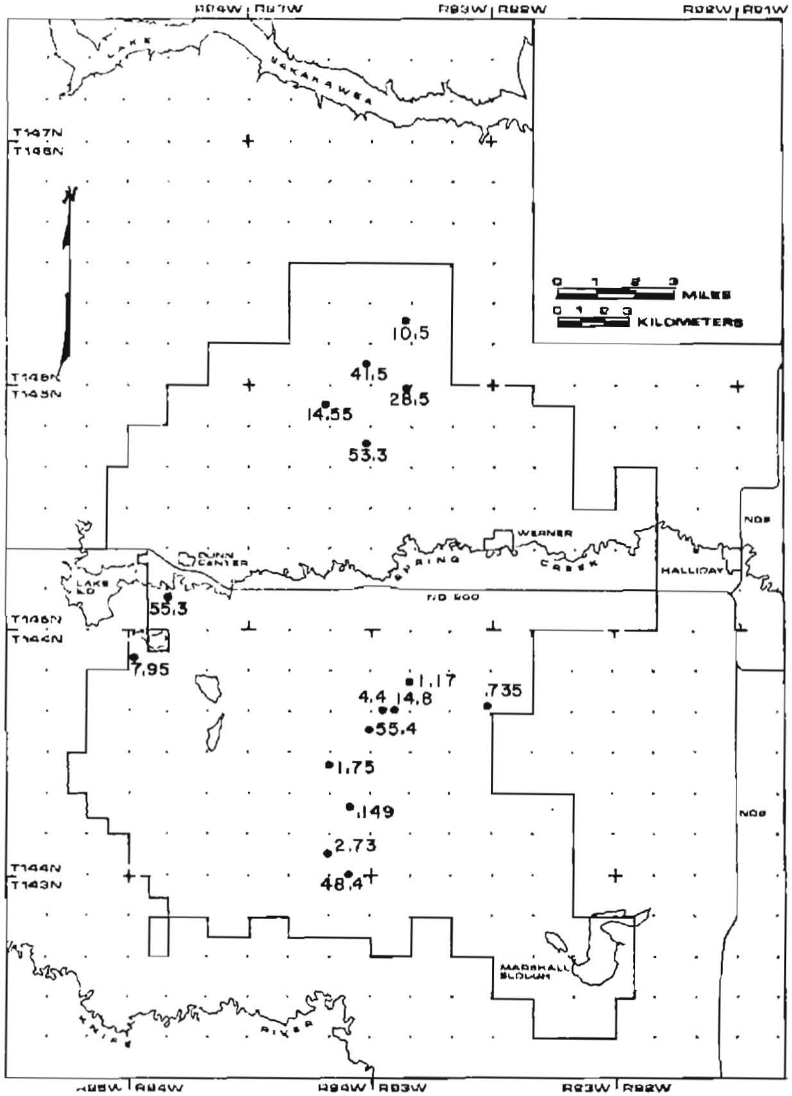


Figure 3.5.3-1 Map of the distribution of values of hydraulic conductivity, in cm/sec (x10^4), in the Dunn Center bed, in the Dunn Center area.

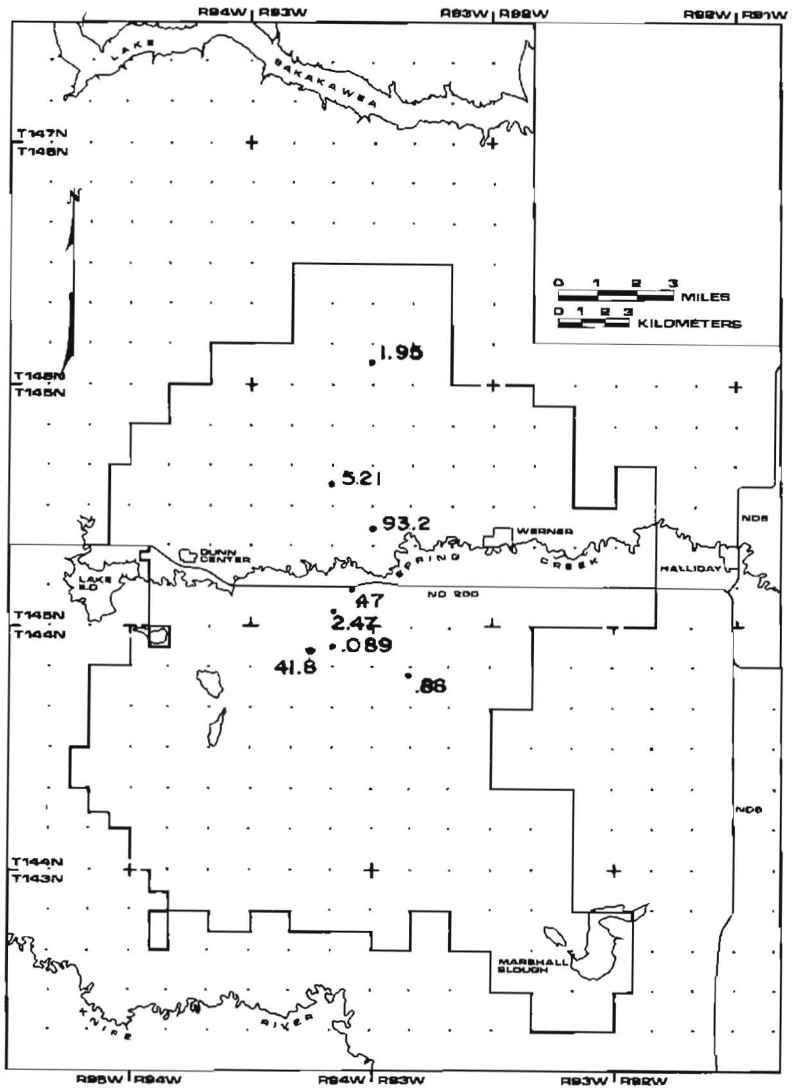


Figure 3.5.4-1 Map of the distribution of hydraulic conductivity, in cm/sec (x10^4), in the E-lignite, in the Dunn Center area.

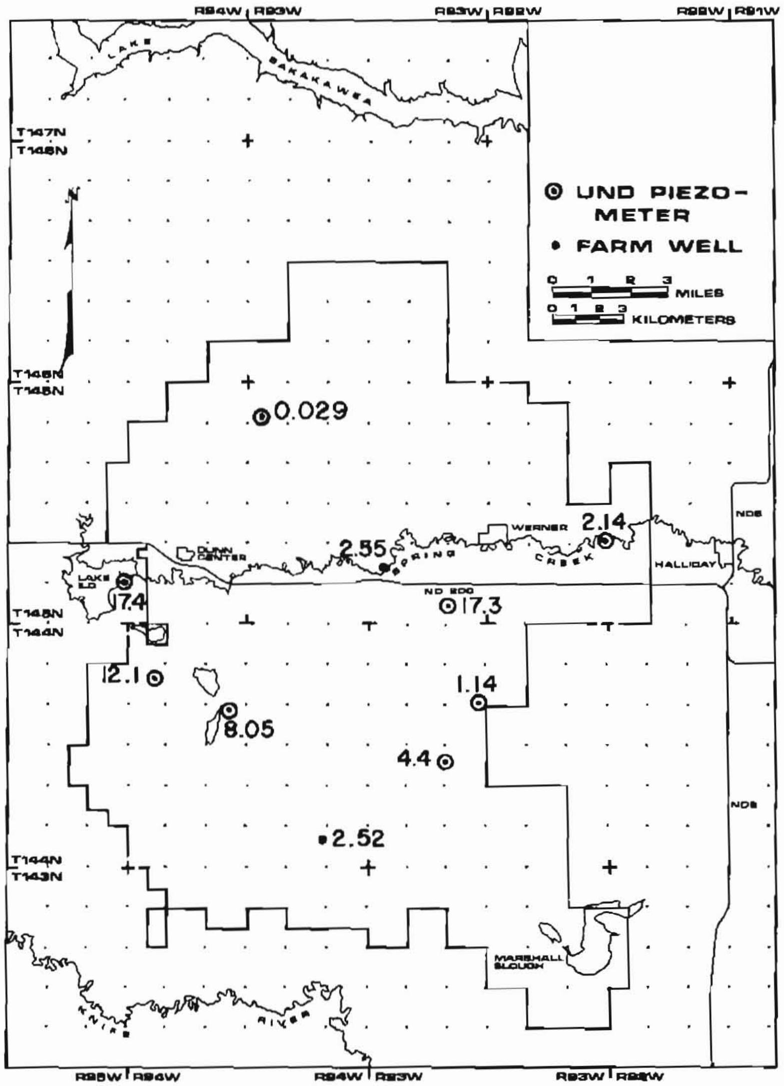


Figure 3.5.4-2 Map of the distribution of hydraulic conductivity, in cm/sec ($x10^4$), in the F-lignite, in the Dunn Center area.

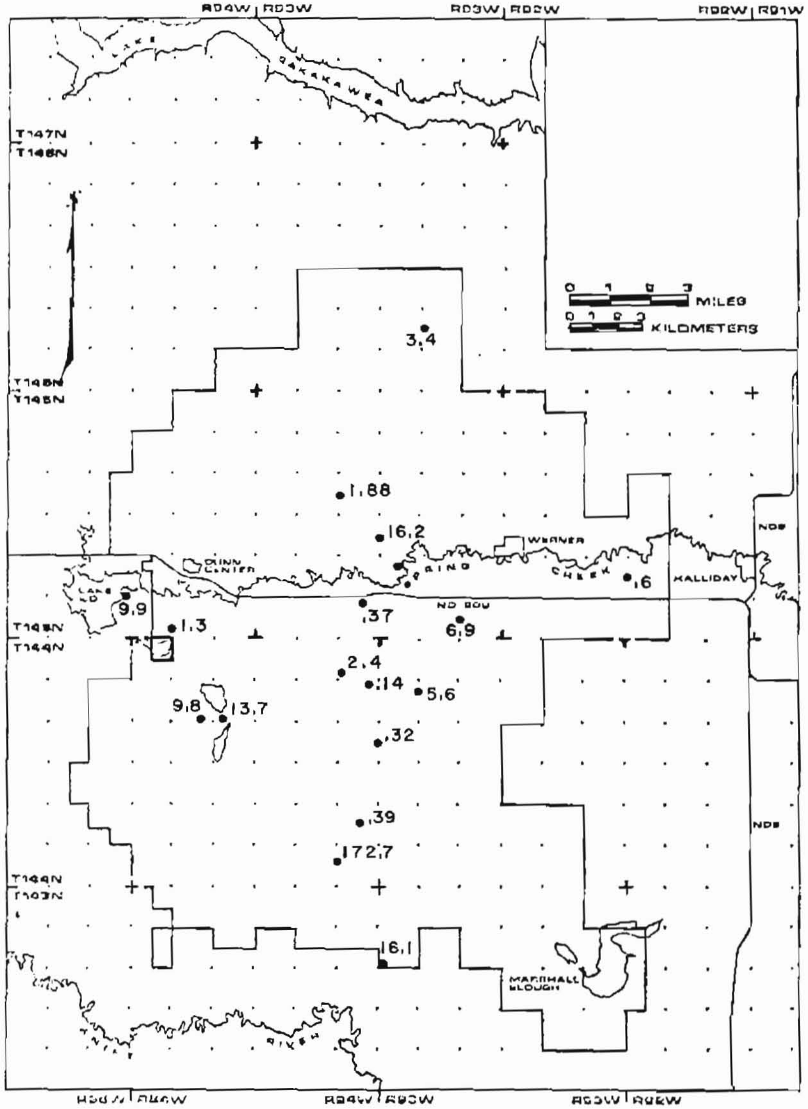


Figure 3.5.4-3 Map of the distribution of hydraulic conductivity, in cm/sec ($x10^4$), in the H-lignite, in the Dunn Center area.

sand or silty sand beds that make up the remainder of the formation are probably similar to those in the lower part of the Bullion Creek Formation and can be expected to have hydraulic conductivity no higher than 10^{-5} cm/sec. On the basis of these inferences, we consider it highly likely that the Cannonball Formation is a significant regional aquitard that isolates the overlying and underlying aquifers from one another.

3.5.8 Ludlow Formation and Hell Creek Formation—Upper Part

Nothing is known of the hydrologic properties of these formations. Because they consist of sediments very like the Sentinel Butte and Bullion Creek Formations and because of the great depth of burial, they are probably aquitards. On the basis of the relationship between depth and hydraulic conductivity that was established above, the lignite beds should have very low hydraulic conductivity, certainly no higher than 10^{-5} or 10^{-6} cm/sec. The sand beds may have hydraulic conductivity values similar to those in the lower part of the Bullion Creek Formation, 10^{-5} to 10^{-6} cm/sec.

3.5.9 Fox Hills Formation and Hell Creek Formation—Lower Part

This important regional system has been extensively studied immediately to the east of the project area in Mercer County (Croft and Wesolowski, 1970; Croft, 1973, p. 17-19, 25-35). It consists of two or three sand bodies that are 20 to 50 feet thick in the lower part of the Hell Creek Formation and upper part of the Fox Hills Formation. Several wells north of the project area, along the Little Missouri River valley, are completed in this interval. All of these wells flow. The municipal well in Halliday is completed in this interval. Two additional municipal wells were drilled to the Fox Hills-Hell Creek aquifer during the summer of 1975, one in Dunn Center and the other east of the project area at Dodge. Neither of these wells was completed at the time field studies were terminated so no new information on the hydrological properties of the aquifer is available. Croft (1973, p. 27, 29) reported that hydraulic conductivity ranged from 7.2×10^{-4} cm/sec to 4.73×10^{-3} cm/sec. The aquifer in the project area consists of about 60 to 100 feet of sand in an interval of about 150 feet. Below this is another 100 to 150 feet of silt of the Fox Hills Formation that does not serve as an aquifer.

3.5.10 Pierre Formation

No new information on the hydrologic properties of the Pierre Formation has been developed during this study. It consists of montmorillonitic clay and is believed to have a very low hydraulic conductivity, probably at least as low as 10^{-10} cm/sec. The low hydraulic conductivity and great thickness of the Pierre Formation make it a very effective aquitard that isolates the aquifers in the Fox Hills Formation from permeable beds lower in the section.

3.6 Groundwater-Flow Systems

3.6.1 Introduction

The interpretation of the groundwater-flow systems is based on the stratigraphic framework presented in section 2.3, the hydraulic conductivity data presented in section 3.3, and on numerous other types of information including well-inventory data, water-level data from the UND and Water Commission wells, analyses of the isotopes, ^{18}O, ^{3}H, ^{13}C, and ^{14}C in well samples, groundwater chemistry data, and observation of surface features influenced by groundwater seepage. The first part of the flow system discussion presents the terminology and conceptual framework of groundwater-flow systems, followed by a flow system interpretation based on geologic and physical hydrologic data. This interpretation is then evaluated and expanded upon using the isotope data and then the water chemistry data. The final step in this section is an overall summary of the flow system characteristics. Although it has been appropriate in this section of the report to have some discussion of the effect of surface water on the groundwater regime, most of the material on surface water-groundwater interactions has been included in section 3.9.

3.6.2 Terminology and Conceptual Framework

Subsurface flow systems consist of two main components: the unsaturated zone and the groundwater zone. The unsaturated zone is above the water table and the groundwater zone below the water table. In practical terms, the water table is the level to which water will rise in wells placed just below the top of the zone that has positive pore-water pressure. Above the water table the pore water is under negative pressure; below the water table all pressures are positive. In this report, water in the unsaturated zone is referred to as soil moisture, although it may occur in the solum (the upper few feet that supports plant life) or in the underlying relatively unweathered geological materials. In some hydrogeological situations more than one water table occurs; in other words there can be a vertical sequence of saturated and unsaturated zones. These situations are generally not common, and when they do occur there is usually one permanent water table that extends as a continuum across the area with one or more minor discontinuous, transient water tables above it. These will be referred to as perched water tables. The unsaturated zone contains moisture, but because this water is under negative pressure (commonly referred to as suction) wells installed in this zone will be dry. Following periods of very heavy or long rainfall or rapid snow melt, downward infiltration of water from the ground surface into the unsaturated zone can cause part or all of this zone to become saturated under positive pressure for short periods of time as infiltration occurs, but it is normal to regard this within the context of flow in the unsaturated zone rather than the groundwater zone.

Before proceeding with discussion of subsurface flow systems in the Dunn Center area, it is necessary to define four additional terms: recharge area, discharge area, infiltration zone, and exfiltration zone. The first two terms refer to the nature of the water table zone, and the second two refer to the unsaturated zone. If groundwater flow has an upward velocity component at the water table, even if this component of the flow direction (vector) is small compared to the horizontal component, the area is referred to as a discharge area. If there is a downward flow component, it is a recharge area. Through the unsaturated zone in a recharge area, the net long-term flux of water is downward. This is called an infiltration zone. Unsaturated zones in discharge areas have a net long-term flux upward and are referred to as exfiltration zones. In some areas, entry or exit from groundwater flow systems occurs directly from the surface environment, at locations where the groundwater zone is joined directly to lakes, streams, marshes, sloughs, or ponds. In areas not affected by volcanic or geothermal activity, all groundwater and soil water is derived from rain and snow. The term groundwater age refers to the time that has gone by since the water infiltrated from the surface environment into the subsurface flow system.

3.6.3 Regional Water Table

The depth to the water table and the elevation of the water table are shown in figure 3.6.3-1 and -2. Except in major topographic lows the permanent water table in the area is relatively deep, ranging between about 30 to 70 feet below ground surface in most of the area. In the major topographic valleys, which are generally areas underlain by the Coleharbor Formation, the water table is at shallower depths and in some places, such as at Lake Ilo, the water table intersects the surface-water regime.

During test drilling, the apparent moisture conditions of the interior of larger cutting samples were noted along with the state of the borehole in terms of water loss. This information provided a rough estimate of the depth to the water table. In many cases, the geophysical logs were a good indicator of the water table depth. With these types of information it was feasible at many sites to install a well in the groundwater zone very close to the water table. The water levels measured in these wells are then a close measure of the actual water table. In some cases the uppermost well at a well nest remains dry even though tests show that the well is not plugged. These dry wells are therefore above the

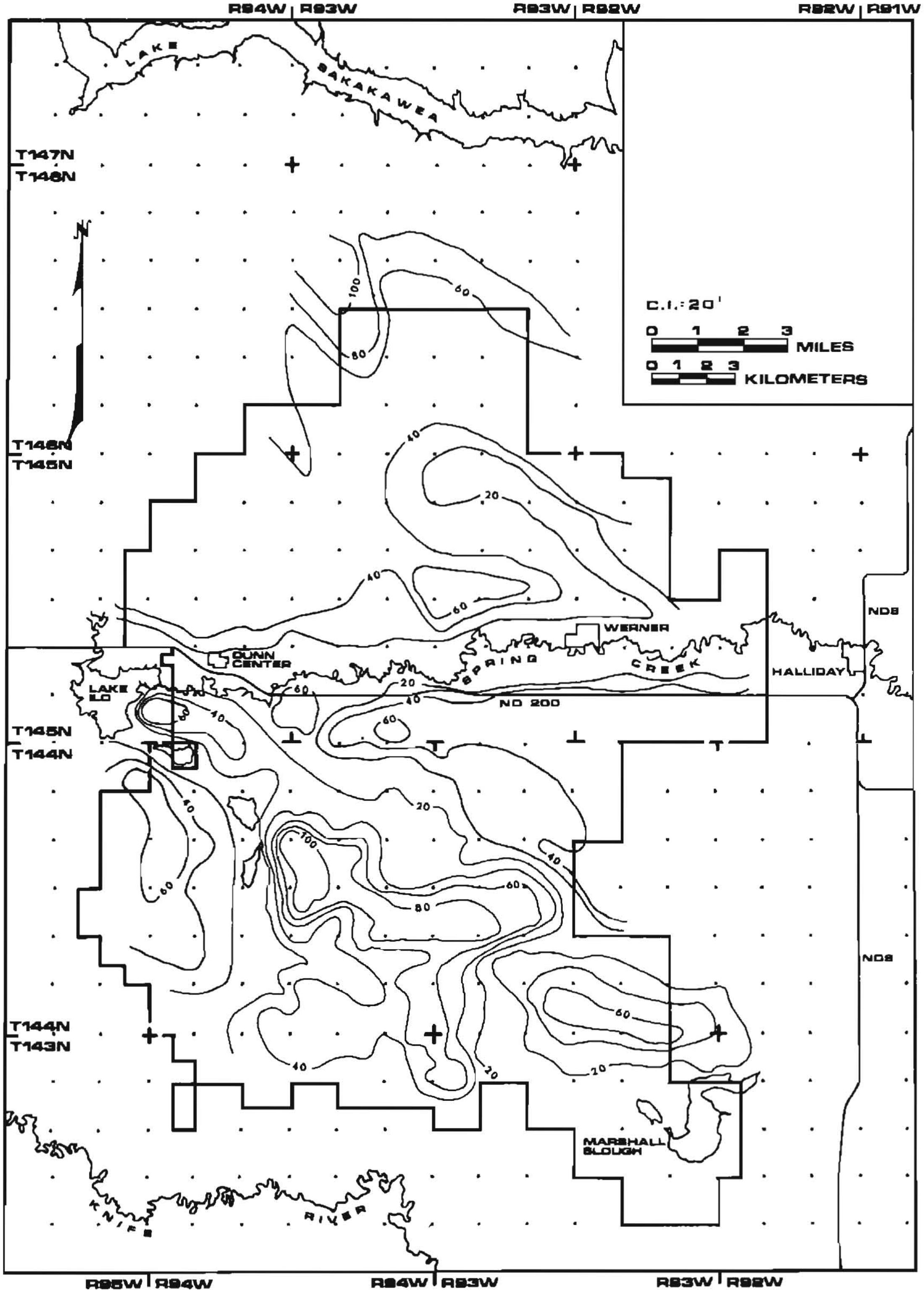


Figure 3.6.3-1 Map of the depths to main water table in the Dunn Center area.

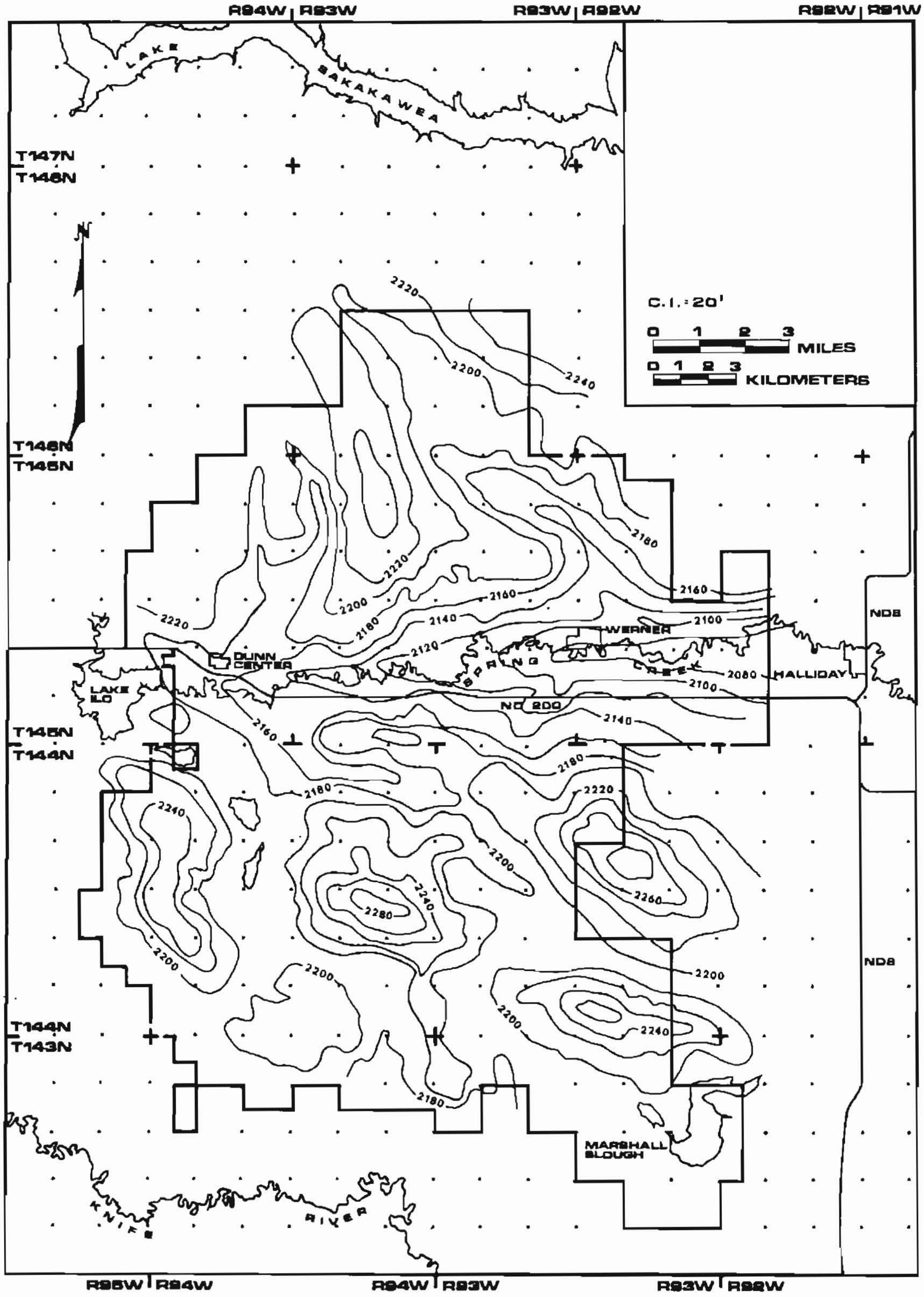


Figure 3.6.3-2 Map of elevation of regional water table in the Dunn Center area.

water table. In several cases, wells were set above what appeared to be the permanent water table to determine whether unsaturated zone or perched water table conditions occur. In preparation of figures 3.6.3-1 and -2 the contours between data points that were used are based on appraisal of the topographic setting, information from well drillers logs, and the stratigraphic setting. During the period of observation well measurement (August 1975 to February 1976) the water table levels varied by less than a few feet at nearly all observation sites. The map is based on representative data for this period.

The available subsurface data indicates that perched water table zones are relatively insignificant in nearly all of the study area. At the drill sites where cores were taken from above the permanent water table (fig. 1.4-2), visual examination of the cores indicated that saturated, positive pore-water-pressure conditions were probably not present.

There is one area, however, where evidence suggests that a significant perched water table zone occurs. It is located beneath the upland area between the valley at the proposed plant site and the Spring Creek valley. Its occurrence is suggested by water level data from the wells at sites 5 and 14 which indicate that there is a water table in the A-lignite at site 14. The regional water table in this area is probably caused by silt and clay beneath this lignite aquifer. The silt and clay aquitard would be expected to severely restrict downward seepage into the sand aquifer below. With restricted vertical recharge and higher lateral outflow from the sand aquifer, much of the aquifer would remain unsaturated.

3.6.4 Hydraulic Head Distribution

The water level data from wells in the Sentinel Butte and Bullion Creek Formations has been grouped for presentation into seven maps: (1) the A-lignite (fig. 3.6.4-1); (2) the Dunn Center bed (fig. 3.6.4-2); (3) the E-interval including the E-lignite (fig. 3.6.4-3); (4) the F- and G-intervals including the F- and G-lignites (fig. 3.6.4-4); (5) the H-interval including the H-lignite and the upper part of the I-interval (fig. 3.6.4-5); (6) the J-interval including the J-lignite and the uppermost part of the Bullion Creek Formation (fig. 3.6.4-6); and (7) the M- and N-intervals including the M- and N-lignite and the lower part of the Bullion Creek Formation (fig. 3.6.4-7). These maps present water level data from the UND observation wells (fig. 3.2-1) and selected inventory wells. Inventory wells with both high quality drillers logs, which permitted identification of the stratigraphic position of the intake zone, and reliable water level data were used. The units that were grouped on each map were selected on the basis of apparent hydrologic consistency of the data, hydrologic importance of the intervals, and adequate geographic distribution of data points to provide a meaningful hydrologic picture. Considerable data are available from other units, such as the Dunn Center interval and the A-interval; but it has not been summarized on maps, both because it lacks adequate geographic distribution being largely concentrated in small areas and because it adds little meaningful hydrologic data not shown in maps of overlying or underlying units.

Figures 3.6.4-8 and 3.6.4-9 show the hydraulic head levels along cross sections of A-A' and B-B' which traverse north-south and east-west through the study area. Figures 3.6.4-10, 3.6.4-11, 3.6.4-12, 3.6.4-13, and 3.6.4-14 show the hydraulic head values along local cross sections in and near valley fill areas. In the interpretation of this data, the regional trends are discussed first, and then some of the local features are considered in more detail.

Figures 3.6.4-8 and 3.6.4-9 indicate that with the exception of the valley fill zones and shallow zones in some of the other lowlands there is a dominant trend of decreasing hydraulic head values with greater depth below ground surface. This progressive downward decrease in water level from well to well is shown, for example, by the seven wells at UND site 75-30. The water table well, which is 35 feet deep, had a water level of 2240.5 feet. Farther below ground surface the water levels were lower in each successively

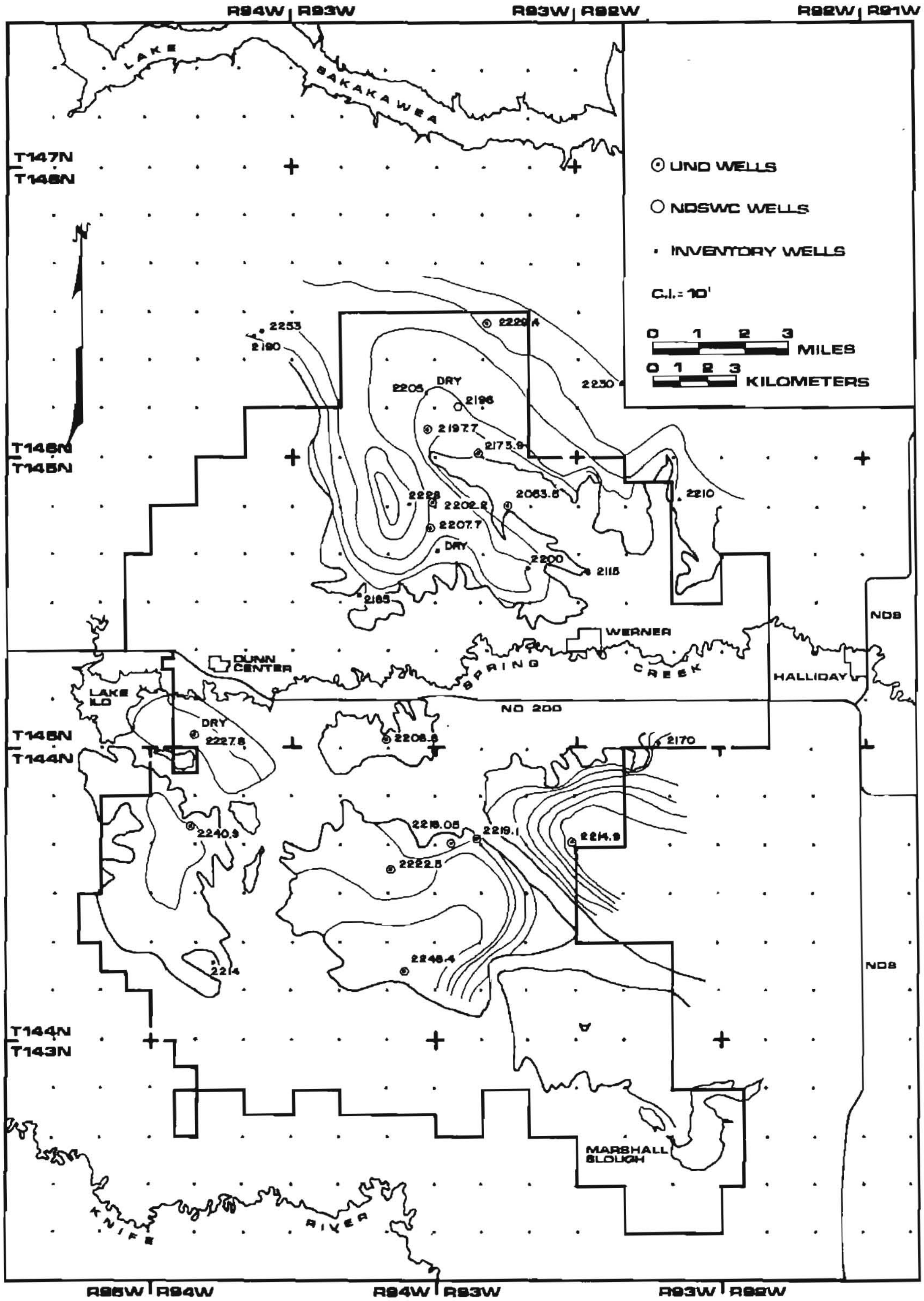


Figure 3.6.4-1 Map of the elevation of the potentiometric surface of the A-lignite .

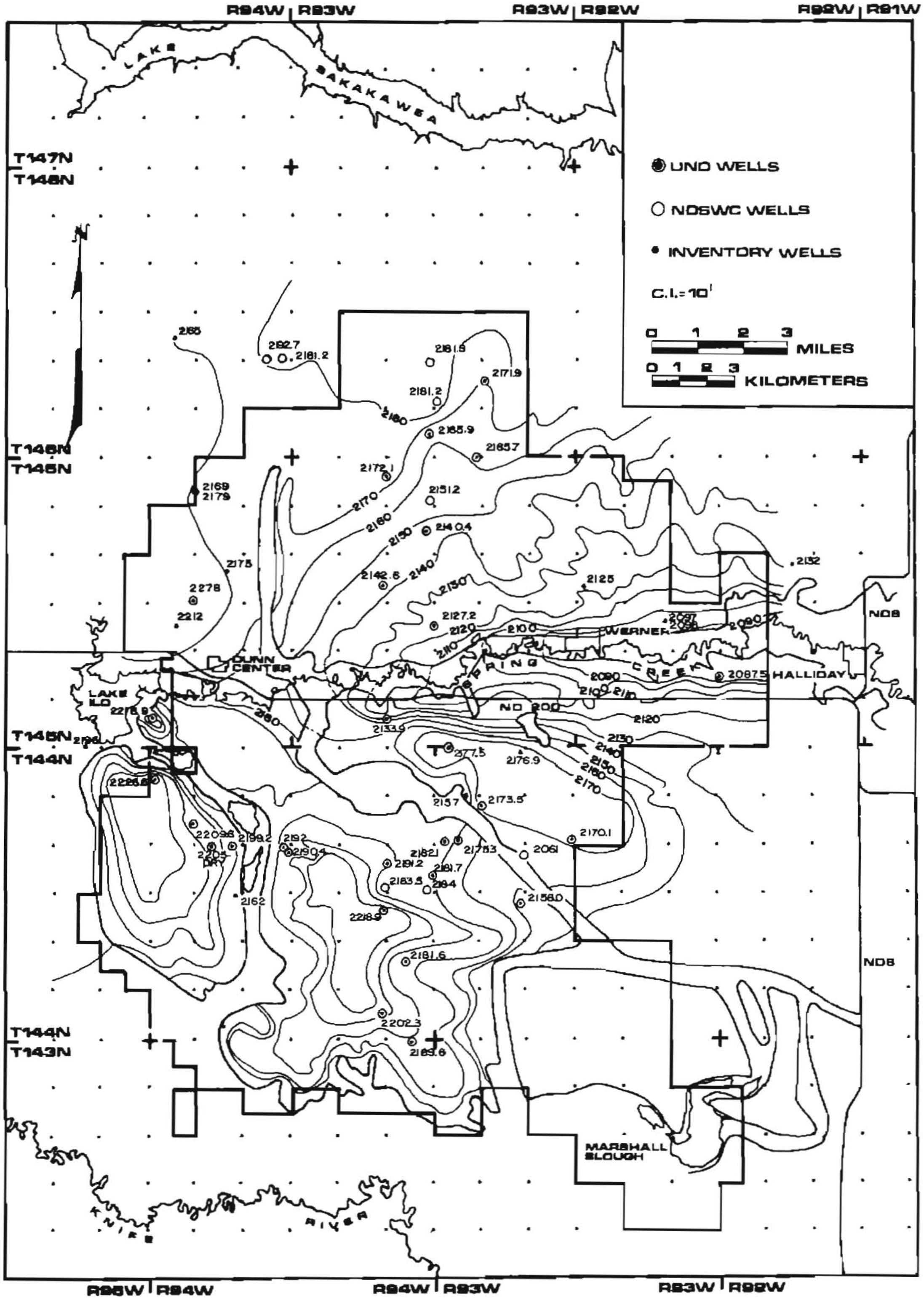


Figure 3.6.4-2 Map of the elevation of the potentiometric surface of the Dunn Center bed.

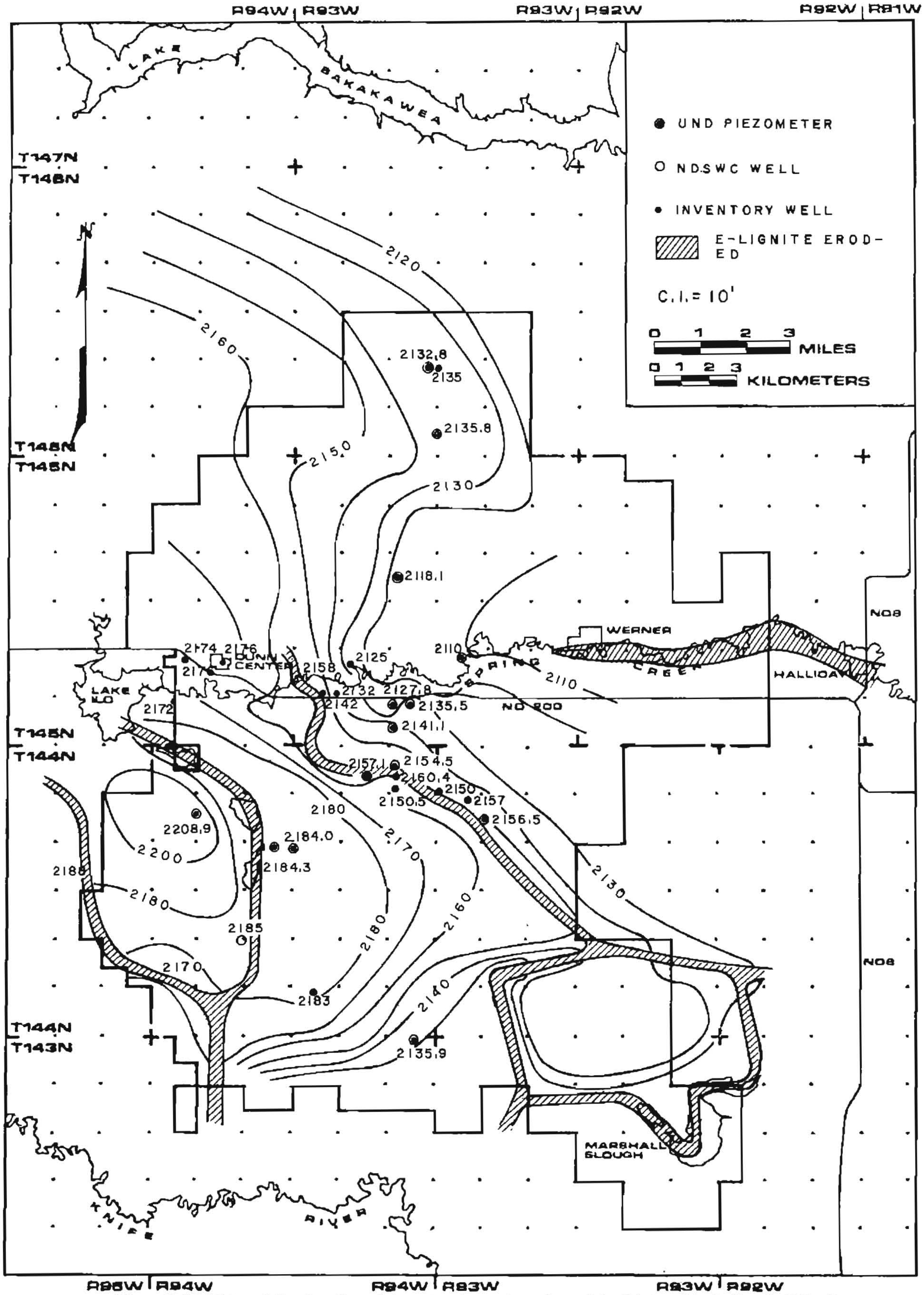


Figure 3.6.4-3 Map of the elevation of the potentiometric surface of the E-interval including the E-lignite.

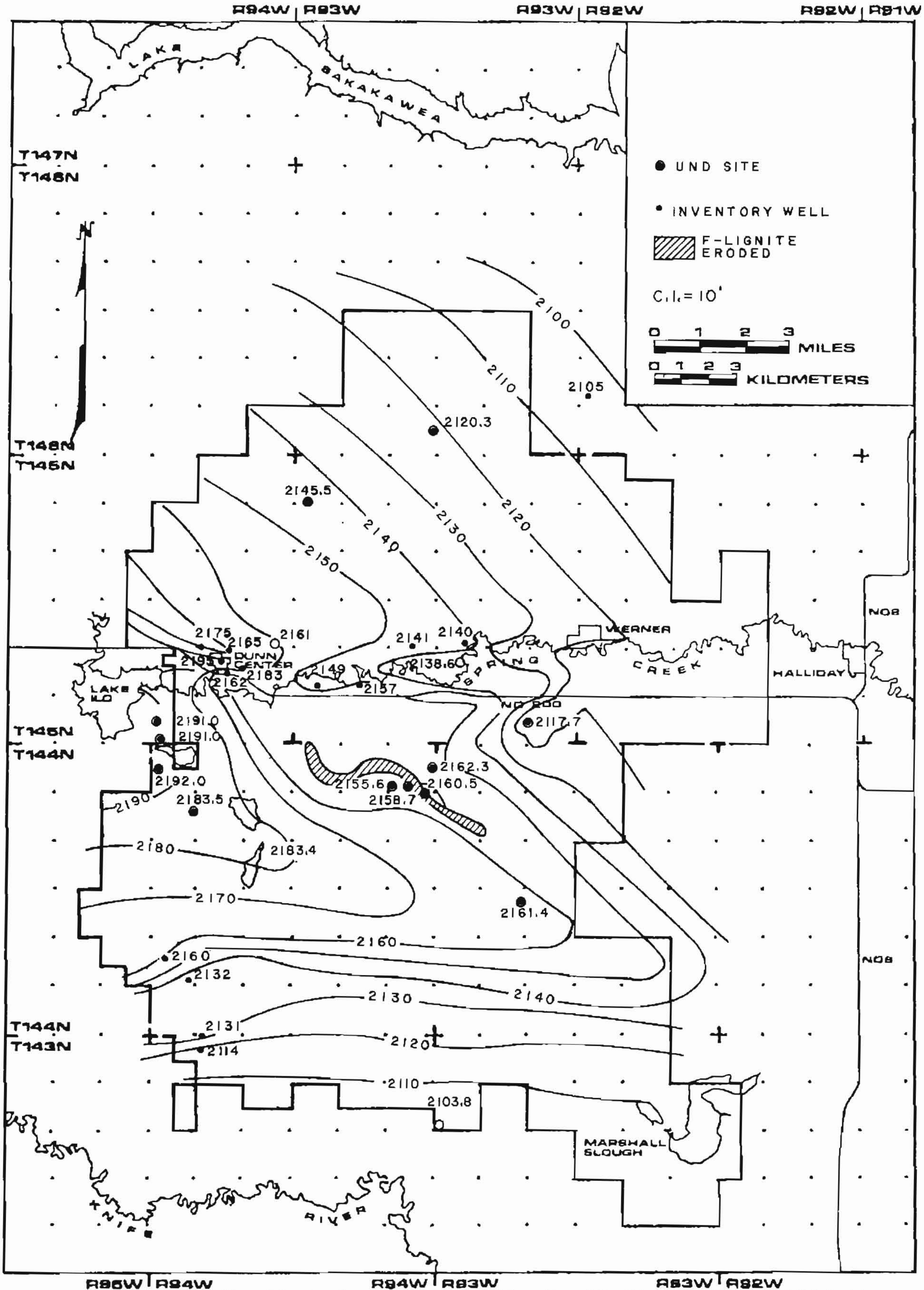


Figure 3.6.4-4 Map of the elevation of the potentiometric surface of the F-interval, F-lignite, and G-interval.

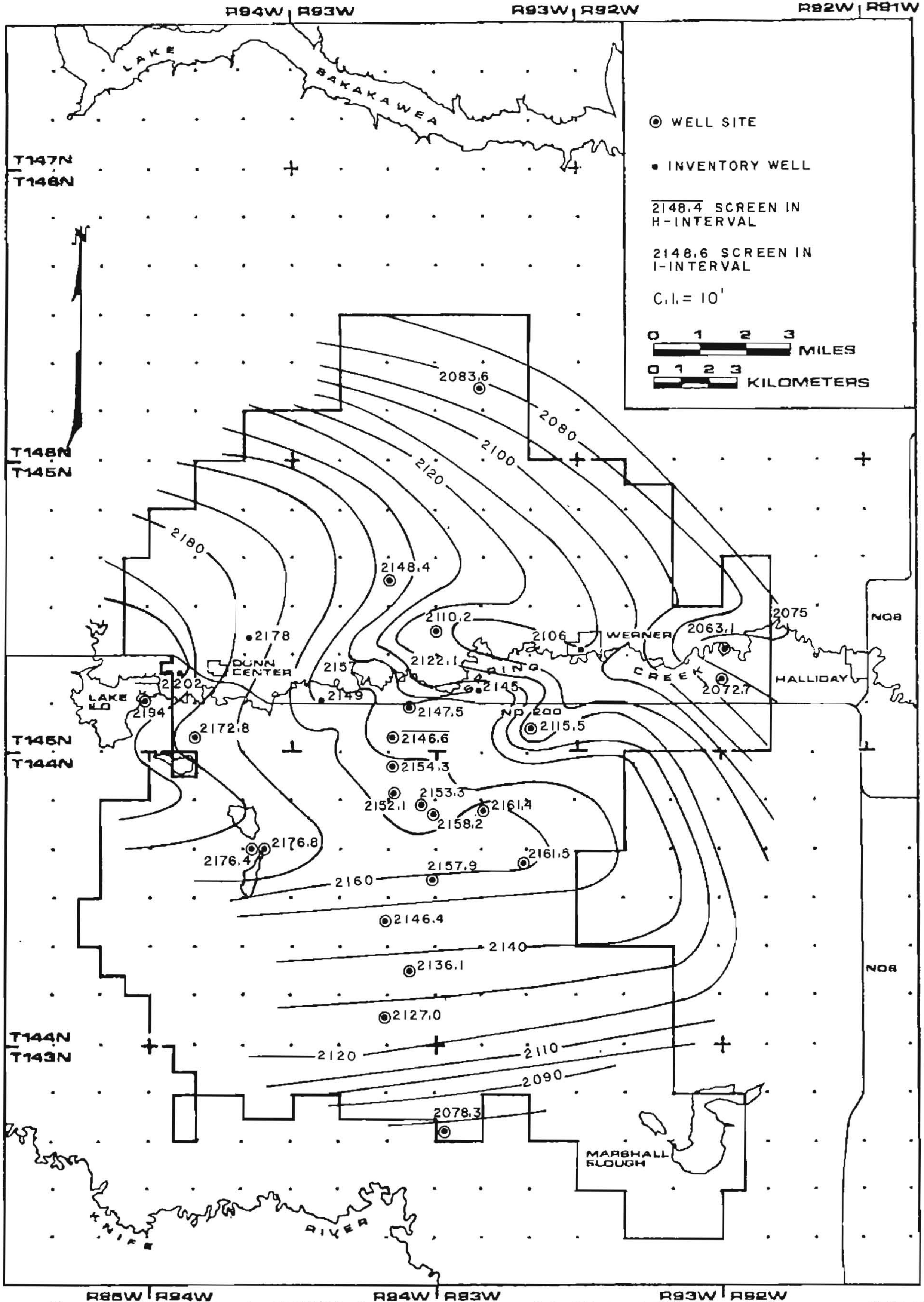


Figure 3.6.4-5 Map of the elevation of the potentiometric surface of the H-interval, H-lignite, and the upper part of the I-interval.

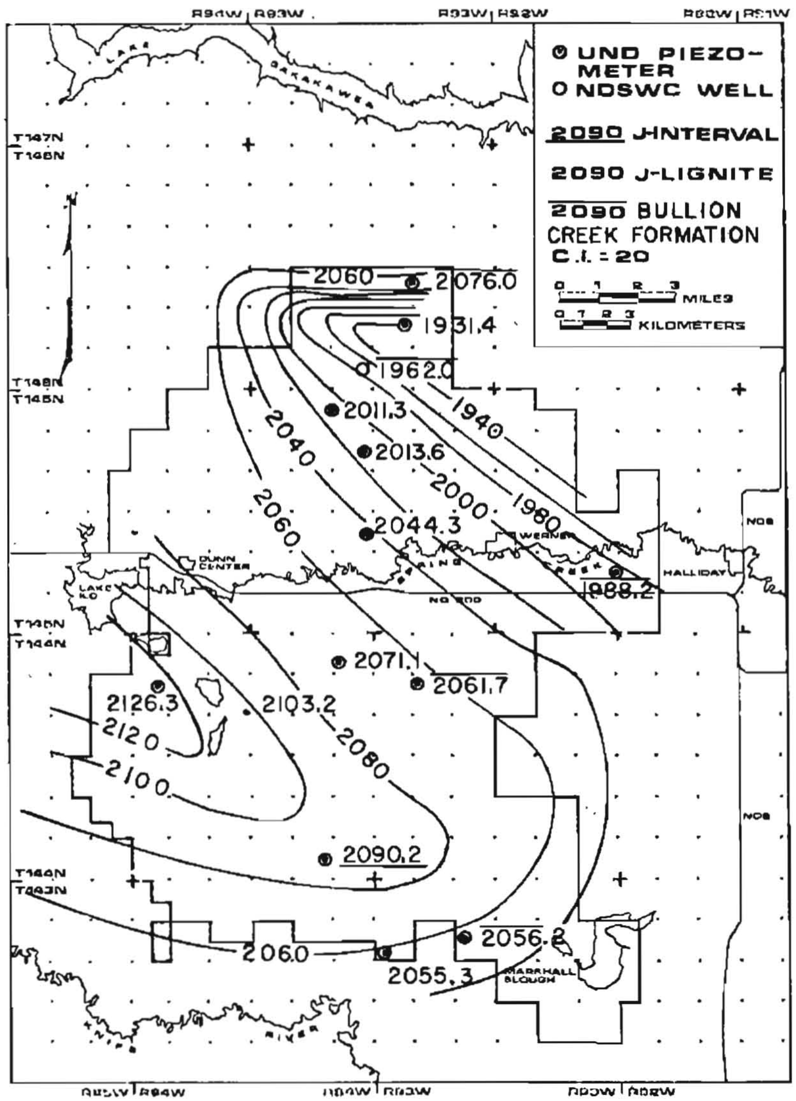


Figure 3.6.4-6 Map of the elevation of the potentiometric surface of the lower part of the Sentinel Butte Formation and the upper part of the Bullion Creek Formation.

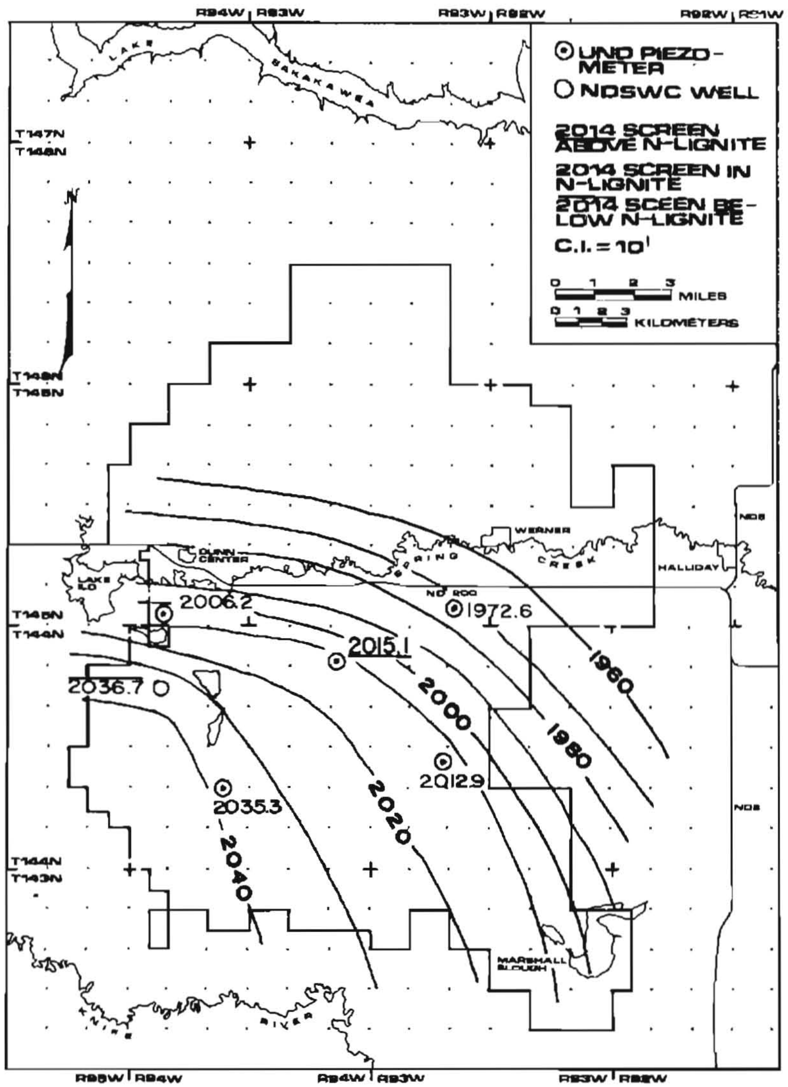


Figure 3.6.4-7 Map of the elevation of the potentiometric surface in the middle and lower part of the Bullion Creek Formation.

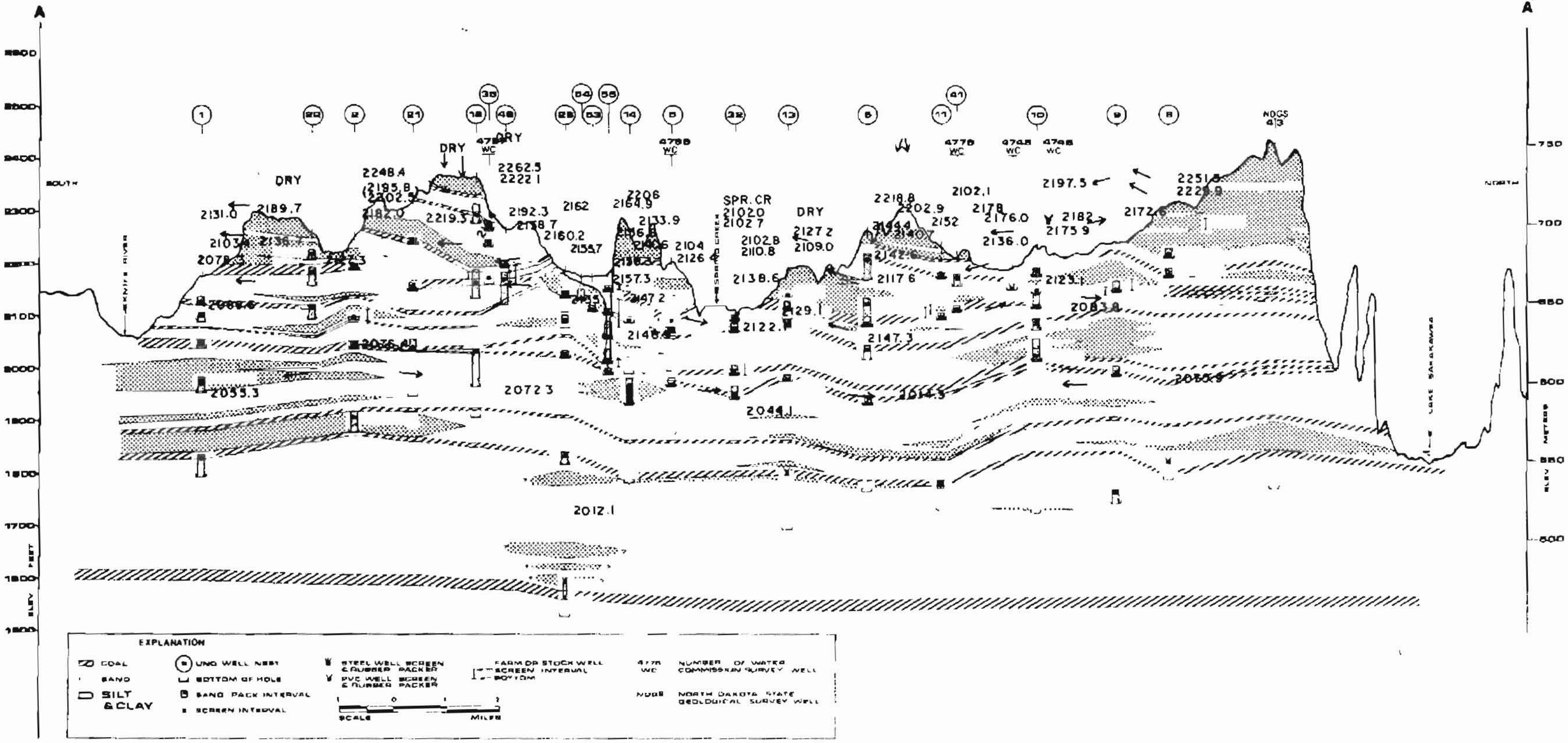


Figure 3.6.4-8 Hydraulic head distribution from observation wells and estimated flow direction components along cross section A-A'. Location of the cross section shown on figure 2.1.10-2.

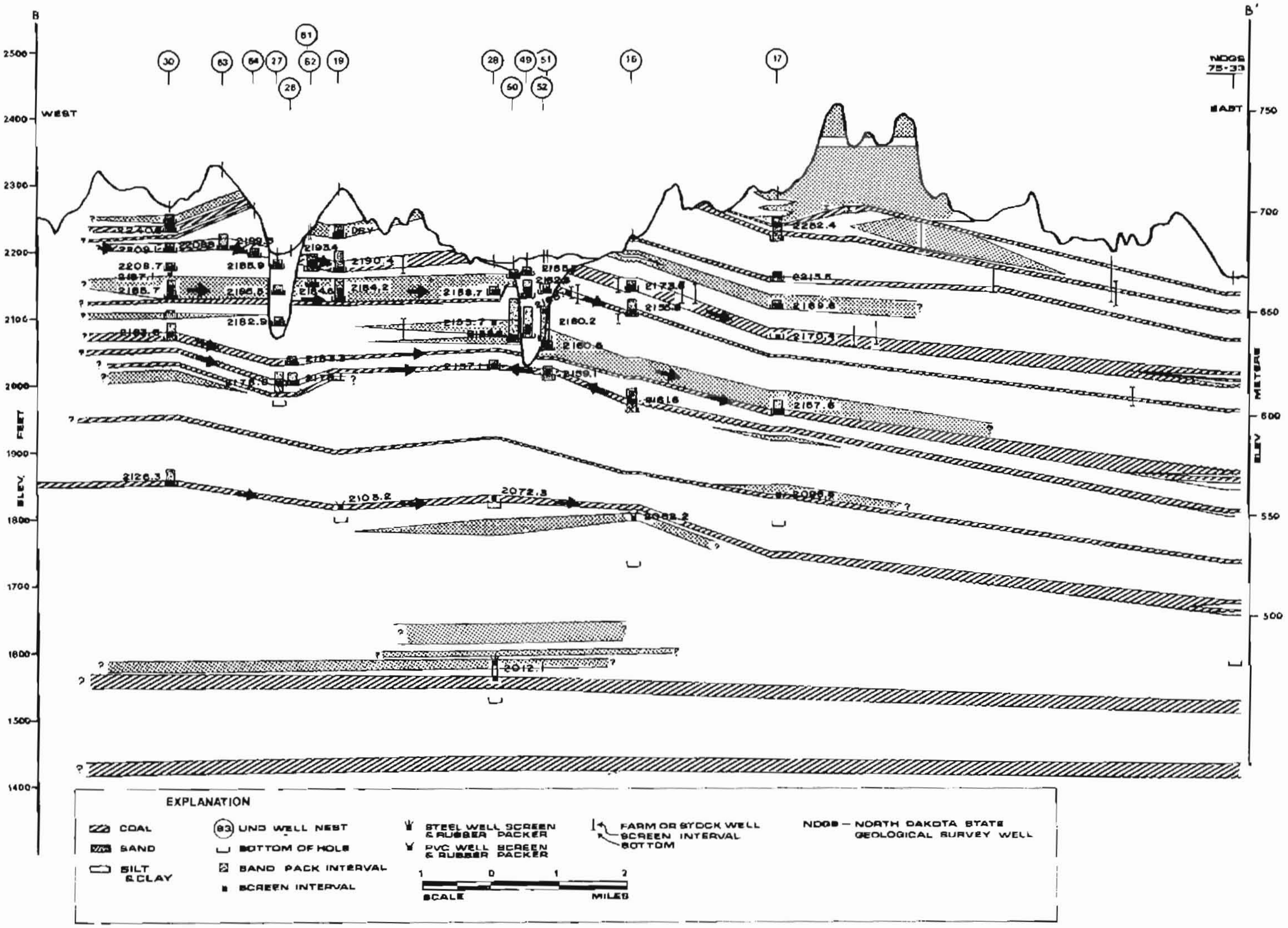


Figure 3.6.4-9 Hydraulic head distribution from observation wells and estimated flow direction components along section B-B'. Location of the cross section shown on figure 2.1.10-2.

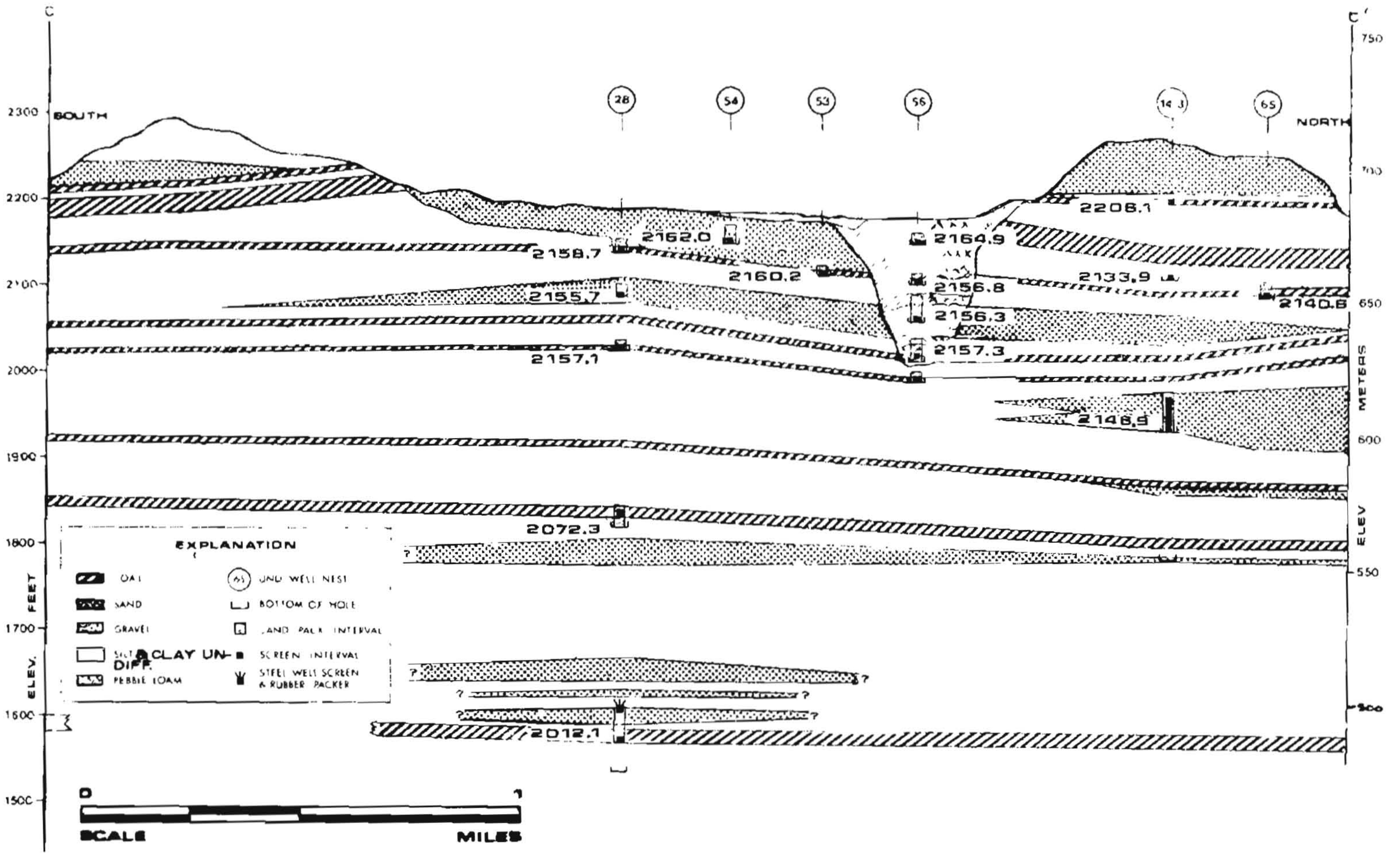


Figure 3.6.4-10 Hydraulic head distribution from observation wells along cross section C-C'. Location of the cross section shown on figure 2.1.10-2.

Figure 3.6.4-11 Hydraulic head distribution from observation wells along cross section D-D'. Hydraulic conductivity values times 10^{-4} cm/sec. Location of the cross section shown on figure 2.1.10-2.

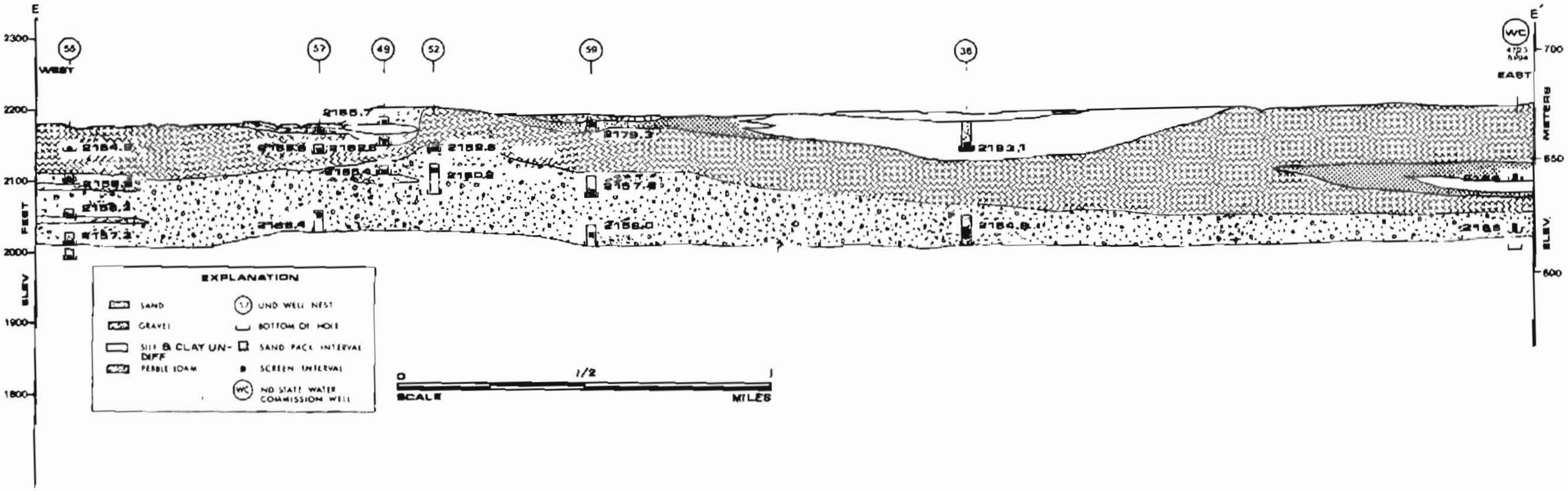


Figure 3.6.4-12 Hydraulic head distribution from observation wells along cross section E-E'. Hydraulic conductivity values times 10^{-4} cm/sec. Location of the cross section shown on figure 2.1.10-2.

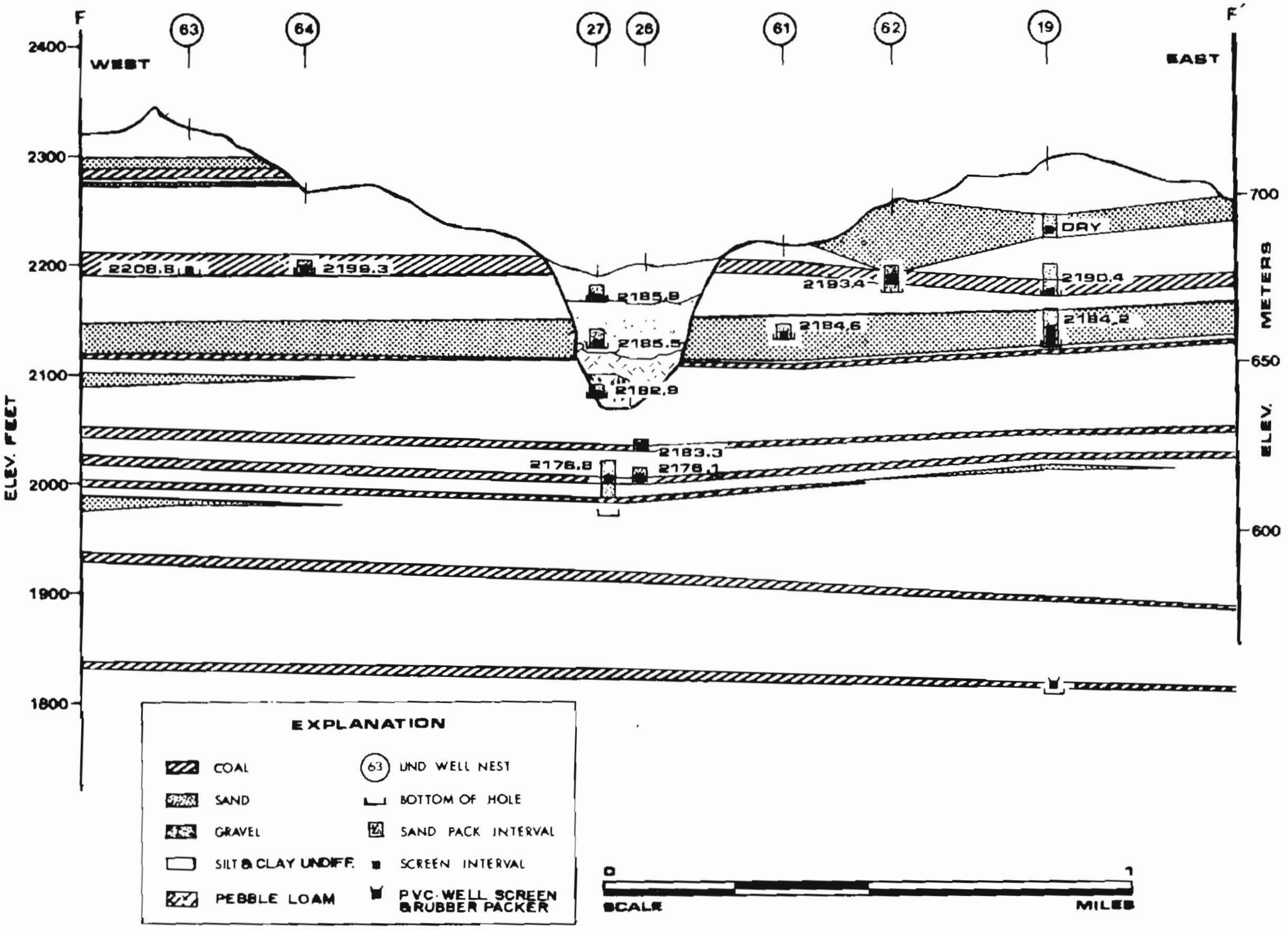


Figure 3.6.4-13 Hydraulic head distribution from observation wells along cross section F-F'. Hydraulic conductivity values times 10^{-4} cm/sec. Location of the cross section shown on figure 2.1.10-2.

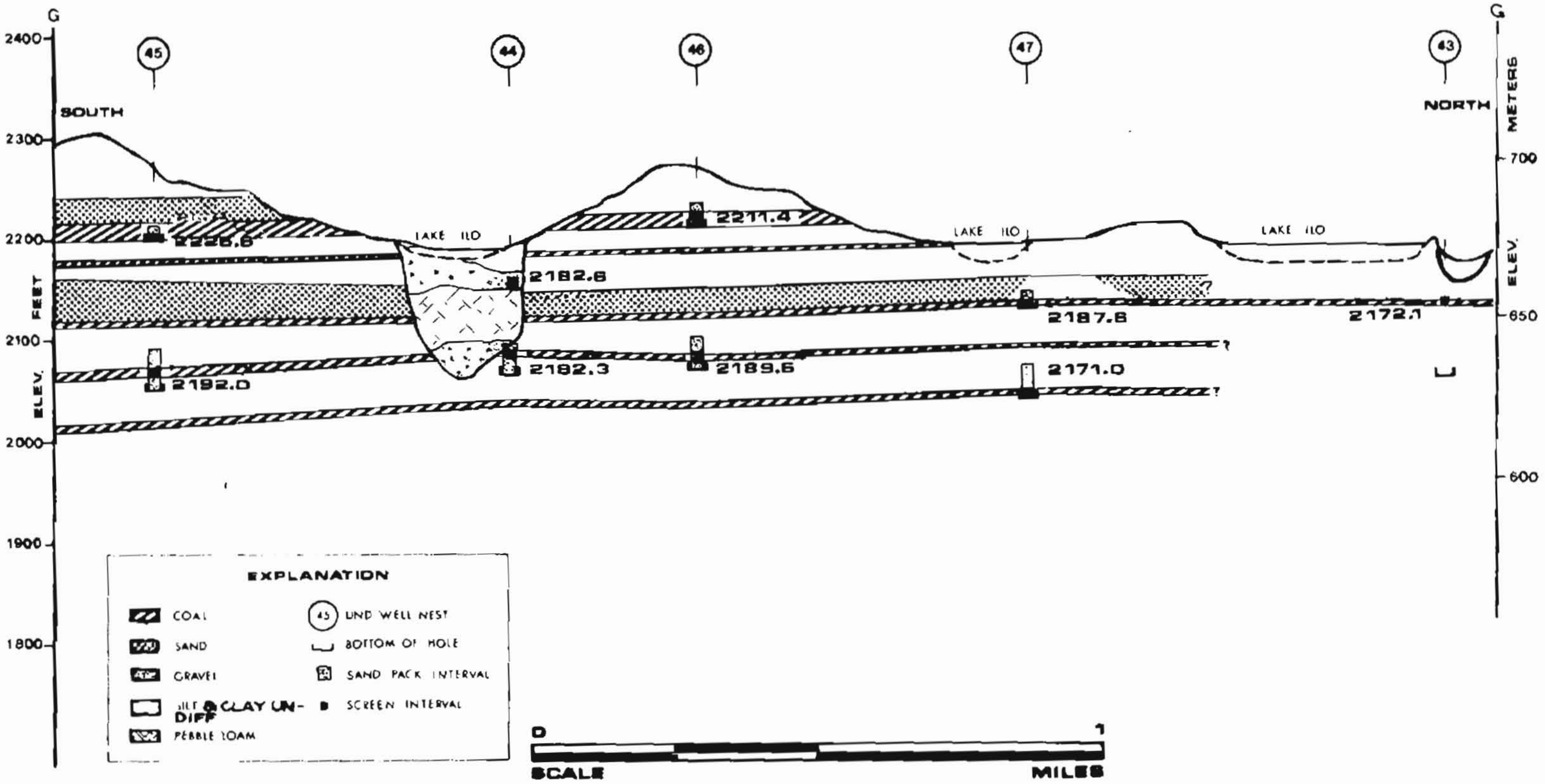


Figure 3.6.4-14 Hydraulic head distribution along cross section G-G'. Hydraulic conductivity values times 10^{-4} cm/sec. Location of the cross section shown on figure 2.1.10-2.

deeper well. The well at 411 feet below the ground surface had a water level of about 2126 feet. The deepest well at the site, which is 970 feet deep had a water level of about 2037 feet.

In general, the lowest hydraulic head values occur in the middle and lower part of the Bullion Creek Formation where they range from about 2040 feet to less than 1960 feet (fig. 3.6.4-7). All head values in aquifers and aquitards above the I-interval are greater than 2060 feet. In these zones, most water levels are above 2100 feet.

Although very little data is available in the Dunn Center area, regionally, it appears that the pattern of decreasing hydraulic head with increasing depth is reversed in the Fox Hills-Hell Creek aquifer. Hydraulic head values in wells drilled into these aquifers are generally very near the land surface and, in many areas, are considerably above the land surface. These hydraulic head data support the conclusion of section 3.5.7 that the Cannonball Formation serves as a regional aquitard that effectively isolates the aquifers in the Fox Hills and Hell Creek Formations from those in the Bullion Creek and Sentinel Butte Formations.

The Little Missouri River valley cuts down through the Sentinel Butte Formation to just below the I-lignite. The Knife River valley extends down to about the interval of the H-lignite. The trend of deeper water levels in deeper wells in the Sentinel Butte Formation is caused by the drain effect of the Little Missouri and Knife River valleys on the layered sequence of lignite aquifers. The Little Missouri valley, of course, exerts the strongest effect because it cuts much deeper into the aquifer-aquitard system. The regional drain, the Missouri River about 80 miles east of the project area, is responsible for the still lower heads in the Bullion Creek Formation. Inspection of the potentiometric maps (figs. 3.6.4-1 to -7) suggests that the influence of local topography on the potentiometric surfaces generally decreases with increasing depth in the stratigraphic system. The potentiometric surface of the A-lignite (fig. 3.6.4-1) is controlled by the local outcrop positions of this aquifer, the local topography, and the structure of the bed. In general, the potentiometric surface reflects the position and shape of the main topographic uplands in the area. The potentiometric surface of the Dunn Center bed (fig. 3.6.4-2) is a relatively complex surface influenced by the position of the main uplands, the intersection of the bed with the valley fill deposits, and the structure of the bed. The Spring Creek lowland is strongly reflected in the potentiometric surface in the central part of the study area.

The potentiometric surface of the E-interval (fig. 3.6.4-3) has an appreciable eastward slope with some significant distortions caused by the influence of the Spring Creek lowland and a few but not all of the major topographic uplands. It is somewhat surprising that the potentiometric surface for this aquifer does not show a strong northward slope toward the Little Missouri valley in the northern half of the area and a general slope southward toward the Knife River lowland in the southern part of the area. Although the number of data points are sparse in much of the area, it appears that the Spring Creek lowland and other topographic trends are a major influence.

The drain effect of the Little Missouri and Knife River valleys, along with the Spring Creek lowland, are strong influences on the potentiometric surface of the F-G interval and the potentiometric surface of the H-interval and upper part of the I-interval (figs. 3.6.4-4 and 3.6.4-5).

Although the number of data points is insufficient for development of an extensive piezometric surface map, figure 3.6.4-7 suggests that the influence of the Knife River lowland on the hydraulic head distribution in the middle and lower Bullion Creek Formation is not very significant and that the influence of the Little Missouri River valley is much weaker than on aquifers in the Sentinel Butte Formation. This would be expected since the middle and lower parts of the Bullion Creek Formation are much below the bottoms of these two valleys.

The only hydraulic head values from the observation well network that may appear inconsistent in terms of the trends established from the rest of the well data were obtained from the 329-foot well at UND site 6. This anomaly shows up strongly on figure 3.6.4-8 where it is evident that the water level elevation of 2148.4 feet in this well in the H-lignite is more than 20 feet above the water levels in this aquifer in wells to the southeast at UND sites 13 and 32 and to the north at UND site 9. The water level is also much higher than the levels in wells in the F- and E-lignites above the anomalous zone and is much higher than the levels in the J-lignite below. The anomaly is therefore a zone of high hydraulic head which has no apparent basis for explanation. Chemical data, which are presented below, indicate that osmotic processes are not the cause. The validity of the water level data from the well was checked on two occasions by partially dewatering the well and observing the level return to the original level. A 500-foot-deep well that was installed in a stratigraphic testhole during the early part of the drilling program and subsequently ruptured was drilled out and then the hole filled with grout to insure that the borehole could not cause vertical connectivity between aquifers. Inspection of the well installation and completion record for the wells at site 6 indicates that the wells have good sand packs and grout seals. At the present time the most reasonable explanation for the anomalously high head values in the 329-foot well at this site involves the presumption that the H-lignite aquifer in this area is well connected hydraulically to zones of high head to the west. This interpretation has been used in preparation of the potentiometric surface shown in figure 3.6.4-4 which has a strong eastward slope across the northern part of the study area. A similar connection by means of a narrow 60-foot thick sand body in the upper part of the I-interval is known to be responsible for anomalously high head values in the H-lignite at UND site 5. It is also possible, although we consider it unlikely, that the high head value results from a break in the well in the sand above Dunn Center bed somewhere above 139 feet, where another well in the nest indicates a head of about 2144 feet.

3.6.5 Flow Patterns and Velocities

Groundwater moves in response to total head gradient, which is the combined effect of mechanical, chemical, and thermal energy gradients. However, it can be shown that because of the low temperature and concentration gradients in groundwater regimes such head at any point in the flow system is a measure of the mechanical energy per unit mass of the water at that point. Groundwater flows in the same general direction as the hydraulic head gradient, but because of directional properties of the permeability, the flow may be at some angle less than 90 degrees to the gradient rather than parallel to the gradient. This directional effect of permeability on the flow line is referred to as anisotropy. Because the degree of anisotropy in the aquifers and aquitards in the study area is not known, and, because local variations in texture and structure of the aquifers and aquitards can cause deviations and distortions in groundwater flow paths, flow lines have not been drawn on the piezometric maps and cross sections. In a few areas where clear hydraulic gradient trends are particularly evident, interpretations of the general groundwater flow directions have been indicated on the diagrams by small arrows. It should be kept in mind that these flow direction indicators do not account for whatever anisotropic or local textural or structural features may be present in the system. It should also be noted that on the cross sections, the flow direction indicators can only suggest the component direction of flow in the plane of the cross section, and that in some areas, the dominant component is in some other plane, since the flow system is a three-dimensional entity.

Below the Dunn Center bed and in some areas above it, the groundwater flow pattern in the bedrock is characterized by primarily vertical flow in the aquitards and mainly lateral flow in the lignite and sand aquifers. As indicated previously, the hydraulic-head values decrease with depth at most sites, which in the stratigraphic setting of the Dunn Center area indicates that flow across the aquitards is generally downward. A major exception to this generalization occurs beneath the Spring Creek lowland where the flow in the aquitards in the F- and E-interval is upward as illustrated in figure 3.6.4-8.

The occurrence of lateral-flow aquifers between vertical-flow aquitards can be considered at least semi-quantitatively in terms of flow rates and mass balance considerations. Lateral seepage fluxes (volume per unit time) and average velocities (distance per unit time) are evaluated using some representative values for hydraulic gradient and hydraulic conductivity. Considering the lignite aquifers, representative lateral hydraulic gradients are in the range of 5 to 50 feet per mile in most parts of the groundwater-flow system. At shallow depths the lignite aquifers have hydraulic conductivities generally in the range of 10^{-2} to 10^{-4} cm/sec, with a trend toward lower values in the deeper lignites. To calculate some representative lateral seepage flow values for lignite-aquifer flow, the Darcy equation can be used

$$q=-KA \text{ grad } h$$

where q is the groundwater flux, K is the hydraulic gradient, A is the cross sectional area through which the flow occurs, and grad h is the hydraulic gradient. For calculation purposes it will be assumed that the lignite has an effective thickness of 15 feet. With these input values, the Darcy equation yields lateral flux values between 0.004 to 4 ft^3/day per foot width of aquifer. The result is obviously very sensitive to the 2 order of magnitude range of hydraulic conductivity values used as input values.

Except for areas where the uppermost lignite aquifer is close to ground surface, or zones where the aquifers are in contact with permeable valley fill sediment of the Coleharbor Formation, the lignite aquifers are fed by vertical seepage water from overlying, and in some cases, underlying aquitards. For purpose of illustrative calculation of the vertical flux through aquitards into the aquifers, the following parameter values will be used: $K=10^{-7}$ cm/sec, grad h=0.2. These values produce a vertical flux of 5 x 10^{-5} ft^3/day per square foot of aquitard. With this vertical leakage flux a 1-foot-wide strip of aquitard as much as several miles long would be required to provide sufficient leakage to account for all of the lateral aquifer flux calculated above (i.e., as much as 4 ft^3/day per foot width of aquifer). Since aquitard conductivities can typically range from about 10^{-5} to 10^{-9} cm/sec, and the vertical gradients in the aquitards commonly range from about .1 to 1, it is evident that the vertical aquitard leakage at any particular location could be orders of magnitude different than the result calculated above for illustrative purposes. The calculation does serve to indicate, however, that even though the aquitard leakage is small on a per square foot basis, over a large area, the leakage is capable of supplying the quantities of lateral aquifer seepage that appear reasonable based on field measurements of head gradients and hydraulic conductivities. Except for the shallowest lignite beds, such as the A- and B-lignites, which have been dissected by erosion, the lignite aquifers and many of the sand aquifers extend for many miles, and, in some cases, many tens of miles, where vertical aquitard leakage supplies the aquifers with water. In terms of flow continuity, aquifer zones that receive water from above through aquitard leakage generally lose water to underlying aquitards by downward leakage and discharge water laterally towards the discharge areas along the major valley slopes. It also should be kept in mind that the flow from the deposits of the Coleharbor Formation in the valley fill provides some lateral source water to the lignite beds that abut against the buried valley walls. At greater depths where the lignite aquifers have lower hydraulic conductivities, less vertical aquitard leakage is required to maintain input and output flow continuity.

Further understanding of the nature of the groundwater flow regime in the Sentinel Butte Formation can be obtained from an analysis of the average flow velocities in the aquifers and aquitards. For this purpose the Darcy equation will be used in the following form:

$$v=\frac{-K}{n} \text{ grad } h$$

where v is the average linearized interstitial groundwater velocity, hereafter referred to simply as the groundwater velocity, n is the effective porosity, and the other terms are as previously defined. Using the same aquifer conductivity and gradient ranges as in the previous aquifer flux calculation, with an assumed effective porosity range of 10^{-2} to 10^{-3}, yields a calculated groundwater velocity range of 0.03 to 300 ft/day, which indicates that relatively high velocities probably occur in some parts of the lignite aquifers. Velocities can be high in aquifers with fracture porosity even though the seepage flux is not high because, as indicated by the Darcy equation presented above, the velocity is proportional to the reciprocal of the porosity. Although no actual field or laboratory measurements of the effective fracture porosity of lignite aquifers in the study area have been obtained, the range of 10^{-2} to 10^{-3} appears to be reasonable in light of data on fractured rock from other areas.

A similar type of calculation for the aquitards, using a hydraulic conductivity range of 10^{-7} to 10^{-9} cm/sec, gradient range of 0.1 to 1, and a porosity of 0.3, yields a calculated velocity range of 10^{-3} ft/day to 10^{-6} ft/day (1 ft in 1000 days to 4 ft in 10,000 years), which indicates that vertical flow through the aquitards is generally very slow, and even negligible, when viewed in terms of a human time scale. Since the stratigraphic studies indicate that many of the silt and clay aquitards are extensive across the area, and since the hydrologic studies indicate that vertical leakage through aquitards is probably a major source of water supplying many of the coal and sand aquifers, it is expected that much of the aquifer water is very old, even in some aquifer zones that are not far below ground surface. Considering the range of velocities of vertical flow in aquitards calculated above, it is reasonable to expect much of the aquifer water to be hundreds or thousands of years old. The topic of groundwater circulation rates and ages will be discussed further in the section dealing with isotope studies.

The only way that groundwater could move much more rapidly between the lignite aquifers would be in situations where sand aquifers provide hydraulic connection between the lignites. Since the sand aquifers in the Sentinel Butte Formation are mainly channel sands that are irregular in pattern and thickness, very detailed stratigraphic and hydrologic information would be required in order to delineate interaquifer connection zones. On the basis of existing data, however, it is evident that hydraulic connectivity between major lignite aquifers below the Dunn Center Bed is very uncommon, except of course between the F- and H-lignites which are generally separated by only a thin interval in the central and northern part of the study area and are joined in the southern part of the area.

3.6.6 Recharge and Discharge

The main discharge areas for aquifers in the Dunn Center area occur along the valley slopes of the Knife River and Lake Sakakawea, in the valley of Spring Creek and at some locations where lignite aquifers extend near ground surface or outcrop. A somewhat surprising situation is that the floors of the valleys with major valley fill deposits, such as occur in the vicinity of the proposed plant site and at UND sites 26 and 27, do not appear to be discharge areas even though the water table in these areas is relatively close to ground surface.

Comparison of the water table elevation map (fig. 3.6.3-2) with the regional topographic map (fig. 1.2-2) indicates that areas of highest water table are the main topographic uplands. These areas must therefore also be regional recharge areas even though the general thickness of the unsaturated zone is relatively large. The spatial and temporal characteristics of the infiltration events that cause the recharge that maintains the regional water-table highs cannot be delineated on the basis of existing data. It is reasonable to expect, however, that most of the recharge occurs in the local depressions that occur in the upland areas and particularly in local depressional areas underlain by sand or lignite rather than silt or clay. As a result of wind action, snow tends to collect in the local depressions, providing more opportunity for significant infiltration during the spring snow-melt period. It is likely that only the most intense or long rainfall events cause sufficient infiltration to produce recharge to the water table zone. These rainfall events can cause surface runoff that results in accumulation of surface water in the local depressions. This would be expected to produce deep-penetrating infiltration at locations where the combination of soil conditions, permeability of geologic materials, and local topography is favorable. Even though the areas of regionally high water-table elevation are extensive in the study area, it is likely that the areas in which infiltration actually passes through the unsaturated zone in these so-called regional recharge areas are relatively small and that the frequency of recharge occurrence is low. Even where recharge occurs in local depressions in the regional uplands, it appears that to cause recharge the infiltration generally must pass through several tens of feet of unsaturated zone before encountering the water table. The thick unsaturated zone combined with the normally low annual rainfall, high potential evapotranspiration during the summer months, and frozen soil conditions during the winter months are characteristic features that would cause low frequency of recharge events. Almost all of the water that falls on the ground surface as rain and snow is returned to the atmosphere by way of direct evaporation from the land surface or by evapotranspiration from plant roots that collect water that infiltrates into the soil but does not penetrate below the root zone. Further comments on groundwater recharge based on isotope data are presented below.

Since the available data indicates that the frequency and areal extent of groundwater recharge is small and that in extensive upland areas the regional water table is much above the major topographic lows that cross the area, it is necessary to conclude that the flow of groundwater away from the recharge areas, either laterally or downward, is very sluggish. In other words, the conditions of low input and low output maintain the extensive areas of regionally high water table. Since the water table slopes and downward gradient components are not small, the cause of the sluggish flow conditions must, in general, be the permeability distribution.

3.6.7 Flow in the Valley Fill

The hydrogeologic conditions through locations in partially buried valleys where there are significant numbers of observation wells are shown in figures 3.6.4-10 to -14. These figures indicate that the hydraulic heads in wells in the valley fill are generally deeper in deeper wells at each nest, indicating that the floors of the valley are recharge areas. The second major trend indicated by these figures is that the head values in the valley fill are generally greater than the local head values in the Sentinel Butte aquifers that intersect the valley walls or that extend beneath the base of the valley fill. In other words, at these locations where there are wells in the valley fill and in the adjacent bedrock such as in the vicinity of the proposed plant site (figs. 3.6.4-10, 3.6.4-11) at UND sites 26 and 27 (fig. 3.6.4-13) and near Lake Ilo (fig. 3.6.4-14), the hydraulic head data indicate that groundwater tends to flow from the valley fill into the bedrock aquifers. Whether or not the actual quantity of water moving from the valley fill into the bedrock aquifers is very significant cannot be determined from the information shown on the cross sections. It should be noted that although, in general, the major valley floor areas are recharge areas, there is groundwater discharge at many locations along the valley side slopes where lignite aquifers outcrop.

A review of figure 3.5.1-2 shows that the principal direction of flow in the valley fill materials is along the valleys. Groundwater divides in the valley fill sediment are broad and do not necessarily correspond to surface water divides. For example, in the valley that underlies the proposed plant site, the surface water divide between Spring Creek and the Knife River is the northern part of sec 27, T144N, R94W, but the groundwater divide appears to be in the southern part of sec 8, T144N, R94W, almost 3 miles northwest of the surface water divide. Flow in the valley fill in the northern part of Mine Area No. 1 appears to be generally toward Spring Creek. In the southern part of the mine area, drainage is toward the Knife River. Where lignite beds intersect the permeable valley-fill sediments, water is either recharged to the valley fill from the lignite, lost from the valley fill to the lignite, or flows from the lignite to the valley fill and back into the lignite depending on the relative values of hydraulic head at that site.

3.6.8 Terminology and Concepts in Isotope Studies

Samples from selected UND wells, farm wells, and town wells were analyzed for oxygen-18, tritium, and carbon-14 and -13. The purpose of these analyses was (1) to gain further information about the sources, flow patterns, and ages of groundwater in the Dunn Center area, (2) to establish some base-line isotopic data that can be used in the future for comparison with new values when mining activities are in progress, and (3) to test for the presence of drill water in observation wells that may not have been adequately cleaned. Before proceeding with discussion of the results of the isotope analyses, some of the terminology and principles necessary for interpretation of the data are presented.

Water (H_2O) is composed of two atoms of hydrogen and one atom of oxygen that are bound by a combination of covalent and ionic bonding processes. The normal hydrogen in water has an atomic number of 1 and an atomic weight of approximately 1 and normal oxygen has an atomic number of 8 and an atomic weight of approximately 16. In the hydrological cycle, nearly all water molecules are composed of these normal hydrogen and oxygen components. Some water molecules, however, are formed partly or entirely of other isotopes of hydrogen and oxygen. Hydrogen has two other isotopes referred to as deuterium and tritium. Normal hydrogen (^1H) has 1 proton in its nucleus, deuterium (^2H, but commonly designated as D) has 1 proton and 1 neutron with an atomic mass of 2, and tritium (^3H, but commonly designated as T) has 1 proton and 2 neutrons for a mass of 3. ^3H is radioactive with a half life of 12.3 years; the other two isotopes are stable. The isotope of oxygen that is of interest here is oxygen-18. In the hydrologic cycle, the abundant type of water molecule is, of course, $^1H_2{}^{16}O$. The molecules $HD^{16}O$, $HT^{16}O$, and $H_2{}^{18}O$ and other combinations occur in only very small concentrations. For example, in sea water $HD^{16}O$ and $H_2{}^{18}O$ occur in average concentrations of 320 and 2000 ppm respectively (Payne, 1972). The isotope ratios, measured in a mass spectrometer, are normally expressed in delta units (per mille) with notation $\delta^{18}O^o/_{oo}$ and $\delta\, D^o/_{oo}$ based on the definition:

$$\delta^o/_{oo} = (R - R_{standard})/(R_{standard}) \times 1000$$

where R and $R_{standard}$ are the isotopic ratios of the sample and standard, respectively. In this study, as is generally the case in hydrology, the standard used is Standard Mean Ocean Water represented by the abbreviation SMOW. The standard is a close approximation of the isotopic composition of the oceans.

Based on the SMOW standard, the ^{18}O content of waters in the hydrological cycle normally range between about 0 and -25 per mille. In inland continental regions the lightest values (i.e., the most negative) are found in snow and the heaviest values in surface water that has undergone considerable evaporation. The ^{18}O values differ for individual rain events depending on the meteorological history of the vapour mass from which the rain is derived and on the temperature of the air mass as the rainfall is produced. Colder climatic conditions tend to produce lighter ^{18}O rainfall values. The ^{18}O content of infiltration water that recharges the water-table zone of groundwater-flow systems depends on the ^{18}O content of the rain or snow that lands on the ground surface and on the extent of evaporation that occurs before the water infiltrates a significant distance into the soil. If the groundwater is being recharged by seepage from a surface-water body such as a lake or river, the ^{18}O content of the groundwater will be the same as the surface water and will mainly reflect the extent of evaporation that occurred in the surface-water environment. The ^{18}O content of the water, as it resides in the groundwater-flow system, remains unchanged by chemical or biochemical processes except in exceptional circumstances, such as in geothermal areas. ^{18}O can therefore be viewed as a conservative natural tracer that is controlled by meteorological factors, surface evaporation, and recharge frequency and occurrence. In favorable circumstances, ^{18}O contents of groundwater can yield useful information on the source areas of recharge, aquifer mixing, and surface water-groundwater interactions.

Tritium has always occurred in water in the hydrologic cycle, but it has only been since 1953 that the concentrations in rain, snow, surface water and young groundwater have become relatively high. The large increase in tritium concentrations occurred in 1953 because of atmospheric tests of thermonuclear devices by the USA and USSR. The atmospheric tests began in 1952, with further series of tests in 1954 and 1958 with a final series of tests in 1961 and 1962 before the moratorium on atmospheric testing. In this study, as in most hydrological studies, the tritium concentrations are expressed in Tritium Units, abbreviated as TU. One tritium unit corresponds to a concentration of 1 tritium atom per 1×10^{18} atoms of hydrogen.

Before atmospheric testing of thermonuclear devices, rain and snow had very low tritium concentrations (believed to have been in the range of 5 to 10 TU; Payne, 1972) that were produced by cosmic ray bombardment of nitrogen in the atmosphere. As a result of the atmospheric testing, the tritium values for rain and snow in the interior of North America rose to peaks above 500 and 1000 TU following the major tests. By 1967 the annual peaks had fallen below about 600 TU and during the past few years have gone down to the range of 50 to 150 TU. The tritium content of groundwater is dependent on the concentration of the rain or snow that fell on the ground surface and on the time elapsed since the water infiltrated below ground surface. Because the half life of tritium is 12.3 years, and because the pre-1953 tritium concentrations were only 5 to 10 TU, concentrations of tritium in pre-1953 water in the groundwater zone are now less than 3 TU, which is below the normal limit of analytical detection. Samples with tritium levels below the level of detection are referred to in this report as having no detectable tritium or, more simply, no tritium. Tritium is usually a relatively simple natural hydrologic tracer to use as an indicator of whether groundwater was recharged before or after 1953. It is necessary to keep in mind, of course, that in some zones groundwater is a mixture of old water and young water and therefore may have tritium concentrations that are difficult to interpret.

The other two isotopes used in this investigation are carbon-13 and carbon-14. Carbon-14 is a radioactive isotope with a half life of approximately 5700 years. In favorable circumstances, the ^{14}C content of dissolved inorganic carbon extracted from groundwater samples can be used as a semi-quantitative indicator of relative age of groundwater. The stable isotope, carbon-13, is usually also analyzed as an aid in the interpretation of the chemical evolution of the groundwater and in the interpretation of the ^{14}C data. The interpretation of carbon isotope data is normally much more difficult than for oxygen and hydrogen isotopes because the dissolved inorganic carbon in groundwater can be derived from several sources and can be altered within the subsurface flow system by a variety of geochemical processes. It is well known that the geochemical processes that alter ^{14}C concentrations in groundwater can be particularly complex in groundwater-flow systems within coal beds. Nevertheless, if due caution is used in the interpretation of the ^{14}C data, there can be a reasonable likelihood that some useful hydrologic information can be obtained.

The carbon-14 analyses used in this study are presented as a percentage of the ^{14}C content of "modern" organic carbon material. This material was in equilibrium with natural atmospheric ^{14}C prior to increases caused by testing of thermonuclear devices. Natural atmospheric ^{14}C is produced by cosmic ray bombardment of nitrogen. Organic matter, such as vegetation and organisms in contact with the atmosphere, has the same ^{14}C

content as the atmosphere. Water that infiltrates through the soil zone dissolves CO_2 produced by oxidation of organic matter and root respiration and thereby acquires similar equilibrium ^{14}C concentrations in dissolved inorganic carbon. When the water moves downward into the water-table zone, the water is no longer in contact with the ^{14}C replenishment source. The ^{14}C concentrations then begin to decrease as a result of (1) radioactive decay, and (2) dilution by non-radioactive carbon that enters the groundwater by dissolution of minerals through various geochemical or biogeochemical processes. If the amount of dilution by non-radioactive carbon can be estimated, the age of the remaining carbon can be estimated from the radioactive decay equation:

$$A=QA_0 2^{-t/T}$$

where T is the half life (5700 years), t is time, A is the measured ^{14}C activity in the sample (as percent modern) and A_0 is the activity at time zero (modern activity), and Q is an adjustment ratio. To obtain Q the effect of dead carbon dilution on the ^{14}C concentration must be estimated. A detailed discussion of this parameter is given by Wigley (1975).

Carbon-13 can be used to estimate the source of dissolved inorganic carbon in groundwater (i.e., the carbon occurring in H_2CO_3, CO_3, and HCO_3). This is feasible because the two main sources of carbon (1) biogenically generated CO_2 from the soil zone or oxidation of coal, and (2) calcite-dolomite dissolution, normally have very different ^{13}C values, ^{13}C concentrations are expressed in per mille delta units in the same manner as ^{18}O concentrations, except that the standard used is a marine limestone, referred to as the PDB standard.

More detailed information on the principles and applications in isotope hydrology are given by Brown et al (1972) and Payne (1972).

3.6.9 Hydrologic Information from Oxygen-18 Data

The results of the ^{18}O analyses of samples from UND observation wells and selected inventory wells are given by Moran and others (1976, app. C-XI). The ^{18}O values are in the range of -18.9 to -9.2 per mille. Of the total of 210 groundwater samples analyzed, 184 are lighter than -14 per mille (i.e., more negative), with the remaining 26 heavier samples having values between -9.2 and -13.9. On the basis of where they occur in the groundwater-flow system, it is highly likely that the samples in the -9.2 to -13.9 range which will be referred to as the heavy group, represent groundwater that was recharged from surface-water sources that underwent significant evaporation or mixtures of groundwater and evaporitic surface water.

When water evaporates from surface water bodies isotopic fractionation occurs, causing the water to become enriched in ^{18}O (i.e., heavier, less negative). In the hydrologic setting of the Dunn Center area, ^{18}O values heavier than about -12 per mille have undoubtedly undergone relatively strong evaporation, whereas values between about -13 and -14 represent weaker evaporitic effects or mixing of evaporitic and non-evaporitic water. The evaporitic water obtained from UND wells may be water from lakes, sloughs, ditches, or streams that has entered the groundwater regime through natural seepage, or it may have entered the system as circulation or wash water during drilling or well installation activities. One of the purposes of the isotopic studies is to identify wells that require additional cleaning before they can be used to provide samples for base-line water quality monitoring points. The evaporitic water from the farm wells indicates surface water seepage, except in the rare case where faulty well construction could cause seepage of surface water down along the well casing into the well intake zone.

Appraisal of the ^{18}O data and consideration of the well depths and the hydrogeologic setting of the wells leads to the conclusion that the following wells are strongly contaminated with surface water used during the drilling and well installation operations: 2-1, 6-3-1, 17-1, 17-2-2, 19-1. These wells have ^{18}O values between -11.6 and -9.3. The following wells are probably moderately or weakly contaminated: 16-3-1, 16-3-2, 30-3, 46-1.

Table 3.6.9-1. *Comparison of oxygen-18 values for wells in the Dunn Center area that were sampled twice during 1975.*

UND Observation Wells

Location	Site No.	Well No.	Date Sampled	^{18}O(0/00) (per mille)	Date Sampled	^{18}O(0/00) (per mille)
146-93-23 CBB 2	8	2	10- 3-75	-10.1	11-13-75	-16.3*
146-93-23 CBB 3	8	3	10- 3-75	-18.9	11-13-75	-18.9
144-94-16 BAB 1	26	1-1	8-15-75	-17.3	10-27-75	-17.1
144-94-16 BAB 2	26	1-2	8-15-75	-17.2	10-27-75	-17.1
144-94-16 BBA 2	27	2	8-15-75	-16.9	10-28-75	-17.0
145-93-27 ABC 1	32	1	10- 1-75	-16.5	11- 3-75	-16.3
145-93-27 ABC 2	32	2	10- 1-75	-16.4	11- 3-75	-16.2
144-94-01 BCB 4	55	4	10-24-75	-13.7	11-12-75	-13.7

*Well was pumped extensively using cylinder and pump jack between samplings.

Farm Wells

Location	Sample No.	Owner	Date Sampled	^{18}O(0/00) (per mille)	Date Sampled	^{18}O(0/00) (per mille)
145-93-10 AAC 1	15, 38	A. Hanson	5-24-75	-17.2	8-23-75	-17.2
145-93-10 AAC 2	14, 39	A. Hanson	5-24-75	-15.9	8-23-75	-15.9
146-93-34 ADD	13, 46	G. Buehner	5-24-75	-17.9	8-23-75	-17.8
146-93-35 BCC	12, 48	G. Buehner	5-24-75	-17.9	8-23-75	-17.9
146-93-34 ADA 1	11, 47	G. Buehner	5-24-75	-16.4	8-23-75	-16.5
146-93-26 CBB 2	9, 49	C. Pelton	5-24-75	-14.9	8-23-75	-14.6
145-94-27 BCB	61, 66	Lake Ilo Pump	8-22-75	- 9.4	10- 8-75	- 9.2
144-93-14 CBB	F71, C6	A. Rohde	10- 1-75	-17.5	10- 2-75	-17.3

These wells have ^{18}O values between -13.9 and -13.4 per mille. The conclusion that these wells are contaminated with drilling or wash water is based on the fact that almost all drill and wash water was obtained from sloughs, streams, or lakes that had been exposed to evaporation processes during several weeks or months prior to drilling use. An example of the effect of continued well cleaning on a well contaminated with drill or wash water is provided by well 8-2 which was sampled after an initial cleaning stage and yielded an ^{18}O value of -10.1 per mille and then was sampled after additional cleaning and yielded a value of -16.3 (table 3.6.9-1) which is in the range of normal groundwater in the area. Six other wells that were sampled at two different cleaning stages and analyzed for ^{18}O gave the following results, with the first sample indicated first: well 8-3, -18.9 and -18.9; well 26-1-1, -17.4 and -17.3; well 26-1-2, -17.1 and -17.2; well 27-2, -16.9 and -17.0; well 32-1, -16.5 and -16.3; well 32-2, -16.4 and -16.2; well 55-4, -13.7 and -13.7. Since the analytical precision of the ^{18}O determinations is approximately ±0.15 per mille, the variations in these samples (where there are variations) cannot be regarded as significant. It is concluded that there are very few wells in the study area that have not been cleaned sufficiently to adequately remove all, or nearly all, of the drill and wash water. The few wells that were identified as being contaminated were not subjected to further cleaning during the present study, but it will be necessary to clean the contaminated wells before new samples are collected from the well network as monitoring proceeds.

Four samples that have ^{18}O values

heavier than -12.6 have not been attributed to contamination. These samples are from very shallow wells (well 39-2, -10.7; well 43-1, -9.9; well 49-2, -12.5; well 58-2, -11.4) that were cleaned thoroughly before sampling. Because the wells were shallow and because they are located very near permanent or ephemeral surface water bodies in areas with downward components of hydraulic gradient, it is reasonable to conclude that the natural seepage from the evaporitic surface water regimes into the groundwater-flow system is the cause of the heavy ^{18}O concentrations. The following samples, which are significantly, but not strongly, heavier than the normal groundwater, are also near surface-water sources and therefore probably result from natural surface water seepage: well 32-4, -13.5, beside Spring Creek; 49-3, -13.3, near a surface stream; and 46-1, -13.4, near Lake Ilo. The conclusion that seepage from Lake Ilo is a significant contributor to the groundwater zone near the lake is supported by ^{18}O data from farm wells as indicated below.

Only six farm wells have ^{18}O concentrations heavier than -14.0 per mille (sample nos. 61, 62, 68, 69, 75, 81, 98). All of these wells are very near the shore of Lake Ilo or are along channels near the lake. The well depths range from 133 feet (sample 81) to 22 feet (sample 68). Since the available hydraulic head data from near Lake Ilo indicates that there is a general downward trend in the hydraulic gradient in the vicinity of the lake, the occurrence of evaporitic water in wells near the lake corroborates the interpretation that Lake Ilo is a significant source of groundwater recharge in the vicinity of the lake. The occurrence of the evaporitic water in farm wells greater than 100 feet deep indicates that seepage from the lake penetrates relatively deeply into the groundwater-flow system. As this lake-derived water moves along flow paths in the groundwater system it will mix by mechanical dispersion and molecular diffusion with groundwater recharged from other sources. There are insufficient observation wells and farm wells in the area to enable the Lake Ilo-derived water to be traced in the groundwater-flow system.

In the discussion presented above, the ^{18}O concentrations of observation-well and farm-well samples with ^{18}O concentrations generally heavier than -13 or -14 per mille were accounted for in terms of seepage from surface water or contamination from drill and wash water. In the following paragraphs the remaining samples that were analyzed for ^{18}O are evaluated. The results along the north-south and east-west cross sections are shown in figures 3.6.9-1 and 3.6.9-2, which include values for many of the UND wells and some of the farm wells. The wells that were identified as being contaminated with drill or wash water were not included on the cross sections. Some of the wells on the cross section were not sampled and analyzed for ^{18}O.

The cross sections indicate that, beneath the proposed plant site, the valley fill wells have ^{18}O concentrations between -12.5 and -15.9. Additional ^{18}O values in the valley fill near the proposed plant-site area are shown along cross section E-E' (fig. 3.6.9-3), along which only one valley fill ^{18}O value is lighter than -16.1. However, in the aquifers of the Sentinel Butte Formation in and near the valley, the ^{18}O concentrations are nearly all lighter than -16.0 per mille. This general difference between the valley fill values and the bedrock values is particularly significant because, as indicated earlier, the hydraulic head values in the valley fill are generally greater than in the bedrock in this area. It can be concluded that the valley fill is not a major source of water for the bedrock in this area, because if it were one would expect to observe similar ^{18}O concentrations. This indicates that the hydraulic connectivity between the valley fill and the adjacent aquifers in the Sentinel Butte Formation is poor, as a result of permeability constraints.

As indicated previously, some of the shallow groundwater in the valley fill deposits in and near the proposed plant area is evaporitic water derived from surface water, probably as seepage from the relatively deep road ditches and from the small stream that meanders along the valley floor. The samples from wells in the valley fill that are in the range of about -14 and -16 are generally slightly heavier than the

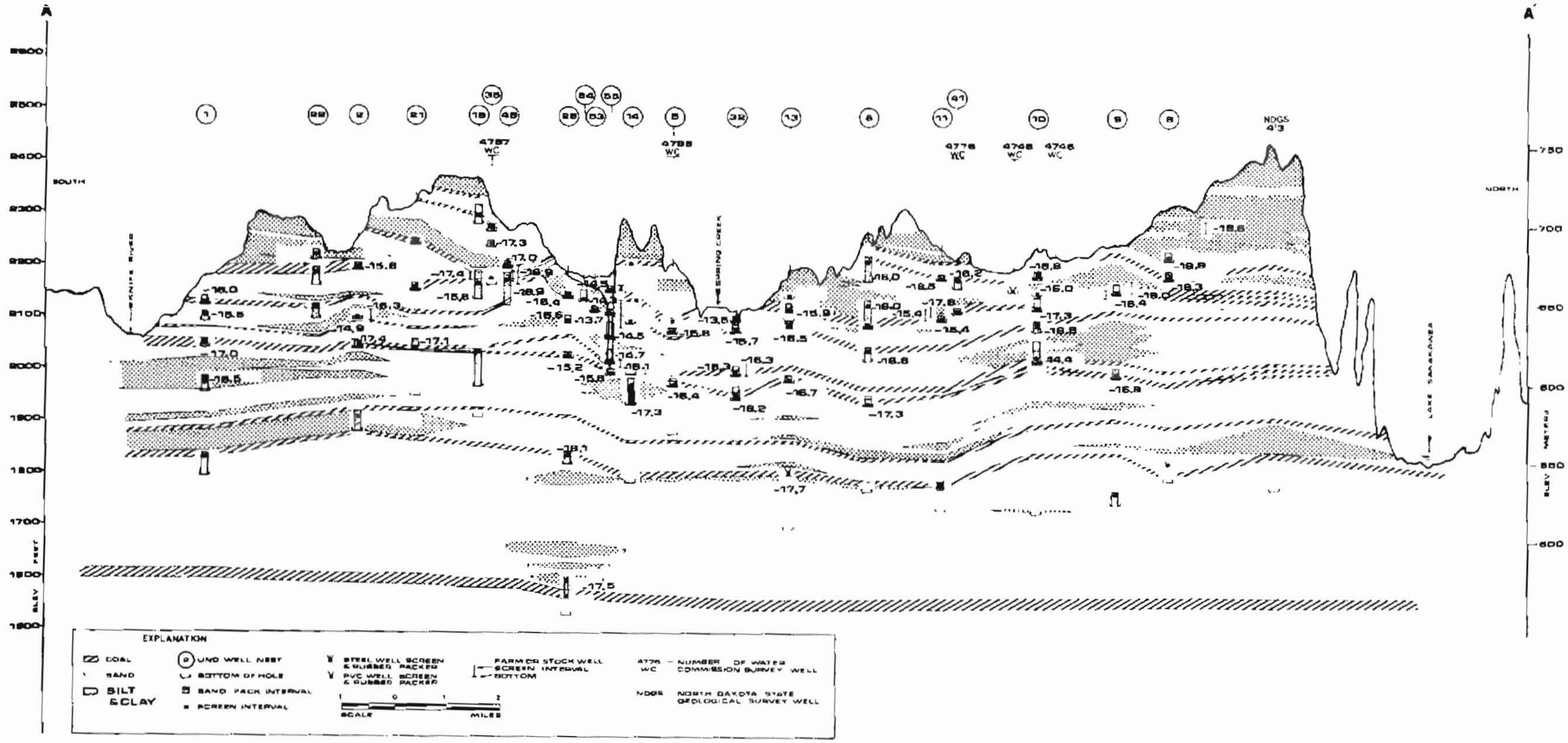


Figure 3.6.9-1 Oxygen-18 concentrations in samples from UND wells and farm wells along cross section A-A'. Location of cross section shown on figure 2.1.10-2.

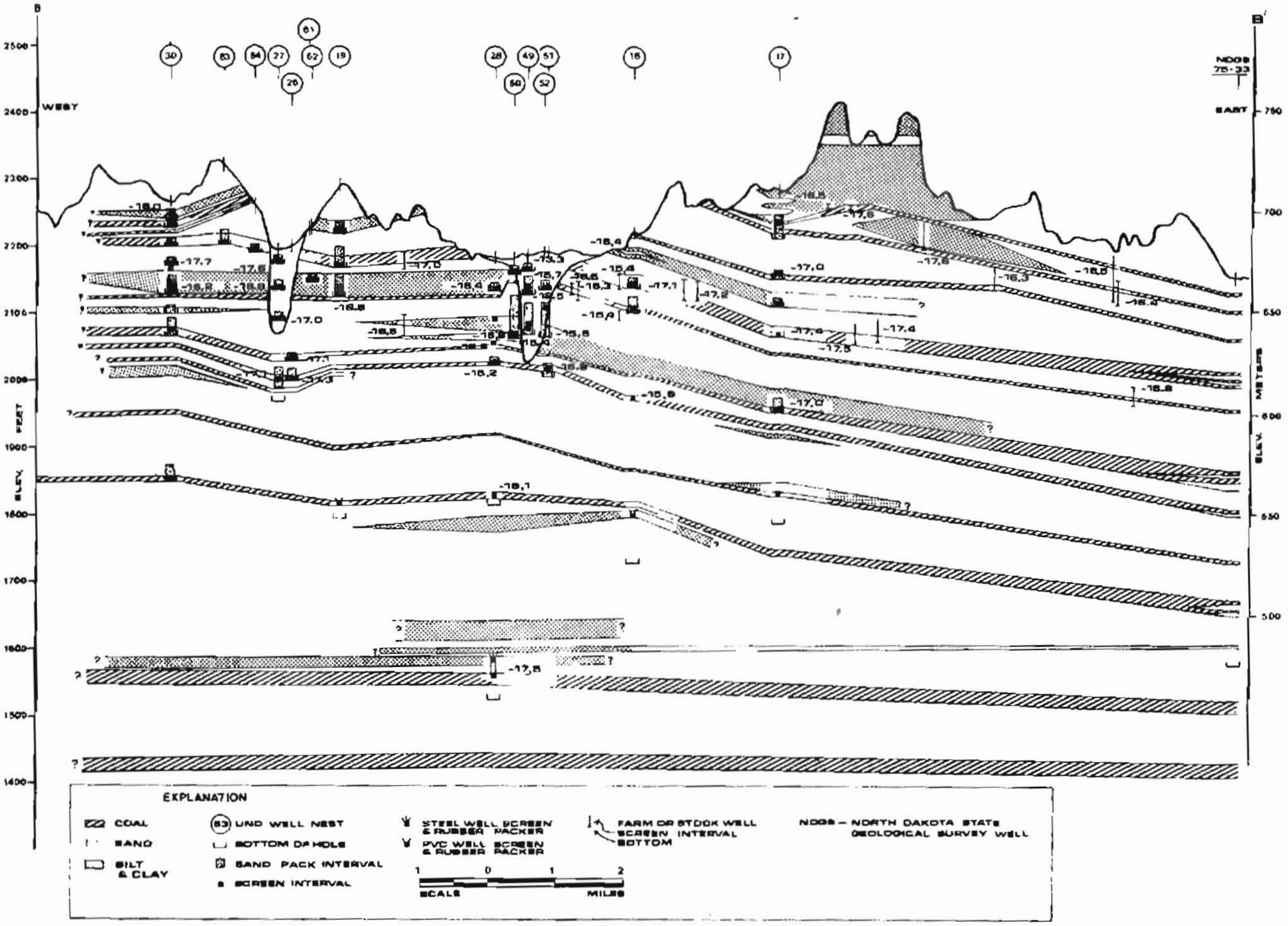


Figure 3.6.9-2 Oxygen-18 concentrations in samples from UND wells and farm wells along cross section B-B'. Location of cross section shown on figure 2.1.10-2.

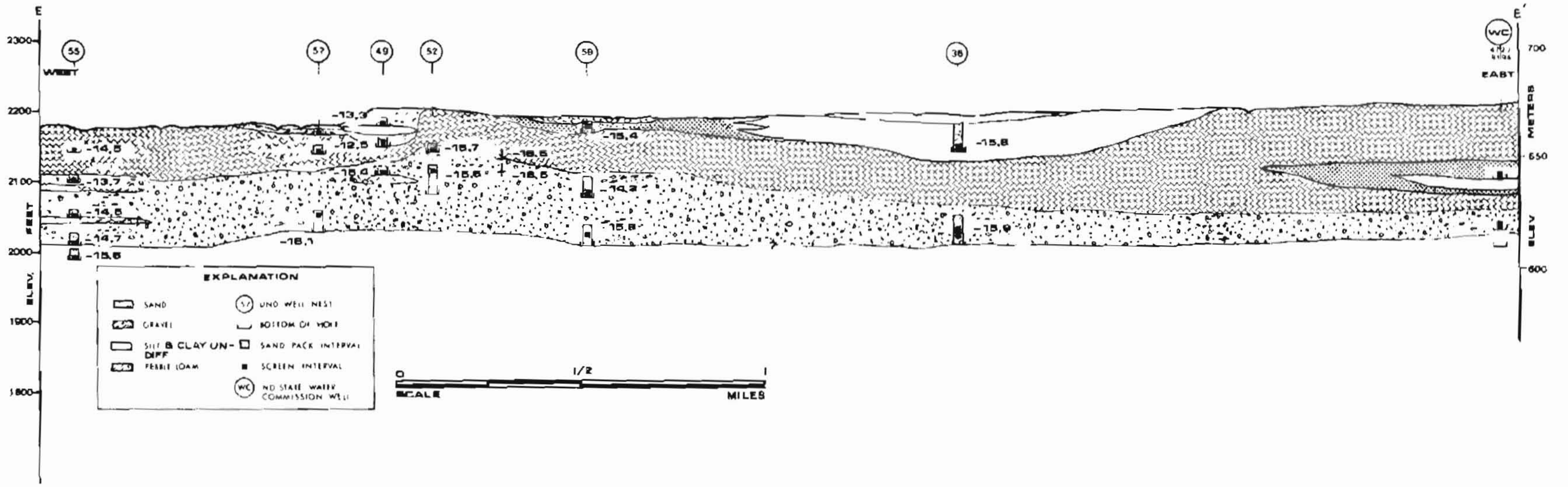


Figure 3.6.9-3 Oxygen-18 concentrations in samples from UND wells along cross section E-E'. Location of cross section shown on figure 2.1.10-2.

bedrock samples, probably because of some mixing of evaporitic water with normal groundwater, or maybe because the annual recharge in the valley floor area is more frequently the result of rainfall. Recharge from rainfall would generally produce heavier ^{18}O groundwater than water derived from snow melt.

The three wells in the valley fill at site 27 are in the range of -17.0 to -18.8 and do not appear to be significantly different than ^{18}O concentrations in the nearby aquifers of the Sentinel Butte Formation. This lack of difference, even in the very shallow valley-fill well at this site, is probably because of the lack of evaporitic surface-water regimes on the valley floor in this area. The sloughs north and south of the site 26-27 area evidently are not contributing to groundwater that flows in the vicinity of site 27.

Almost all of the UND and farm wells that have not already been discussed in terms of surface water seepage, drill and wash water contamination, or valley fill occurrence in the proposed plant site area, have ^{18}O concentrations in the range of -15.5 and -17.9. This range typifies what we will regard as normal groundwater in the Sentinel Butte Formation.

Of all the farm wells that were sampled and analyzed for ^{18}O there are only two wells with values lower than -17.9. Both of these wells with values of -18.0 and -18.6 are located in the relatively shallow groundwater zone near UND sites 8 and 9 at the northern end of cross section A-A' (fig. 3.6.9-1). There are four UND wells with ^{18}O concentrations lighter than -17.9. One of these four is located in the shallow well at site 8 near the two farm wells mentioned above. This area is an upland recharge area, and it is reasonable to expect that the anomalously light ^{18}O values in this area are an indication of recharge processes contributing water in this area. Anomalously light ^{18}O values in groundwater-flow systems are normally an indication of contributions from cold weather sources, such as spring snow melt or recharge during cold climatic periods such as occurred during the Pleistocene Epoch. Since the shallow groundwater in the vicinity of site 8 is in a recharge area of primarily sandy deposits, it is very unlikely that this water is Pleistocene in age. This conclusion is confirmed by tritium data discussed below. The upland area at the northern end of the study area has numerous small topographic depressions that collect wind-blown snow. These depressions would be expected to cause appreciable infiltration during periods of spring snow melt. Some of the depressions have permanent sloughs; others have ephemeral sloughs. Snow melt that infiltrates significantly below land surface before warm weather causes appreciable evaporation will maintain its light ^{18}O values. It is likely that this type of recharge process supplies the shallow groundwater zone in the northern upland. Since there are no relatively heavy ^{18}O values in this area, it is very unlikely that much water from the permanent ponds or the ephemeral ponds that often persist into the summer produce much recharge to the groundwater zone. The two anomalously light ^{18}O wells are also anomalous with respect to their water chemistry. This will be discussed in more detail below. At this point, the hydrologic significance of the anomaly is only briefly mentioned. The water from these two wells has the lowest total dissolved solids, calcium concentrations, and alkalinity of all of the wells analyzed in the study area. This is consistent with the interpretation that the water is derived from recharge of snow melt in the spring through soil zones that are not capable of contributing much larger amounts of dissolved carbon dioxide to the water than is already present due to equilibrium with the above ground atmosphere. This would be expected to occur if the water infiltrates as a slug relatively rapidly through the soil (solum) when the soil is very cold or even partially frozen in the spring. Under cold conditions there is very little biochemically assisted oxidational decay of organic matter in the A and B horizons, which generates carbon dioxide that produces increased carbonic acid. This normally causes greatly increased mineral dissolution, and therefore much higher total dissolved solids, alkalinity, and cation concentrations.

The question can be raised as to

whether or not there is any particular hydrologic significance to the fact that the normal groundwater in the study area has oxygen ^{18}O values in the range of approximately -15.5 to -17.9 and why there is much variability of ^{18}O values within this range within individual aquifers and with depth in the various segments of the region. The variability is probably caused by the multiplicity of microenvironments, in which groundwater recharge occurs. It is also likely that since the water in groundwater-flow system varies in age from very young to many thousands of years or older, variations in climatic conditions over this time span have influenced the ^{18}O concentrations of recharge water.

In order to obtain a preliminary indication as to whether or not ^{18}O data obtained from wells on a single sampling occasion are representative of conditions that occur over significant time periods, some of the farm wells were sampled on two, and in a few cases three, occasions between spring and fall. The wells with double ^{18}O analyses are listed in table 3.6.9-1. This table indicates that the differences between sample results are almost without exception close to or smaller than the ±0.15 analytical precision of the ^{18}O determinations. Although the time periods between sampling are not long, the results are consistent with the hypothesis that the groundwater generally moves slowly, and therefore, if changes do occur they probably would only show up over very long periods of monitoring.

3.6.10 Hydrologic Information from Tritium Data

The results of tritium analyses on 49 farm wells and 9 UND wells are listed in tables 3.6.10-1 and 3.6.10-2. In the tritium investigation emphasis was placed on the farm wells to avoid the possible influence of contamination by drill and wash water. The general lower limit of detection of significant tritium concentrations, with the analytical methods used in this study is approximately 10 TU, although the exact limit depends on the time that the sample is monitored in the liquid scintillation counter, the efficiency of the counter, and the background radioactivity levels. In tables 3.6.10-1 and 3.6.10-2 samples with apparent tritium concentrations less than 10 TU have been designated as below detection because, in general, concentrations below 10 TU cannot be distinguished with a high degree of confidence from background radioactivity levels inherent in the counting procedures. Values above 10 TU have been reported with their standard error limits as determined from the monitoring statistics. Table 3.6.10-1 indicates that of the 49 farm wells analyzed for tritium, 9 have concentrations greater than 30 TU, 5 are between 10 and 30, and the rest are below detection. As indicated above, tritium concentrations across the continent and elsewhere rose dramatically in 1953. Monthly average tritium values for a precipitation sampling station located in Bismarck, North Dakota, are reported by the International Atomic Energy Agency (1975) for the years 1964 to 1969. Calculated from these data the weighted mean annual tritium concentration in precipitation at Bismarck in 1964 was 2900 TU. The weighted mean annual values decreased to 377 TU in 1969. From tritium values for sampling points elsewhere in the interior of North America, it is estimated that for the past few years tritium concentrations in rain and snow in the Dunn Center area have varied from about 50 to 150 TU. A sample of rain collected in the area on September 27, 1975, gave a value of 102±9 TU. With this background information on the tritium variations in precipitation, the well data from the Dunn Center area are now interpreted.

The 9 farm wells with tritium concentrations greater than 30 TU evidently are located in groundwater zones where the water is younger than 23 years. Seven are at depths less than 50 feet below ground surface and therefore are situated in the shallowest part of the groundwater-flow system. The two other farm wells with greater than 30 TU are at 96 and 130 feet below ground surface. The 130-foot well is very near Lake Ilo. It was sampled on two different occasions and gave tritium values of 130 and 15 TU, which is a large variation. Both samples had

Table 3.6.10-1. *Results of tritium analyses of farm wells in the Dunn Center area that were sampled during 1975.*

Location (twp-rge-sec)	Sample Number	Date Sampled 1975 (month/day)	Owner	Well Depth or Intake Interval	Specific Conductance (umhos)	Tritium (TU)*
144-93-23 ADA 2	2	5-23	Rohde, E.	210	2200	16±12**
145-92-25 ABA	5	5-24	Town-Halliday	1510-1555	2300	Nil**
146-93-10 BAA	7	5-24	Voight, A.	Spring	2100	Nil**
146-93-3 CDD	8	5-24	Voight, A.	1525	2100	Nil**
146-93-34 ADA 1	11	5-24	Buehner, Gene	126-137	2000	Nil
146-93-35 BCC	12	5-24	Buehner, Gene	143-165	800	Nil
146-93-34 ADD	13	5-24	Buehner, Gene	160	900	Nil
145-93-10 AAC 2	14	5-24	Hansen, A.	15-30	3100	40±8**
145-93-10 AAC 1	15	5-24	Hansen, A.	84-91	1100	13±8**
145-93-10 AAC 1	38	8-19	Hansen, A.	91	1100	Nil
145-92-6 CCC	16	5-24	McMahon, J.	45-58	1000	Nil
145-92-18 CBA 1	19	5-24	Christiansen, A.	40	3000	38±7**
145-92-18 CBA 2	20	5-24	Christiansen, A.	180	2700	Nil
145-93-29 BCA 2	22	5-24	Lynch, G.	60-70(f)	1900	Nil
144-94-4 ADA	25	5-24	Iverson Bros.	40-50	1700	Nil
144-94-13 BCB	29	5-24	Hueske, J.	67-105	4900	Nil
144-94-12 AAB	30	5-24	Mjolhus, R.	51-65	2000	Nil
144-94-1 BCA 1	32	5-24	Trampe, E.	71-106	2600	Nil
144-94-22 BAA	33	5-24	Skjefte, A.	40-80	5200	Nil
144-94-34 BAB 2	35	5-24	Trampe, B.	97	2900	Nil**
143-93-22 DCA 1	41	8-19	Hausauer, P.	118-130(f)	1800	Nil**
144-94-24 BDB	45	8-20	Roschild, P.-Hauck, R.	178-190	2700	Nil
146-93-22 ADD	50	8-20	Buehner, Gene	59-85	190	Nil
146-93-22 CCC	51	8-20	Buehner, Gene	69-90	1600	Nil
144-93-07 AAB 1	52	8-21	Kling, I.	74-95	1900	Nil
144-93-07 AAB 2	53	8-21	Kling, I.	102-150	2400	Nil
144-93-11 ABC	55	8-21	Pollestad, S.	147-158	1900	13±10**
144-93-2 DCB	56	8-21	Pollestad, S.	180	2100	Nil**
144-93-18 ADB 1	57	8-22	Wemager, A.	22	3600	53±9** 50±13
145-94-28 DDB	60	8-22	Lake Ilo NWR	150	1800	Nil**
145-94-27 BCC	61	8-22	Lake Ilo Pump	130	1000	130±12**
145-94-27 BCC	66	10-8	Lake Ilo Pump	130	1000	15±6**
144-92-8 CAC 4	62	8-22	McNamara, J.	50	2000	56±9**
144-92-9 BCA	64	8-23	McNamara, E.	260	3200	11±16
144-92-8 CAC 2	65	8-23	McNamara, J.	81	3500	Nil
144-93-12 CDD	F67	10-1	Reiersgaard, J.	130	——	Nil
144-93-14 CBB	F71	10-1	Rohde, A.	300	——	Nil
144-93-15 ACB	F72	10-1	Dalham, J.-Renne, A.	96	——	35±10** 40±13**
144-93-8 ABB 2	F74	10-1	Kling, H.	111-140	——	Nil
144-93-8 ABB 2	F75	10-1	Kling, H.	111-140	——	Nil**
145-93-30 CDB 2	F77	10-1	Pelton, W.	117-130(f)	——	Nil
144-93-8 ABB 1	C3	10-2	Kling, H.	108-140	——	14±2**
145-94-28 ADB 2	67	10-8	Kittelson, O.	127-140	1800	Nil**
145-94-32 DCC 1	68	10-8	Murphy, C.	22-38	1900	21±8**
145-94-32 DCC 2	69	10-8	Murphy, C.	15	6796	99±13**
144-95-2 CBC	70	10-8	Mittlestad, R.	——	2000	Nil**
145-94-20 DDC 1	73	10-10	Saetz, J.	31	3200	26±9**
145-94-20 DDC 2	75	10-10	Saetz, J.	40	2100	252±13**
144-94-05 BBB	81	10-28	Fritz, F.	120-160	1800	Nil**
144-94-05 BBC	98	10-3	Fritz, F.	35	——	192±14**

*Expressed in tritium units.
**Sample distilled before analysis.

Table 3.6.10-2. *Results of tritium analyses of samples collected UND observation wells in the Dunn Center area during 1975. Results are expressed in tritium units (TU).*

Location	Well No.	Intake Interval (ft)	Stratigraphic Unit	Date Sampled	Specific Conductance (micromhos)	Tritium (TU)[a]
146-93-23 CBB 3	8-3	77-93	A interval	11-13	1646	15±7
144-93-08 BCB 2	16-2	235-262	H lignite	11-3	2692	Nil
144-93-08 BCB 4	16-3-2	60-80	DC lignite	11-3	2307	34±8[b]
144-94-25 CAA 1	21-1	260-280	H lignite	10-15	2435	23±10
143-94-01 ABB 1	22-1	75-105	DC lignite	7-30	——	16±7
144-94-07 DAA 3	30-1	35-38	A lignite	12-9	8460	44±6
145-93-27 ABC 1	32-1	140-165	H lignite	10-1	1897	Nil
144-94-13 CBB 2	48-1	60-70	A lignite	10-13	4563	60±6
144-94-12 ABA 3	52-1	42-52	Coleharbor	10-1	1564	Nil

[a] All samples distilled before analysis.

[b] Identified from tritium and oxygen-18 data as being contaminated with drill or wash water.

very high ^{18}O values (-9.4 and -9.6 per mille), indicating that the groundwater supplying the well is derived from the lake. When the second sample was taken the well was pumped for a much longer period than for the first. The decreased tritium concentration in this sample evidently was caused by the drawing in of much older water from the surrounding aquifer during the longer pumping period. The fact that the TU value of the second sample is so low is useful in that it indicates that the well is not drawing the evaporitic water from the lake by way of vertical circulation along the casing that could occur if the well were poorly constructed. The present lake water would have tritium values close to precipitation values and therefore could not produce a TU value as low as 15.

The five farm well samples that have tritium concentrations in the range of 10 to 30 represent a mixture of pre-1953 water and post-1953 water. Some of these values are just barely above the limit of detection. Water recharged to the groundwater zone since 1953 would have much higher tritium values even with the decrease caused by radioactive decay. Two of these wells are less than 31 feet deep and therefore would be expected to have tritium. The other four wells are in the depth range of 90 to 160 feet below ground surface. Consideration of the individual hydrogeologic settings of these well sites indicates that the very low tritium concentrations could possibly be a result of leakage of shallow water or surface water along the outside of the well casing because of poor well construction, or could be a result of mixing of older and modern water as the groundwater moves from the recharge areas to the zones from which it is pumped. The ^{18}O values from these three wells are in the range of -15.4 to -17.2 and therefore are not anomalous.

The remaining 34 of the 49 farm wells analyzed for tritium contain no significantly detectable tritium. It can be concluded, therefore, that these groundwaters are greater than 23 years old. The depths of these wells are almost all in the range of 80 feet to 200 feet below ground surface. Three wells are between 200 and 300 feet. There are only two wells more than 300 feet deep. These are located at 1535 and 1524 feet in the Fox Hills Formation. The most important hydrologic information to be obtained from the tritium data is that post-1953 water has not penetrated over a widespread area to depths generally greater than 50 feet below ground surface. It should be noted that almost all of the farm wells analyzed for tritium are located in the Sentinel Butte Formation. Since the regional water table in the Sentinel Butte Formation is generally between 50 and 150 feet below ground surface it is evident that in terms of the groundwater zone, tritium is generally below detection in the shallow part of the groundwater-flow system as well as in the deeper parts. The tritium data is therefore in agreement with the conclusion derived previously based on hydraulic head and hydraulic conductivity data indicating that the groundwater-flow systems in the bedrock are generally very sluggish because of the widespread occurrence of aquitards and the low frequency of major recharge events. The highest tritium concentrations detected in any of the farm or UND wells was 252±13 TU (sample no. 75 well depth 40 ft). All other values were below 200 TU. This indicates that no significant zones of the high tritium water that occurred in the late 1950's and 1960's have been detected in the wells. Some of this water has probably mixed with older non-tritiated groundwater to produce much lower tritium concentrations in some zones.

Of the nine UND wells sampled, three have major tritium concentrations (in the range of 30 to 60), three have detectable but very low values (in the range of 15 to 23), and three have no detectable tritium. The three higher tritium concentration wells are in shallow lignite aquifers, at depths from 35 to 80 feet below ground surface. Two of the three wells with minor tritium concentrations are also less than 100 feet deep, and one is 280 feet deep. The hydrogeologic setting of this deeper well indicates that it is very unlikely that tritium occurs at this depth as a result of natural seepage. It is more likely that the small amount of tritium detected in the sample is due to the presence of a minor amount of drill or wash water in the well. One of the major uses of tritium in studies of this type is similar to ^{18}O in that it is a good indicator of the status of well cleaning. The drill and wash water used was surface water and therefore contains high tritium concentrations because it is almost invariably obtained from lakes, ponds, sloughs or streams. For example, UND well 16-3-2 at 80 feet, which is one of the three highest tritium concentration wells, was designated as being moderately contaminated on the basis of ^{18}O data. It is expected that with further cleaning the tritium values for this well will go below the detection level.

Of the three UND wells with no detectable tritium, one is located at relatively shallow depth (well 52-1 at 52 feet) in the main valley fill aquifer in the plant site. This lack of tritium at such shallow depth in the sand and gravel aquifer indicates that the pebble-loam and silt that overlies the aquifer in the proposed plant site area is sufficiently extensive and has sufficiently low hydraulic conductivities to prevent infiltration of significant amounts of young water downward into the aquifer. Seepage of recharge water into the aquifer is very slow; and, therefore, it must be concluded that seepage of water out of the sand and gravel aquifers is also very slow. This conclusion is consistent with the observation derived previously on the basis of ^{18}O data which indicates that the seepage out of the valley fill into the lignite aquifers that abut against the walls of the buried valley is not a large enough amount to be identifiable. Samples from other UND wells in the valley fill aquifers are presently being analyzed to determine if the absence of tritium is an extensive characteristic of the system.

3.6.11 Interpretation of the Carbon Isotope Data

The results of carbon isotope analyses of samples from 14 wells, which includes 9 farm wells and 5 UND wells, are listed in table 3.6.11-1, along with other isotope and chemical data for the same wells. The carbon-14 values range from 1.3 to 119 percent modern. The carbon-13 values range from -9.5 to -16.9 per mille. Nine of the ^{13}C values are between -9.7 and -12.9 per mille.

On the basis of a study of ^{14}C and ^{13}C distributions in aquifer systems of deltaic origin with significant lignite contents, Winograd and Farlekas (1974) have indicated that interpretation of ^{14}C data in terms of groundwater ages and flow rates can be very difficult. Deltaic, lignite-rich aquifer systems are considered a major problem with regard to hydrologic use of carbon isotopes because of the tendency for the groundwater chemistry in these systems in some areas to be strongly influenced by CO_2 (gas) generated within

Table 3.6.11-1. *Results of carbon isotope analyses of samples that were collected from farm wells and UND wells in the Dunn Center area during 1975. Other isotopic and chemical data are included for comparison.*

Location	Sample No.	Date (1975)	Owner or Site No.	Total Depth or Intake Zone	Strat. Unit	^{18}O per mille	Tritium	Elect. Cond.	pH	Total Dissolved Inorganic Carbon	^{13}C per mille PDB	^{14}C Percent modern
144-93-23 ADA 2	2	5-24	Rohde, E.	210	DC(L)	-17.0	Nil	2000	8.0	1270	-15.3	7.2
145-92-25 ABA 7	7	5-24	Halliday	1555(F)	FH	-17.0	Nil	2300	8.5	1100	- 9.7	1.3
146-93- 3 CDD	8	5-24	A. Voight	1525(F)	FH	-17.4	Nil	2100	8.2	1150	-10.5	1.8
145-93-21 CDD	23	5-24	G. Lynch	100(F)	F(L)	-16.2	—	1700	8.4	750	-10.0	45.3
144-94-34 BAB 2	35	5-24	B. Trampe	100	E(L)	-16.7	Nil	2800	8.0	740	-15.6	11.3
144-93-07 AAB 1	C4	10- 2	I. Kling	95	DC(L)	-16.8	—	5100	7.1	550	-12.9	5.9
144-93-14 CBBC 6	F71	10- 1	A. Rohde	300	DC(L)	—	Nil	—	—	—	-10.7	4.8
144-93- 8 ABB 2	F75	10- 1	H. Kling	140	DC(L)	-17.2	Nil	—	—	—	-16.9	13.1
145-93-27 ACB	F78	10- 2	UND 32-2	120	CH	-16.1	—	—	—	—	- 9.5	24.3
144-94-12 ABA	96	10-27	UND 52-2	89	CH	-15.6	—	—	—	—	-13.5	13.3
144-94-05 BBC	98	10- 3	F. Fritz	20	F(L)	-10.0	192±14	2323	8.3	—	-12.6	119.2
144-94-01 CDD		10-24	UND 49-1	72-120	CH	-15.4	—	2400	7.3	890	-12.7	13.3
146-93-23 CBB	109/110	11-13	UND 8-3	77-93	A(I)	-18.9	15±7	340	7.7	80	-12.5	45.5
144-94-07 DAA	113/114	10-29	UND 30-1	35-38	A(L)	-16.3	44±6	8400	8.2	1330	-10.3	8.4

(F)=Flowing Well
A(I)=A Interval
A(L)=A Lignite
DC(L)=Dunn Center bed
E(L)=E Lignite
F(L)=F Lignite
CH=Coleharbor
FH=Fox Hills

the aquifers. According to Winograd and Farlekas there are two main mechanisms that can cause CO_2 generation within the aquifers: (1) coalification of lignite, and (2) oxidation of the cellulose content of the lignite. If CO_2 is generated by one or both of these mechanisms in the groundwater-flow system, H^+ will be produced (i.e., pH decrease) by the reactions:

$$CO_2+H_2O \longrightarrow H_2CO_3$$
$$H_2CO_3 \longrightarrow H^++HCO_3^-$$
$$HCO_3^- \longrightarrow H^++CO_3^{2-}.$$

If calcite or dolomite is present in the system the excess hydrogen ions will be consumed by dissolution of these minerals, illustrated here by calcite dissolution:

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

It is evident from the above equations that the dissolved inorganic carbon in the groundwater will be increased by the inputs of carbon from both the CO_2 production and the carbonate mineral dissolution. If the lignite carbon and the carbonate minerals are more than about 50,000 years old, these carbon inputs to the groundwater will contain no significant ^{14}C because this isotopic fraction would have been lost by radioactive decay. This old carbon is usually referred to as dead carbon because of its lack of significant carbon-14. If ^{14}C data for groundwater are to be used as groundwater age indicators, it is necessary to estimate the percentage of dead carbon derived from these sources within the total dissolved inorganic carbon in the well samples. With the available data from the Dunn Center area it is not possible to make accurate estimates of this type. The purpose of the following discussion is to interpret that data in a semi-quantitative manner as a basis for determining whether or not the carbon isotope data is consistent with the geochemical and hydrologic trends described on the basis of other kinds of data elsewhere in this report.

Dissolution of calcite or dolomite consumes CO_2. If the dissolution occurs below the water table in systems where CO_2 is not replenished by lignite coalification or oxidation of organic matter, the CO_2 partial pressure in equilibrium with the water will decrease and will continue to decrease as long as carbonate mineral dissolution proceeds. The calculated CO_2 partial pressures for water samples from the UND and farm wells are commonly below the value for the earth's atmosphere (i.e., below $10^{-3.5}$atm), which indicates that CO_2 consumption without replenishment must be occurring.

The pH and HCO_3^- data for the UND

and farm-well samples indicate that calcite dissolution is a major geochemical process within the groundwater-flow system. This is discussed in more detail below. It is necessary for purposes of ^{14}C data interpretation to derive estimates of the effect of dissolution below the water table of calcite. For the Dunn Center groundwater these estimates are particularly important since the groundwater has very high dissolved inorganic carbon concentrations, almost entirely in the form of HCO_3^-.

In this interpretation some of the methods described by Wigley (1975) will be used.

The ^{13}C values for CO_2 gas in the soil zones of recharge areas are controlled by either the Calvin or the Hatch-Slack photosynthetic cycles for plant ecosystems. The Calvin cycle occurs in humid, semi-humid, and some semi-arid regions. The Hatch-Slack cycle is typical of arid regions. The soil zone ^{13}C for CO_2 gas in the Calvin cycle is -25±3 per mille, whereas for the Hatch-Slack cycle values close to -16 per mille are normal. If infiltrating water with soil zone CO_2 dissolves carbonate minerals in the soil zone (i.e., above the water table) to the extent that the pH rises and nearly all of the CO_2 in the water is converted to the HCO_3^- form (which would be the case for pH values between about 7 and 9), the ^{13}C of the dissolved inorganic carbon (i.e., the C in the HCO_3^-) will have a value of $(-25\pm3)+8= =17\pm3$ per mille. The ^{13}C value is increased because of isotopic fractionation between the carbon species. If a Hatch-Slack photosynthetic cycle is assumed, the ^{13}C value of the carbon in the HCO_3^- will be about -8 per mille. When the infiltrating water enters the groundwater-flow system and thereby becomes removed from the CO_2 reservoir of the unsaturated zone, dissolution of carbonate minerals can then begin to alter the ^{13}C of the water because the carbon system can no longer maintain isotopic equilibrium with the soil air.

It is expected that the calcite in the Sentinel Butte Formation has been transported and deposited in the sediments in particulate form by mechanical processes, rather than deposited as precipitates in the fresh water depositional environments. It is assumed that the original depositional environment of the calcite was marine and therefore that the ^{13}C values of the calcite is close to zero. In the near future this assumption will be checked by ^{13}C analyses of core samples from the Sentinel Butte Formation. It is expected, therefore, that dissolution of calcite below the water table in closed-system conditions will cause a decrease in the ^{13}C of the dissolved inorganic carbon in the water, and a decrease in the ^{14}C content.

If the dissolved inorganic carbon (DIC) content of the water when it enters the sub-water-table zone is designated as mC_o and the total DIC after some calcite dissolution below the water table is mC, then the new ^{13}C value after dissolution will be

$$^{13}C_o \times \frac{mC_o}{mC}$$

where the ^{13}C of the carbon from calcite dissolution below the water table is taken as zero (per mille). Since the ^{13}C values of all of the samples analyzed (table 3.6.11-1) are less than -9.7 per mille (i.e., more negative) and since the Hatch-Slack cycle would produce ^{13}C values of about -8 per mille after dissolution above the water table, it does not appear feasible for the Hatch-Slack cycle to be applicable to the Dunn Center system. This is what would be expected considering the present and past climatic regimes of the region. The Calvin cycle for initial ^{13}C values is therefore used in the following analysis.

If the ^{13}C of soil-zone gas generated by the Calvin cycle is taken as -25 per mille, Wigley (1975) has shown that dissolution of calcite under a wide range of initial soil-zone CO_2 partial pressures will produce equilibrium ^{13}C values of -16.5 per mille for open system dissolution (i.e., dissolution above the water table) and -13.7 per mille if all of the dissolution occurs below the water table. Various hybrid combinations of both open and closed system dissolution produce values between these two extremes. In Wigley's analysis dissolution of calcite to equilibrium occurs with a specified initial CO_2 partial pressure. Continued dissolution because of Ca^{2+} removal by cation exchange is not taken into account. For Wigley's extreme case (complete closed system dissolution) the ^{13}C value of -13.7 per mille is produced with an end point mC_0/mC value of 0.532. Therefore, under these conditions about half of the DIC would be derived from closed system calcite dissolution, and consequently the initial ^{14}C value would be diluted by about 50 percent dead carbon.

If, as is the case in the Dunn Center area, calcite dissolution continues because of Ca^{2+} removal by exchange with Na^+ on clay minerals, the mC_0/mC value will decrease and the ^{13}C values of the DIC will increase (i.e., becomes less negative). This interpretation adequately accounts for the ^{13}C values observed for the Dunn Center samples, the highest of which is -9.7 per mille.

For ^{14}C with a half-life of 5700 years the radioactive decay equation can be written in the form

$$t=-8260\ln\frac{R}{Q}$$

where t is the adjusted (sometimes referred to as corrected) groundwater age, R is the ratio of sample ^{14}C to the ^{14}C content of a modern standard and Q is the adjustment factor to account for dilution by dead carbon due to carbonate mineral dissolution. Following Wigley (1975) Q will be taken as mC_0/mC. To obtain an estimate of the true age of the groundwater with carbon isotope data listed in table 3.6.11-1, R can be obtained from the ^{14}C% modern column, by expressing the measured ^{14}C values as a ratio rather than as percent. To obtain estimates of the effects of Q on the ages that can be calculated using the above equation an extreme case will be evaluated.

For illustrative purposes it will be assumed that the infiltrating recharge water starts off with a relatively high CO_2 partial pressure of $10^{-1.5}$ atm, which is two orders of magnitude above the CO_2 partial pressure in the earth's atmosphere. It is further assumed that calcite is dissolved to equilibrium entirely under closed system conditions. According to Wigley this will result in an equilibrium ^{13}C value of -13.7 per mille and a mC_0/mC of 0.53. It will be further assumed that dissolution continues (under closed system conditions) because of exchange removal of Ca^{2+} and that the ^{13}C content of the DIC reaches a value of -9.7, which is the highest of the values obtained for groundwater in the Dunn Center area. If the ^{13}C of the calcite is taken as zero, the mC_0/mC that will occur when the ^{13}C reaches -9.7 is 0.38. This value is obtained by simply multiplying 0.53 by the ratio -9.7/-13.7. If the groundwater chemistry has evolved to this point (i.e., to the point where $^{13}C=-9.7$ and $mC_0/mC=0.38$) before sufficient time had elapsed for a significant percent of ^{14}C to be lost by radioactive decay, the water would have an apparent percent modern value of 39 percent. Under the assumed conditions used in this calculation, the only way the ^{14}C value could be lower would be if sufficient time had elapsed for radioactive decay to be important. For example, if 5700 years (one-half-life) had elapsed, the ^{14}C value would be reduced from 38 to 19 percent. Inspection of table 3.6.11-1 indicates that only three of the eleven ^{14}C values are above 20 percent modern. Four of the values are below 10 percent modern.

The above analysis indicates that it is very likely that the samples with low ^{14}C values have acquired their low values to at least a major extent through radioactive decay. The ^{14}C data are therefore consistent with the interpretation based on hydrologic data, which indicates that groundwater many thousands of years old is common within the groundwater-flow system.

It should be kept in mind that the assumption of complete closed system dissolution through the entire calcite dissolution process as assumed in the above example is an extreme case which will produce the lowest mC_0/mC ratio feasible within the geochemical framework that seems to best fit the data. The highest ^{13}C value from the 14 analyses in table 3.6.11-1 was used in the calculation. If a more representative ^{13}C value were used, the mC_0/mC factor calculated with Wigley's model would be higher and thus decrease the effect of dead carbon on the ^{14}C values. This does not take into account, however, that some oxidation of organic matter may occur within these aquifers. Such processes would lower both the ^{13}C and ^{14}C contents and could possibly account for the lower ^{13}C values observed in these samples. In this case Wigley's model is not applicable and age corrections based on his assumption would be too small, i.e., the corrected ages would still be too old. Nevertheless, even in view of this we can safely assume that the water in these aquifers is thousands of years old. The two samples from the Fox Hills aquifer (table 3.6.11-1) have ^{14}C values less than 2 percent modern, which suggests that this water is extremely old. It likely was recharged into the groundwater-flow system during Pleistocene time. The three highest ^{14}C concentrations, in the range of 45 to 119 percent, have detectable tritium concentrations, which indicates that these waters are less than 23 years old. The sample with 119 percent ^{14}C has a tritium concentration of 192±14 TU. The ^{14}C concentration is more than 100 percent of the modern standard because the water contains ^{14}C caused by atmospheric testing of thermonuclear devices. The modern standard is based on the ^{14}C content of biogenic carbon prior to 1953 increase.

UND well 30-1 has a moderate tritium concentration and a ^{14}C concentration of 20 percent. The hydrogeologic setting in which this well is located suggests that this water may be a mixture of young and older water.

3.6.12 Hydrologic Interpretation of Water Chemistry Data

The purpose of this section is to interpret on a hydrological basis the results of chemical analyses of UND, Water Commission, and farm wells. Results of analyses made available by the United States Geological Survey are included as part of the data base. The water chemistry data is considered from a water quality and use suitability viewpoint in a later section. In the present discussion, only the major ionic components, pH, and electrical conductivity are considered, since it is these constituents that are of most relevance in terms of hydrologic implications and major geochemical processes. The geochemical model to account for the observed major ion chemistry is discussed in detail in a later section.

Much of the electrical conductivity and Na^+, Ca^{2+}, HCO_3^-, SO_4^{2-}, and Cl^- data are displayed along cross sections A-A' and B-B' in figures 3.6.12-1 to -12. The electrical conductivity of samples from UND and farm wells in four aquifer units are shown in figures 3.6.12-13 to -16. The chemical data, grouped according to stratigraphic position of the wells, are summarized in table 3.6.12-1. Samples from the UND wells that have been identified on the basis of isotope data as being contaminated with drill or wash water have not been included on the figures. All of the chemical analyses used in this investigation are tabulated by Moran and others (1976, app. C-XI).

The chemical analyses of water samples in the Dunn Center area are grouped by water type and stratigraphic unit in table 3.6.12-1. When the mean values of the ratios, EPM (Na+K)/EPM total cation vs. EPM (HCO_3)/EPM total anion are plotted for each water type in table 3.6.12-1, 11 groups of analyses are evident (fig. 3.6.12-17). The values of these ratios are referred to as the Na-HCO_3 content of the water in the following discussions.

Five groups, Groups I-V, consisting of 76 analyses from the Coleharbor Formation, A-interval and lignite, Dunn Center bed and Dunn Center interval, E-interval and lignite, F-interval, G-interval, H-lignite, I-interval and J-lignite, form a set with a mean Na-HCO_3 composition of 39-44. This set ranges from $(NaCa)HCO_3$ type water of Group I, through $Na(SO_4HCO_3)$ type water of Group IV, to $CaSO_4$ type water of Group V. The unifying characteristics of this set are low salinity and low pH. The mean conductivity is 1294 micromhos/cm and the mean pH is 7.4. In general, the pH increases with increasing bicarbonate content and to a lesser extent with increasing sodium content. The conductivity tends to increase with increasing sodium content.

Group I consists of 3 analyses of

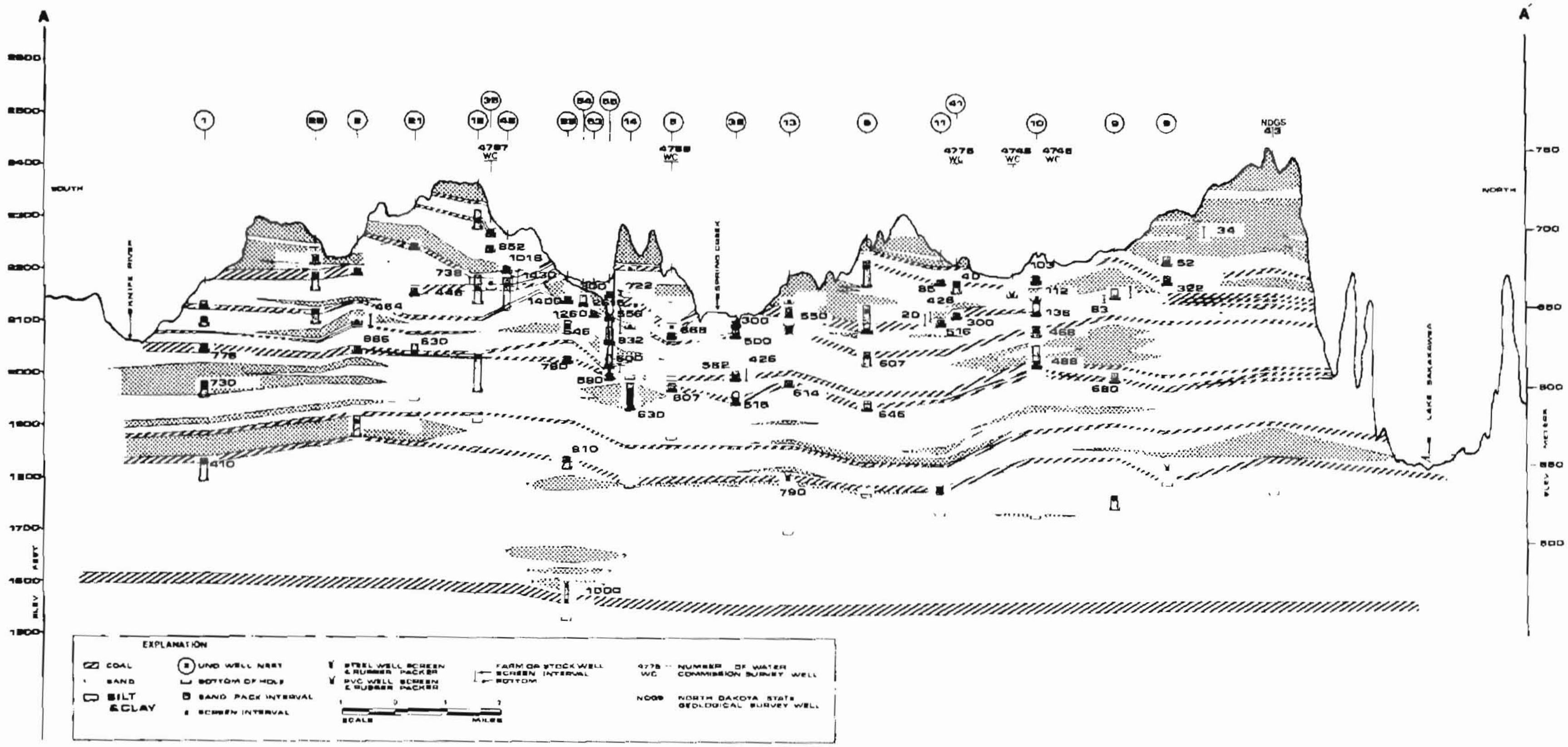


Figure 3.6.12-1 Concentrations of Na^+ (mg/liter) in samples from UND and farm wells along cross section A-A'. Location of cross section shown on figure 2.1.10-2.

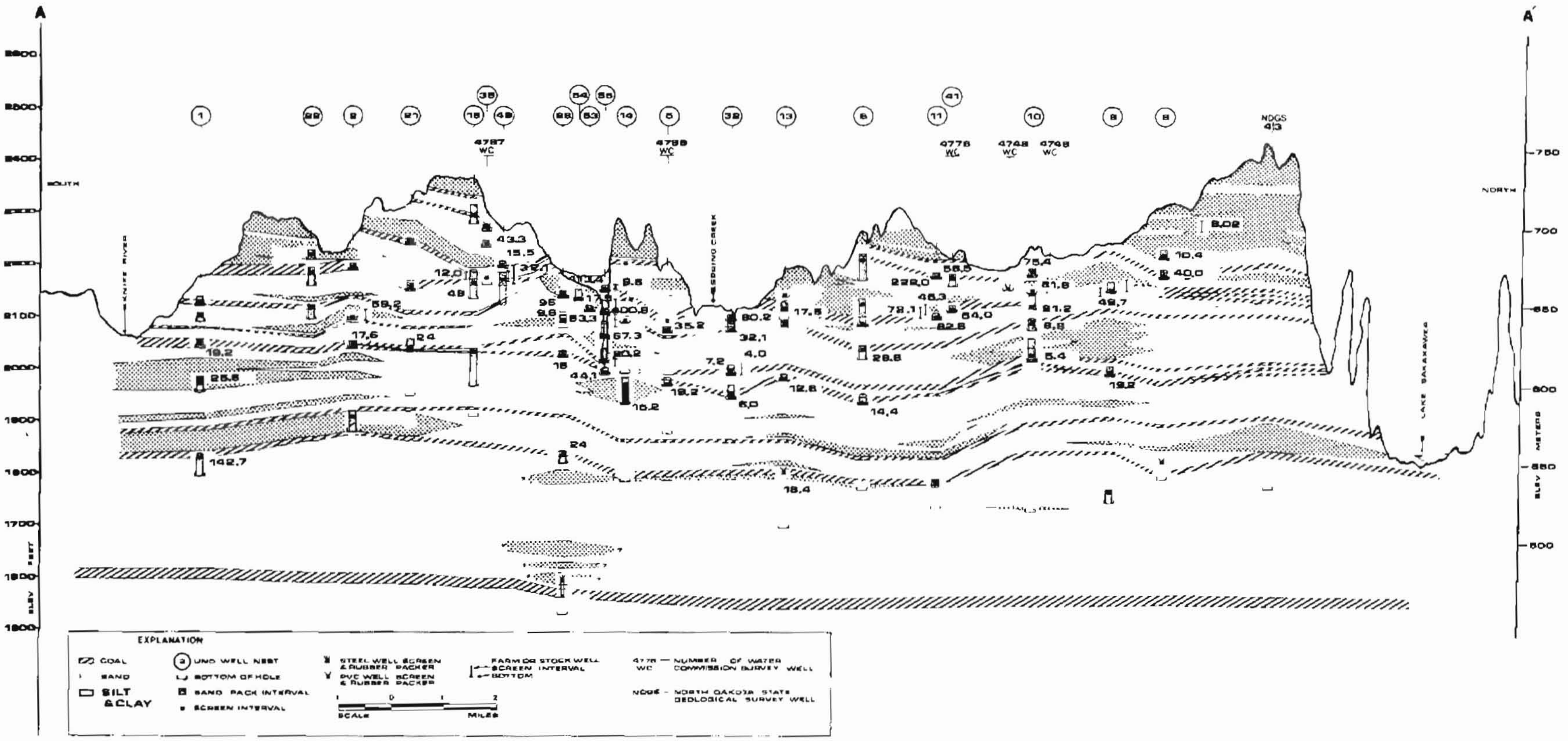


Figure 3.6.12-2 Concentrations of Ca^{2+} (mg/liter) in samples from UND and farm wells along cross section A-A'. Location of cross section shown on figure 2.1.10-2.

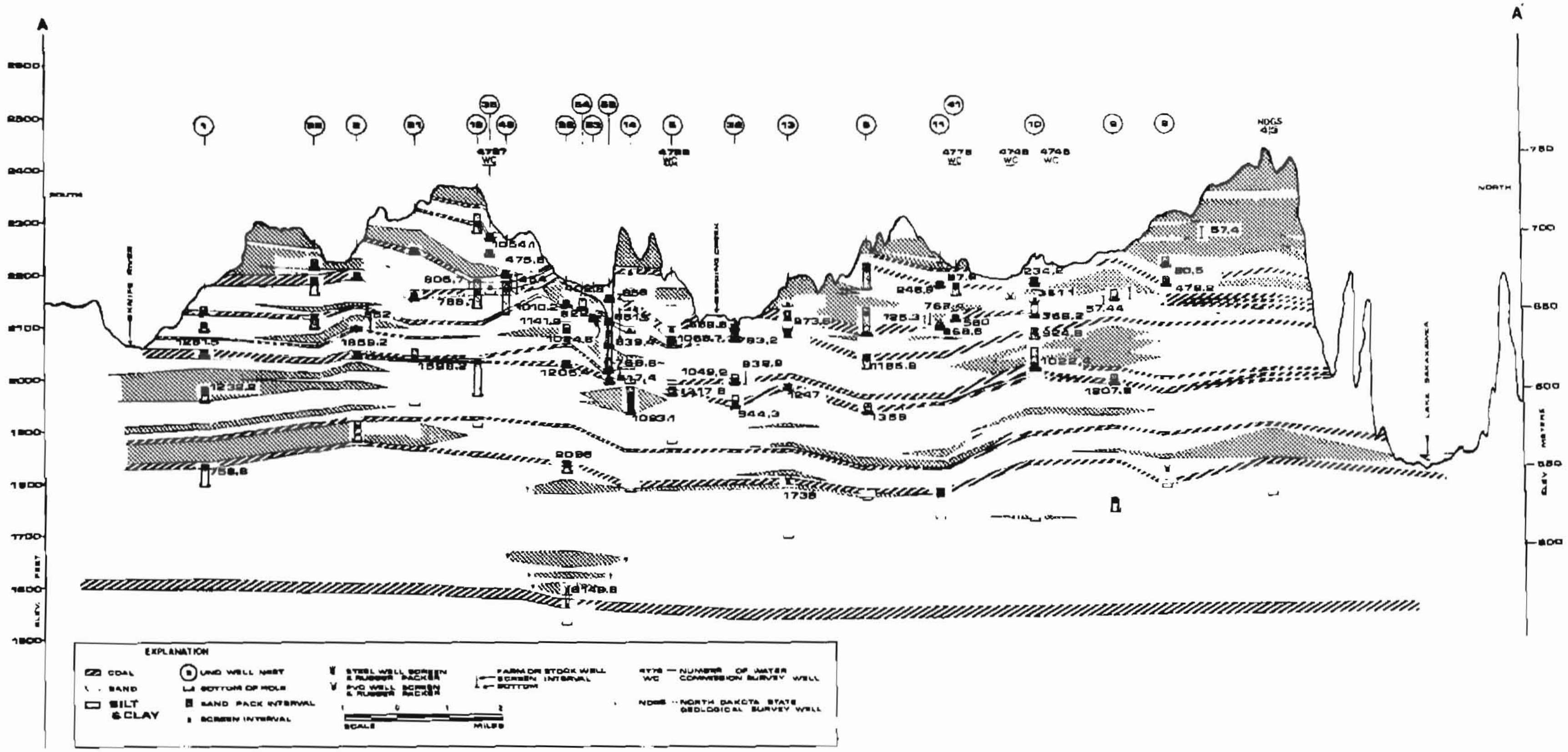


Figure 3.6.12-3 Concentrations of HCO_3^- (mg/liter) in samples from UND and farm wells along cross section A-A'. Location of cross section shown on figure 2.1.10-2.

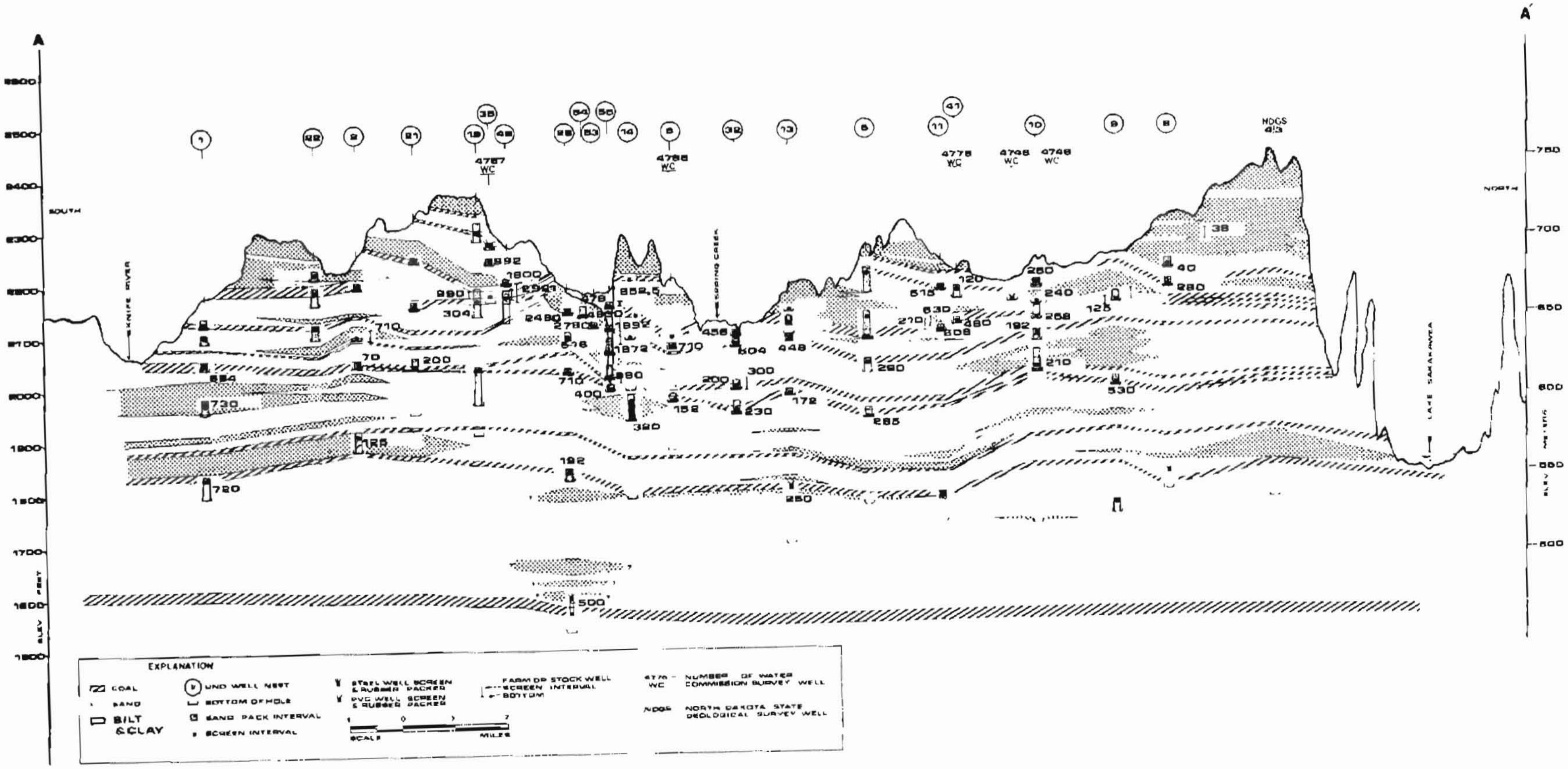


Figure 3.6.12-4 Concentrations of SO_4^{2-} (mg/liter) in samples from UND and farm wells along cross section A-A'. Location of cross section shown on figure 2.1.10-2.

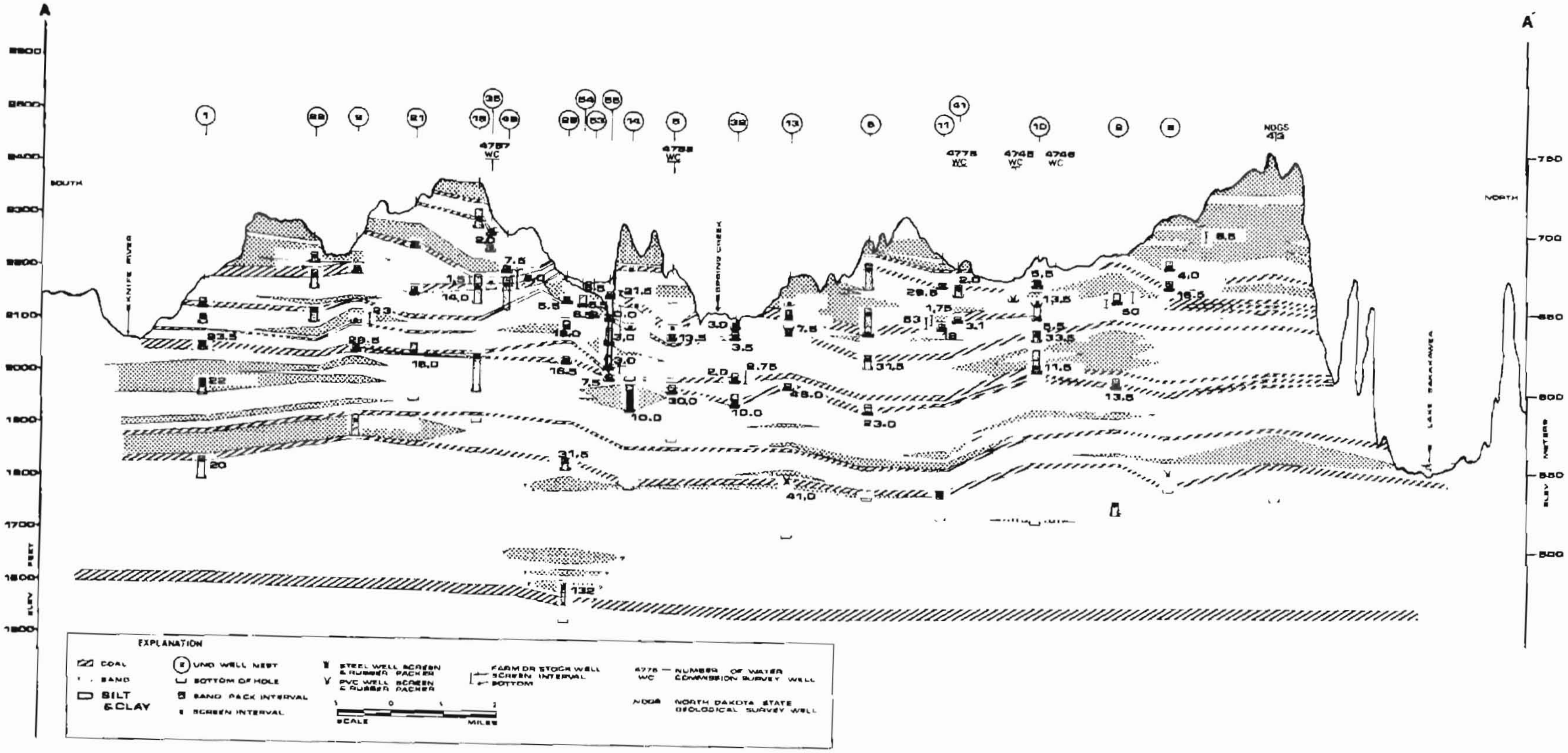


Figure 3.6.12-5 Concentrations of Cl⁻ (mg/liter) in samples from UND and farm wells along cross section A-A'. Location of cross section shown on figure 2.1.10-2.

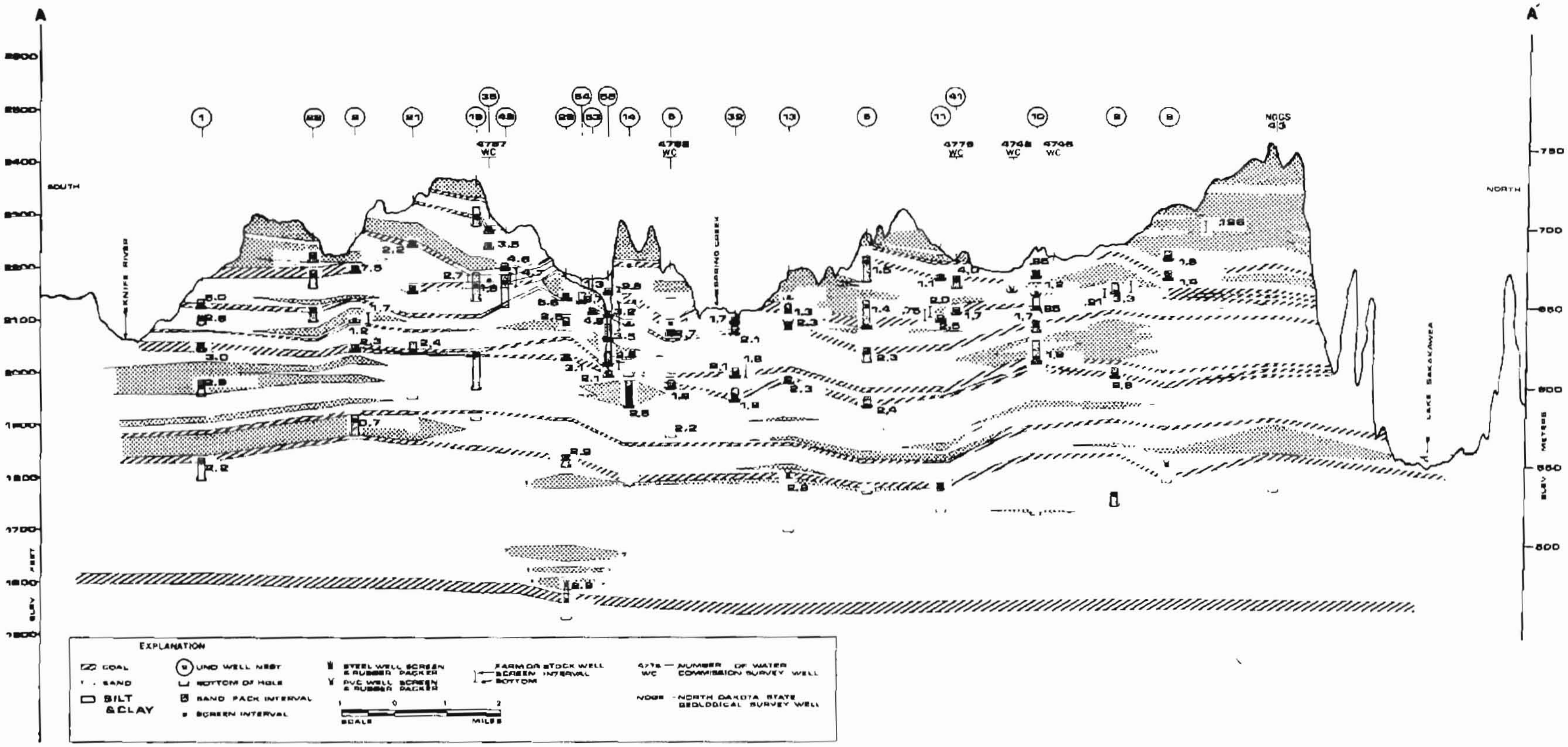


Figure 3.6.12-6 Electrical conductivity, in milli mhos/cm, of samples from UND and farm wells along cross section A-A'. Location of cross section shown on figure 2.1.10-2.

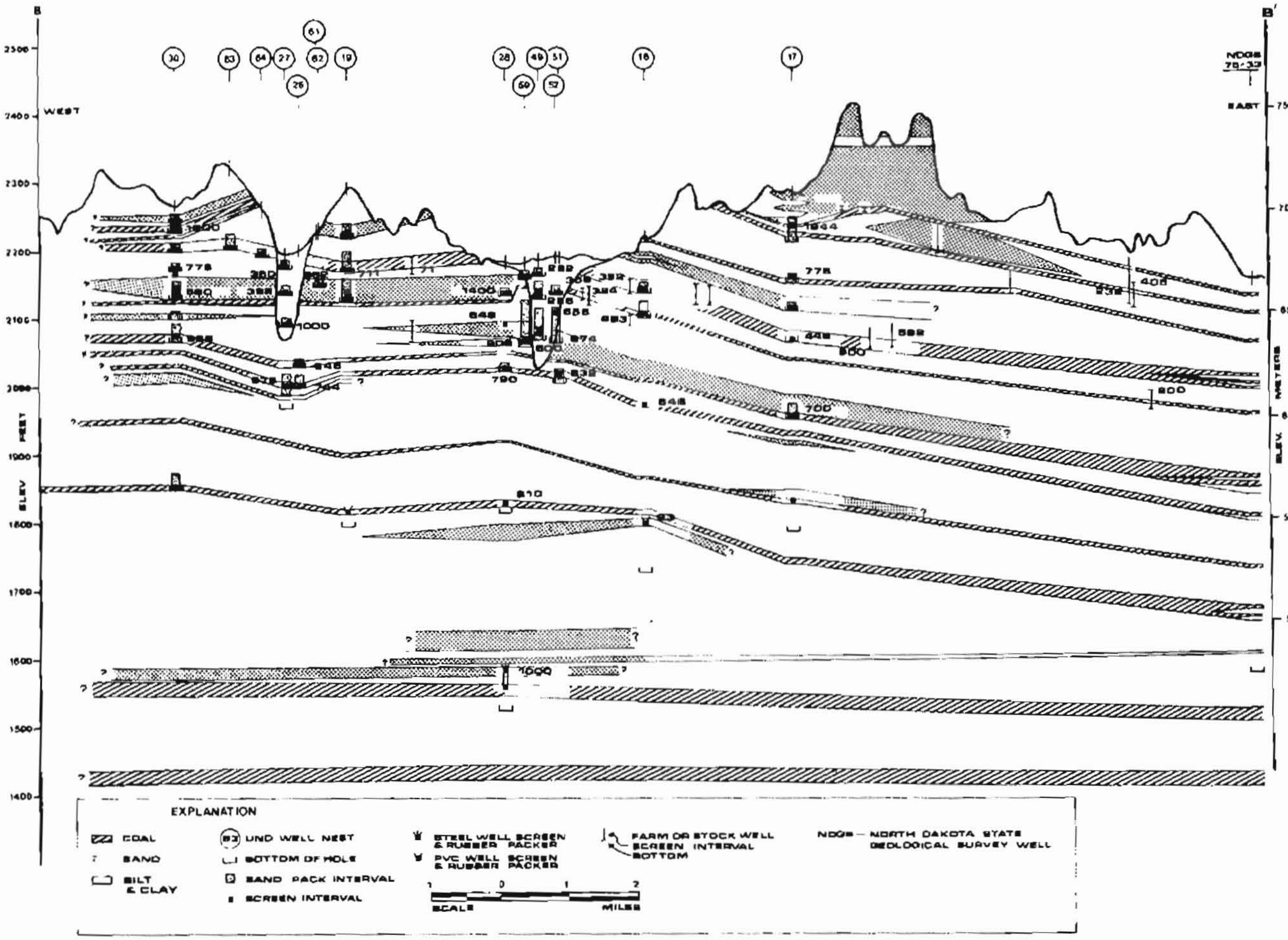


Figure 3.6.12-7 Concentrations of Na^+ (mg/liter) in samples from UND and farm wells along cross section B-B'. Location of cross section shown on figure 2.1.10-2.

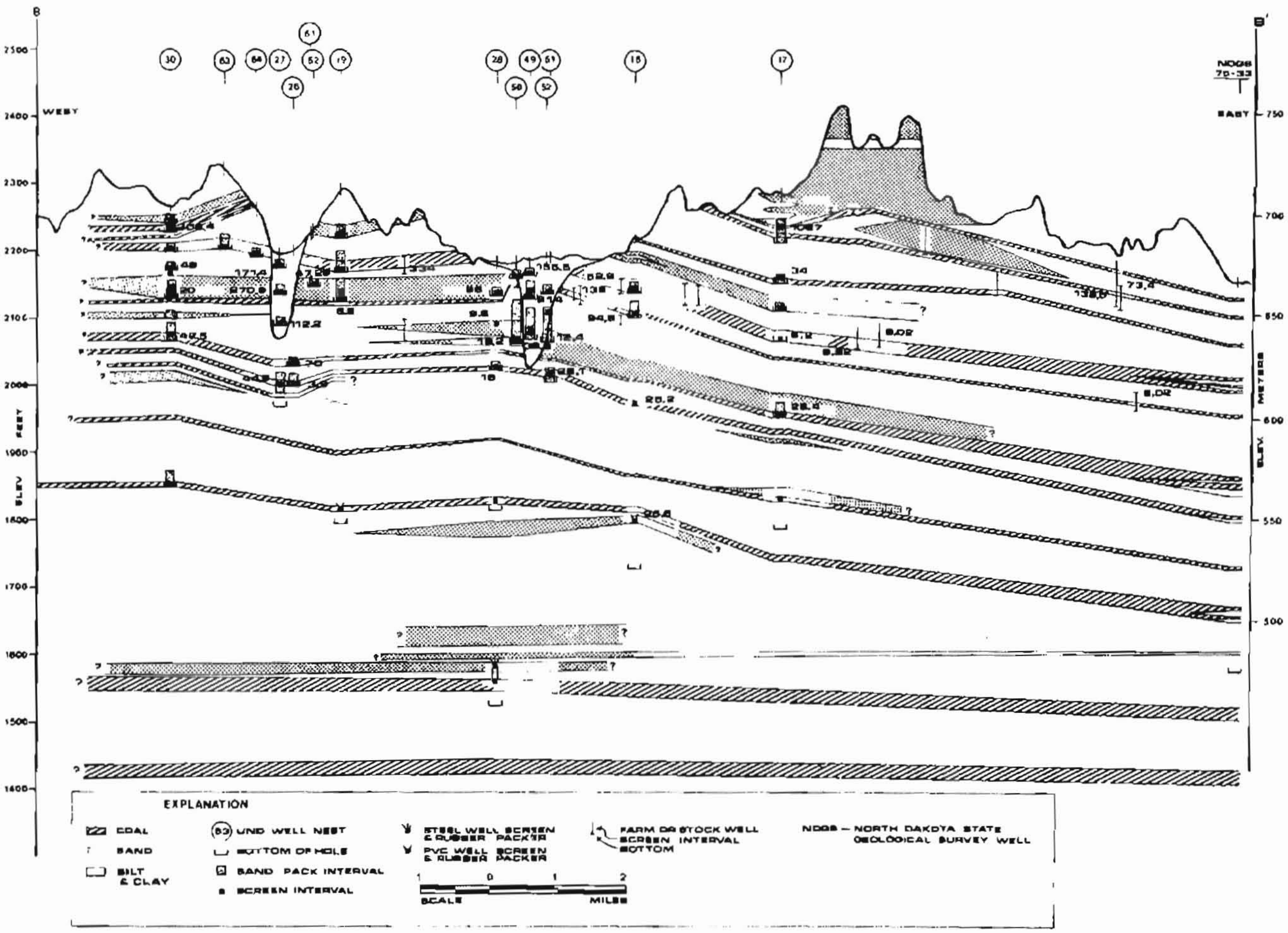


Figure 3.6.12-8 Concentrations of Ca^{2+} (mg/liter) in samples from UND and farm wells along cross section B-B'. Location of cross section shown on figure 2.1.10-2.

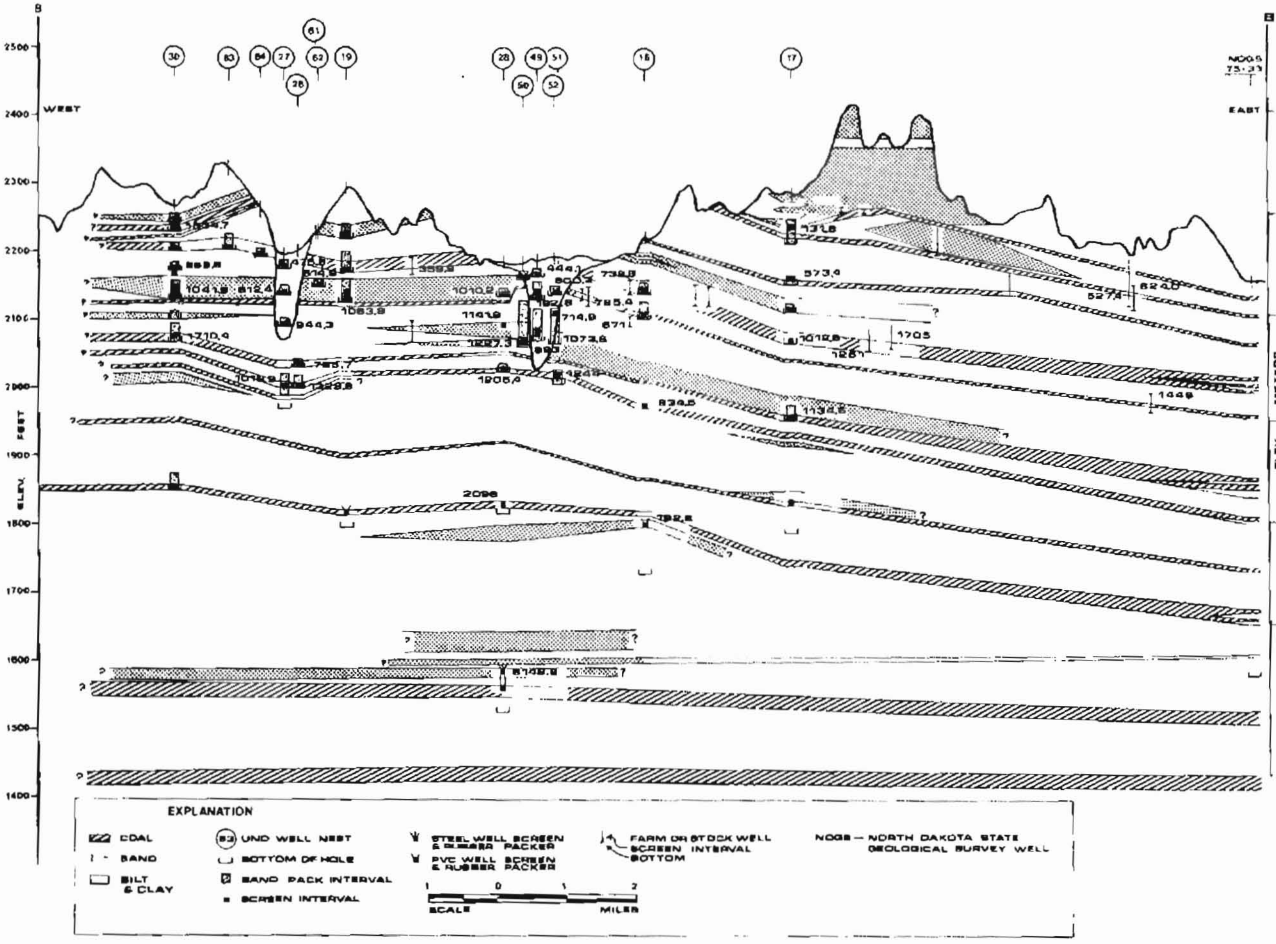


Figure 3.6.12-9 Concentrations of HCO_3^- (mg/liter) in samples from UND and farm wells along cross section B-B'. Location of cross section shown on figure 2.1.10-2.

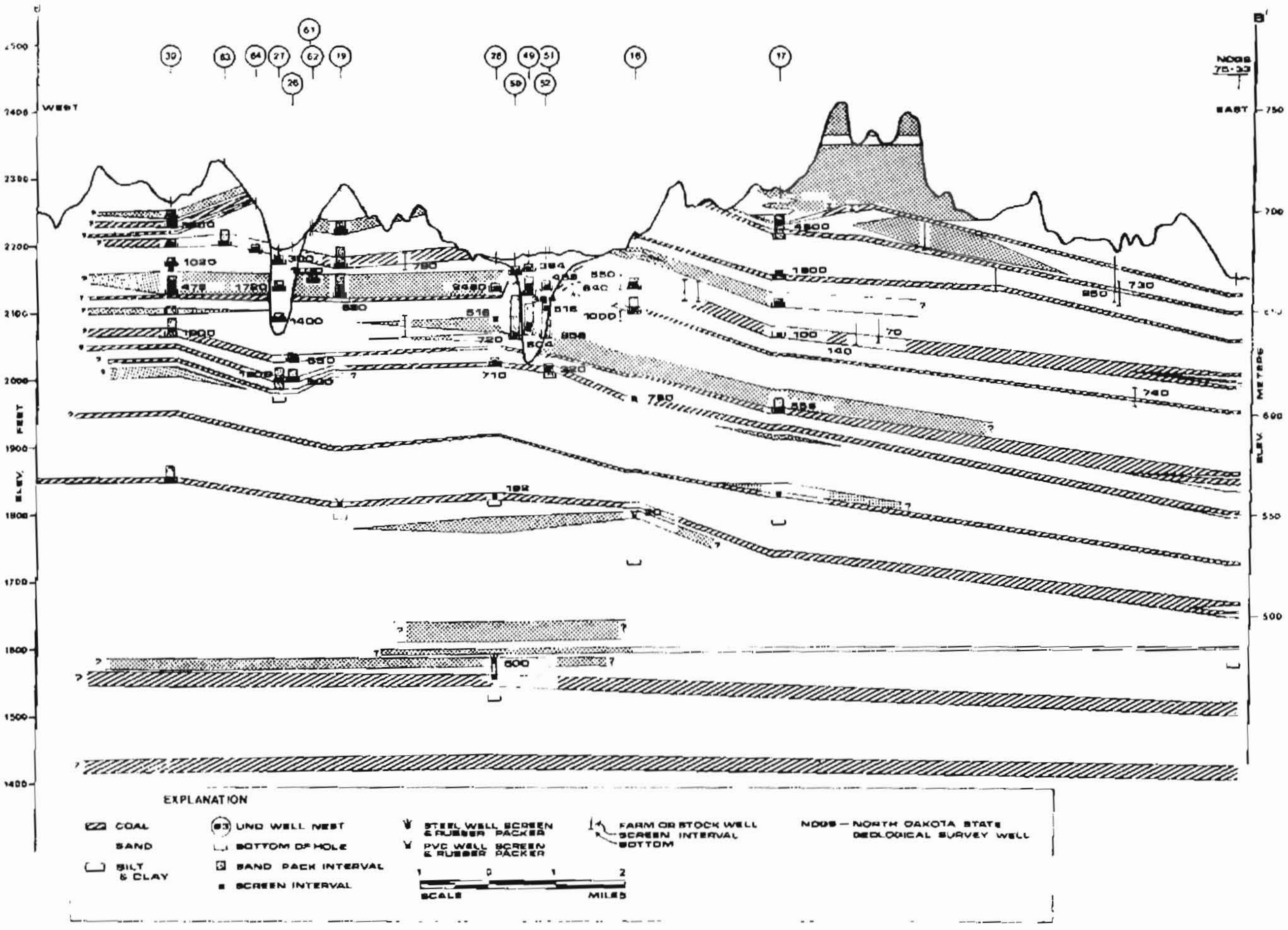


Figure 3.6.12-10 Concentrations of SO_4^{2-} (mg/liter) in samples from UND and farm wells along cross section B-B'. Location of cross section shown on figure 2.1.10-2.

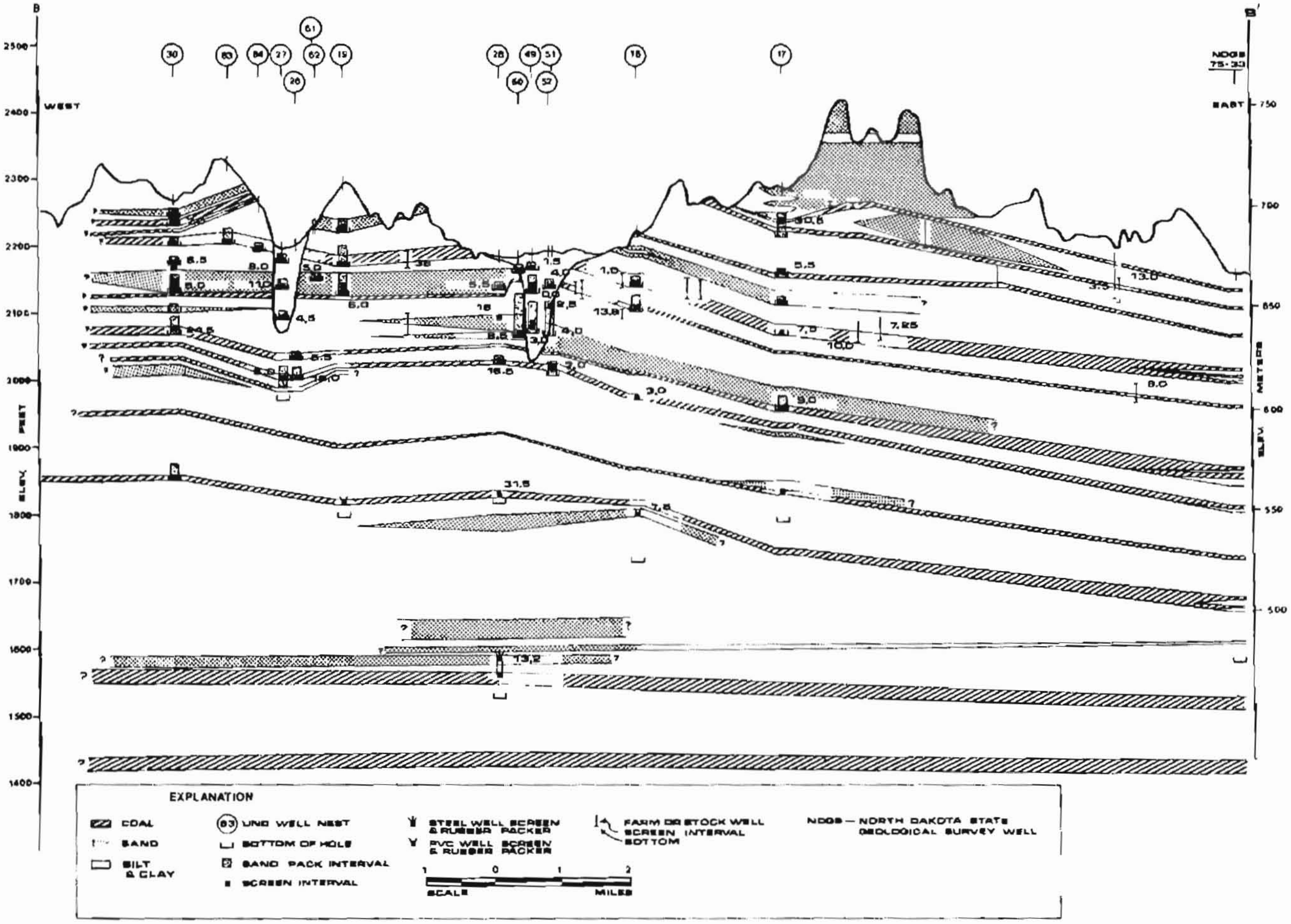


Figure 3.6.12-11 Concentrations of Cl⁻ (mg/liter) in samples from UND and farm wells along cross section B-B'. Location of cross section shown on figure 2.1.10-2.

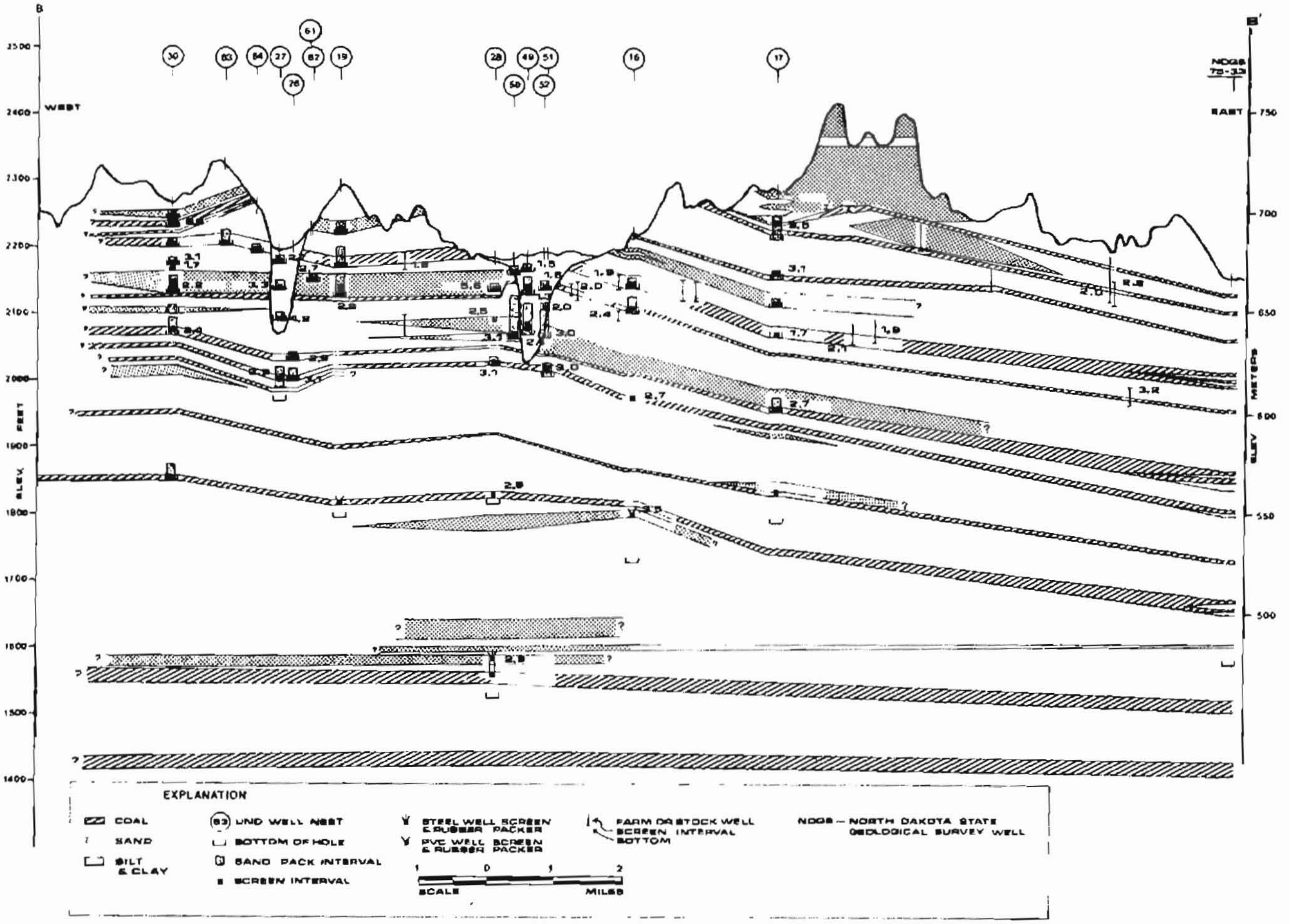


Figure 3.6.12-12 Electrical conductivity, in milli mhos/cm, of samples from UND and farm wells along cross section B-B'. Location of cross section shown on figure 2.1.10-2.

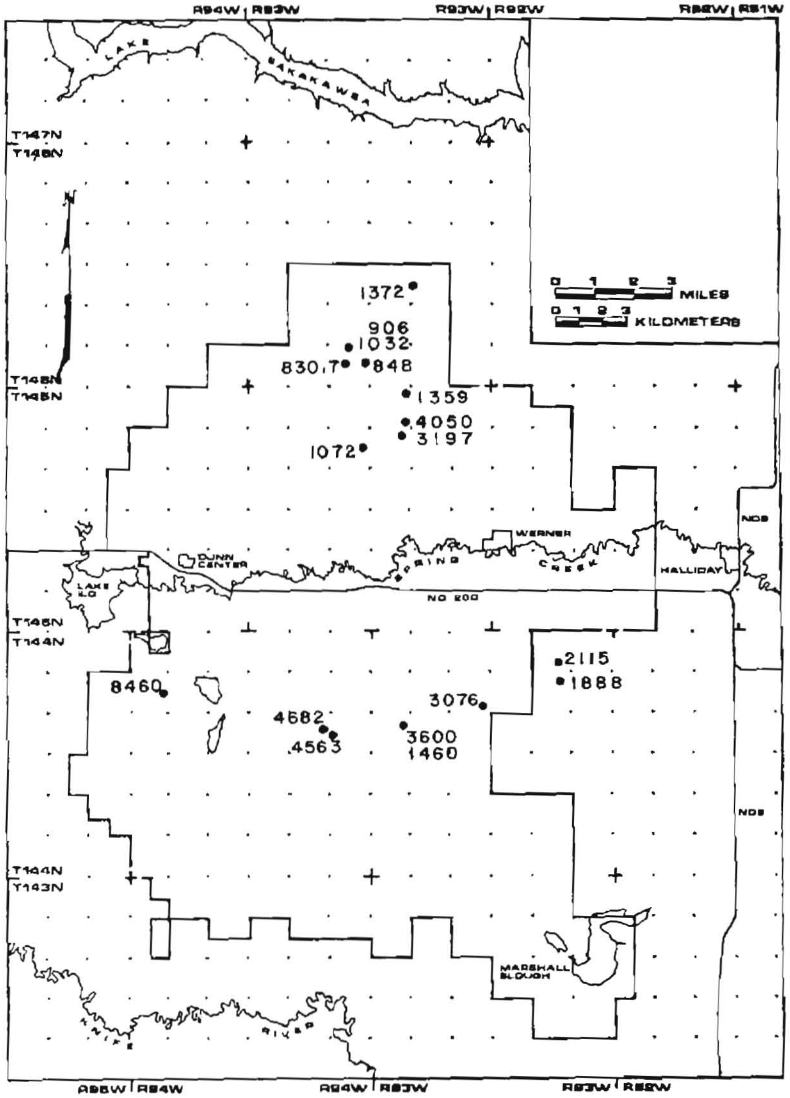


Figure 3.6.12-13 Map of electrical conductivity, in micro mhos/cm, of water samples from UND and farm wells in the A-lignite.

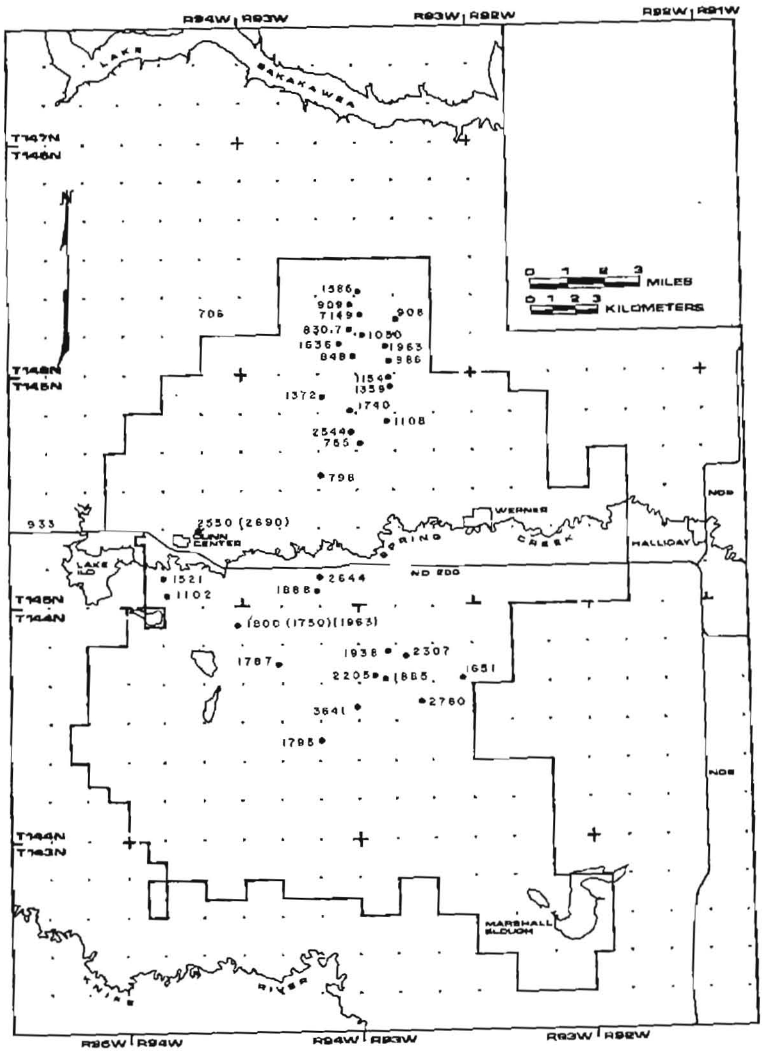


Figure 3.6.12-14 Map of electrical conductivity, in micro mhos/cm, of water samples from UND and farm wells in the Dunn Center bed.

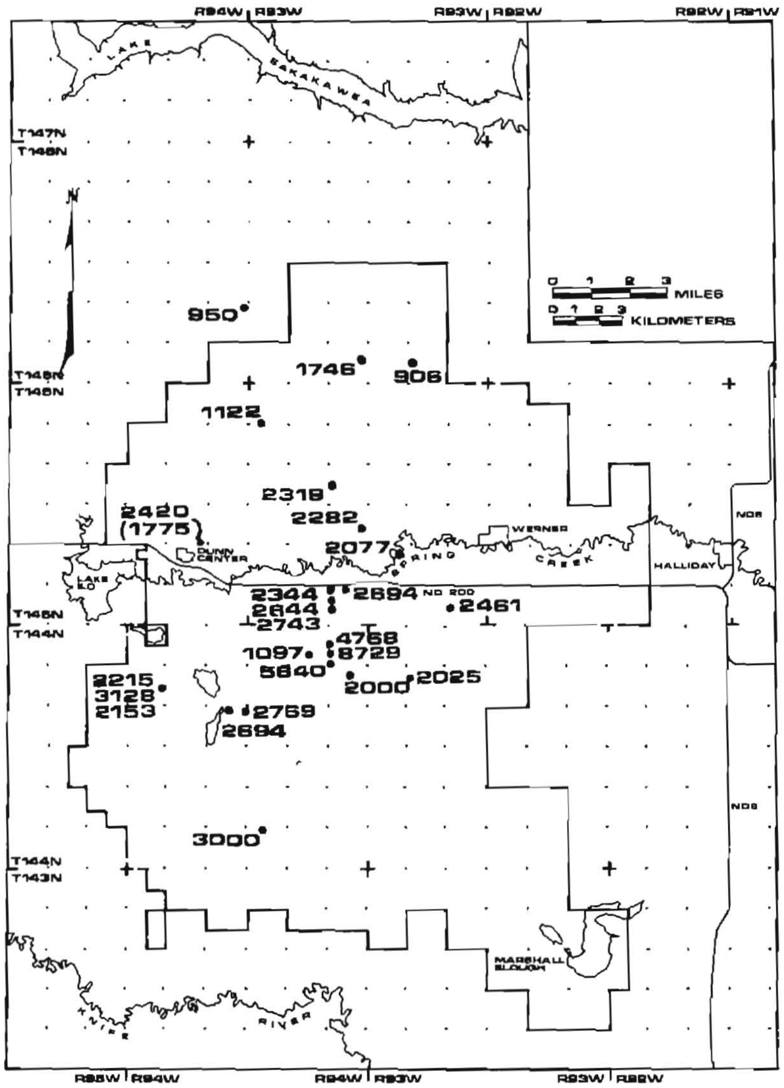


Figure 3.6.12-15 Map of the electrical conductivity, in micro mhos/cm, of water samples from UND and farm wells in the E-interval, including the E-lignite.

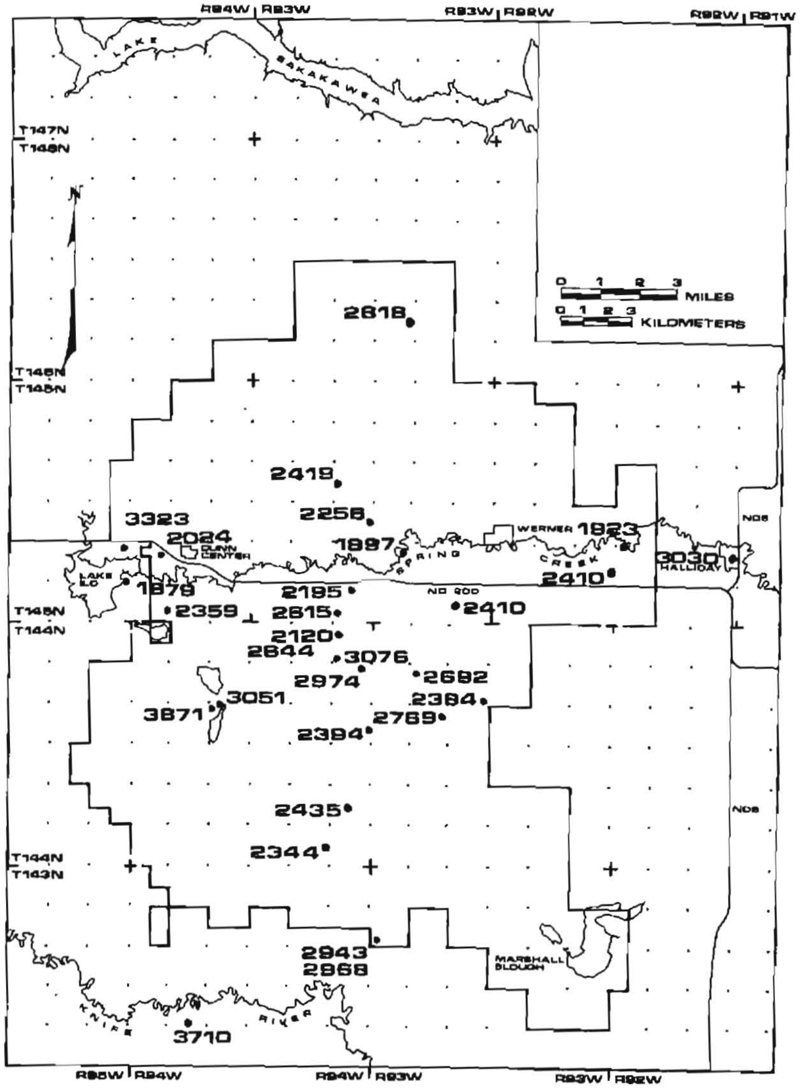


Figure 3.6.12-16 Map of the electrical conductivity, in micro mhos/cm, of water samples from UND and farm wells in the upper part of the I-Interval and the H-interval, including the H-lignite.

Table 3.6.12-1. *Summary of chemical analyses of groundwater in the Dunn Center area.*

Stratigraphic Unit	Water Type	Analysis Group	Number of Samples	Statistic	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	HCO_3 mg/l	CO_3 mg/l	Cl mg/l	SO_4 mg/l	Specific Conductance Mmhos/cm	TDS mg/l	pH
Coleharbor	$NaHCO_3SO_4$	IX	39	$\bar{x}$	62	25	469	7.9	748	0.8	4.7	577	2116	1292	8.0
				s	36	15	228	4.1	187	0.0	3.8	389	830	546	0.2
	$NaCaHCO_3SO_4$	III	7	$\bar{x}$	141	41	239	7.4	420	0.0	2.5	454	1436	681	7.8
				s	58	16	68	2.7	150	0.0	2.4	179	307	—	0.3
	$CaNaSO_4$	VI	5	$\bar{x}$	296	111	320	15	544	0.2	5.0	1464	2529	1280	7.7
				s	143	43	166	6.4	126	0.0	5.6	649	785	—	0.4
	$CaMgHCO_3SO_4$	II	5	$\bar{x}$	115	49	47	6.3	430	0.0	4.3	260	985	790	7.9
				s	54	30	27	2.7	179	0.0	3.9	43	502	396	0.2
	$CaHCO_3$	V	2	$\bar{x}$	72	18	11	2.8	282	0.0	6.2	192	519	—	7.8
	$NaSO_4$	VII	2	$\bar{x}$	267	276	1530	40	974	0.0	19	4691	8407	—	7.7
B Lignite	$NaSO_4$	VII	2	$\bar{x}$	149	141	952	34	771	0.0	0.0	2895	5288	—	7.6
	$NaSO_4HCO_3$	VIII	1		42	28	842	14	987	0.0	10	1000	3474	—	8.0
	$NaCaHCO_3$	I	1		43	16	63	1.5	415	0.0	22	38	4531	—	6.8
A Interval	$MgCaNaHCO_3SO_4$	II	7	$\bar{x}$	42	22	31	14	179	0.0	4.1	96	676	—	7.3
				s	20	16	23	20	123	0.0	3.4	84	503	—	0.4
	$NaMgSO_4$	VII	2	$\bar{x}$	318	373	846	18	313	0.0	59	3445	5577	—	7.0
	$NaSO_4HCO_3$	VIII	1		43	3.9	852	16	1054	0.0	2.0	992	3563	—	8.2
A Lignite	$CaNaSO_4HCO_3$	V	6	$\bar{x}$	127	40	104	6.8	221	0.0	10	494	1008	—	7.5
				s	56	23	18	1.2	38	0.0	11	162	198	—	0.3
	$NaSO_4$	VII	5	$\bar{x}$	126	52	1144	20	682	0.2	14	2350	4876	—	7.8
				s	66	37	464	7.8	369	0.0	16	998	2112	—	0.4
	$CaMgHCO_3$	II	2	$\bar{x}$	86	38	23	3.1	329	0.0	1.0	149	739	559	7.0
	$NaHCO_3SO_4$	IX	2	$\bar{x}$	38	12	325	11	456	0.0	11	315	1416	—	7.5
	$NaHCO_3$	XI	2	$\bar{x}$	8.4	0.8	581	6.0	1478	2.6	8.6	105	2002	—	8.4
Dunn Center Interval	$NaHCO_3SO_4$	IX	3	$\bar{x}$	29	11	610	14	708	1.6	7.1	825	2415	—	8.2
				s	17	14	103	3.4	9.5	0.0	9.5	182	351	—	0.3
	$NaCaMgHCO_3SO_4$	II	2	$\bar{x}$	67	40	89	9.4	318	0.0	19	174	1029	—	7.9
	$NaCaMgHCO_3$	I	1		24	16	52	2.4	249	0.0	0.0	44	470	256	7.2

Table 3.6.12-1. *Summary of chemical analyses of groundwater in the Dunn Center area.*—Continued

Stratigraphic Unit	Water Type	Analysis Group	Number of Samples	Statistic	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	HCO_3 mg/l	CO_3 mg/l	Cl mg/l	SO_4 mg/l	Specific Conductance Mmhos/cm	TDS mg/l	pH
Dunn Center Bed															
	$NaCaHCO_3SO_4$	III	19	$\bar{x}$	91	36	155	8.1	357	0.7	4.6	408	1533	1243	7.4
				s	45	15	127	3.8	88	0.0	4.1	303	1623	748	0.5
	$NaHCO_3SO_4$	IX	8	$\bar{x}$	46	21	454	15	781	2.0	6.3	458	2011	1545	8.1
				s	22	13	131	9.4	184	2.8	6.3	117	452	—	0.4
	$CaMgSO_4$	V	7	$\bar{x}$	233	72	80	6.2	293	0.0	29	732	1613	1742	6.7
				s	112	34	35	1.3	132	0.0	18	350	462	191	0.3
	$NaHCO_3$	XI	5	$\bar{x}$	6.2	4.7	504	17	934	34	5.4	255	1884	575	8.6
				s	5.1	4.1	185	16	343	49	2.1	223	655	—	0.6
	$NaSO_4$	VIII	1		31	8.7	900	12	1018	3.6	18	1640	3641	—	8.4
	$NaCaHCO_3$	I	1		26	16	53	2.3	249	0.0	1.6	46	442	274	7.9
	$NaMgSO_4$	VII	1		283	484	1820	14	728	0.0	239	5210	10000	1990	7.3
E Interval															
	$NaSO_4HCO_3$	IX	6	$\bar{x}$	26	5.1	650	12	930	5.2	7.0	722	2540	1555	8.4
				s	18	3.0	84	3.5	164	5.1	2.6	254	386	671	0.2
	$NaSO_4$	VII	2	$\bar{x}$	57	121	2008	25	916	0.0	5.5	3665	7185	—	8.0
	$NaHCO_3SO_4$	II	1		97	41	246	8.5	444	1.2	0.0	248	1122	—	8.3
E Lignite															
	$NaHCO_3SO_4$	IX	20	$\bar{x}$	25	11	630	11	865	5.1	7.8	718	2455	—	8.2
				s	15	14	206	6.0	244	8.0	9.6	567	817	—	0.4
	$NaCaHCO_3SO_4$	III	5	$\bar{x}$	173	38	240	7.4	626	0.0	34	444	1540	1653	7.4
				s	68	12	93	1.6	162	0.0	24	143	491	—	0.4
F Interval															
	$NaHCO_3SO_4$	X	7	$\bar{x}$	15	3.8	692	16	1011	23	8.8	547	2531	—	8.6
				s	5.9	3.4	171	15	149	49	5.0	278	560	—	0.4
	$NaSO_4HCO_3$	IV	2	$\bar{x}$	77	38	479	9.8	662	0.0	18	855	2040	—	7.5
	$NaMgSO_4$	VII	1		415	228	591	12	760	0.0	47	2640	5220	4880	7.9
F Lignite															
	$NaHCO_3SO_4$	X	20	$\bar{x}$	16	5.0	582	5.4	971	8.8	5.2	479	2257	1315	8.3
				s	16	4.4	139	4.1	262	9.7	6.2	282	320	120	0.3
	$NaSO_4$	VII	2	$\bar{x}$	175	141	945	26	462	0.0	125	2449	4154	—	7.4
	$NaMgSO_4$	VII	1		319	326	789	21	749	0.0	309	2250	5820	—	7.4

Table 3.6.12-1. *Summary of chemical analyses of groundwater in the Dunn Center area.*—Continued

Stratigraphic Unit	Water Type	Analysis Group	Number of Samples	Statistic	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	HCO_3 mg/l	CO_3 mg/l	Cl mg/l	SO_4 mg/l	Specific Conductance Mmhos/cm	TDS mg/l	pH
G Lignite & Interval															
	$NaHCO_3$	XI	5	$\bar{x}$	13	2.7	709	5.9	1025	6.6	5.6	262	2065	2385	8.4
				s	8.2	3.4	239	1.0	260	9.1	2.2	59	196	—	0.2
	$NaSO_4HCO_3$	IV	2	$\bar{x}$	60	38	312	12	480	0.0	17	555	1616	—	7.3
	$NaCaMgSO_4$	VI	2	$\bar{x}$	176	48	234	12	278	0.0	7.0	974	2039	—	6.6
	$NaSO_4HCO_3$	IX	1		8.0	2.9	662	5.0	582	0.0	3.5	874	1722	—	8.1
H Interval															
	$NaHCO_3SO_4$	VIII	3	$\bar{x}$	43	21	749	8.2	1109	2.0	4.3	868	3128	—	8.1
				s	37	17	145	5.0	280	0.0	1.5	238	540	—	0.2
H Lignite															
	$NaHCO_3$	XI	15	$\bar{x}$	15	3.6	641	8.7	1367	2.8	18	189	2272	—	8.5
				s	9.6	4.2	111	5.0	258	7.9	14	90	289	—	0.3
	$NaHCO_3SO_4$	IX	9	$\bar{x}$	19	6.1	716	10	1034	13	9.3	792	2955	—	8.3
				s	12	3.0	93	4.8	188	5.1	7.4	395	499	—	0.2
	$CaMgSO_4$	V	1		244	102	137	7.9	271	0.0	15	1040	2000	1670	6.6
I Interval															
	$NaHCO_3SO_4$	X	5	$\bar{x}$	24	8.6	719	9.5	1217	5.5	10	562	2868	—	8.2
				s	14	7.1	76	5.8	323	0.0	6.8	316	282	—	0.4
	$NaCaSO_4HCO_3$	VI	1		207	58	388	24	586	0.0	3.0	1098	2384	—	—
J Lignite															
	$NaHCO_3$	XI	2	$\bar{x}$	21	1.2	800	13	2072	18	36	221	2923	—	8.3
	$NaMgSO_4$	VI	1		115	161	478	53	488	0.0	9.5	1575	2974	—	8.3
	$NaHCO_3SO_4$	IX	1		87	15	550	13	1027	0.0	13	704	2435	—	8.3
	$NaSO_4HCO_3$	III	1		143	56	410	20	759	0.0	20	720	2220	—	8.3
N Interval & Lignite															
	$NaHCO_3$	XI	5	$\bar{x}$	12	3.7	743	13	1632	25	33	55	2720	1990	8.8
				s	8.1	2.9	111	5.4	523	25	25	66	393	—	0.2

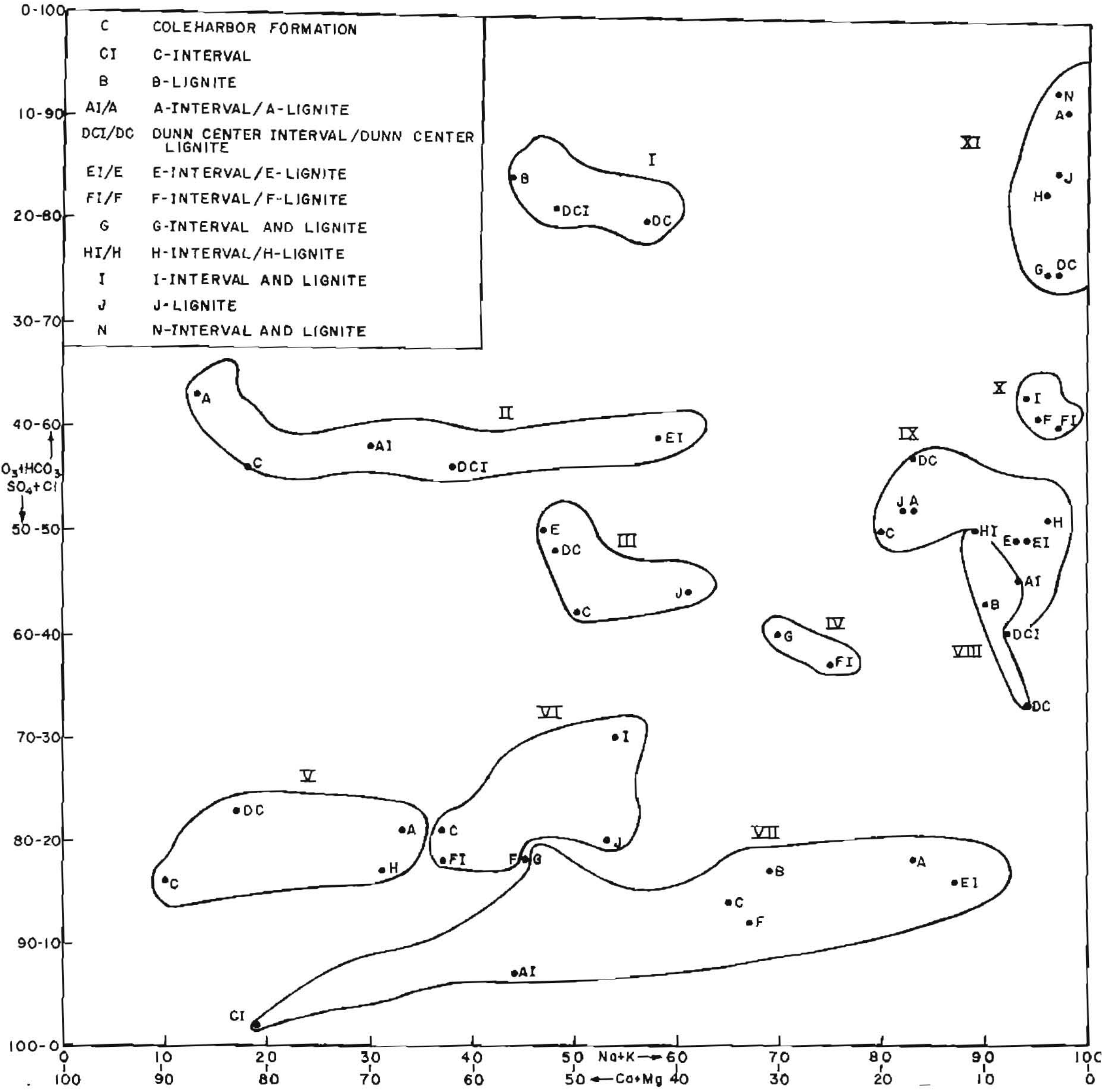


Figure 3.6.12-17 Plot of mean values of the ratios Na+K/Ca+Mg to HCO_3+CO_3/SO_4+Cl of groundwater in the Dunn Center area grouped by water type and by stratigraphic unit. The analysis group is shown by Roman numerals. The analyses are summarized in table 3.6.12-1 and their distribution is shown in figures 3.6.12-18 to -25.

(CaNa)HCO_3 type water with a mean Na-HCO_3 content of 50-82. One sample from the B-lignite has a specific conductance of 4531 and a pH of 6.8. The other two samples from the Dunn Center interval and Dunn Center bed have a mean conductivity of 456 and pH of 7.6.

The analyses in Group I are scattered in the northern and central part of the project area. These samples reflect water that has been recharged almost entirely through sand, so very little dissolved mineral matter has entered the water. A further requirement may be recharge directly into the aquifer without passing through a soil zone. There are too few samples in the group to permit any meaningful generalizations about the origin or significance of this type of water.

Group II consists of 17 samples of Ca(HCO_3SO_4) type water, with a mean Na-HCO_3 composition of 27-58, from 5 units, the Coleharbor Formation, A-interval, A-lignite, Dunn Center interval, and E-interval (fig. 3.6.12-17). The sodium content of the group ranged from a mean of 0.13 for 2 samples from the A-lignite to 0.58 for a single sample from the

E-interval. The bicarbonate content varied from a mean of 0.56 for 2 samples from the A-interval and 5 samples from the Coleharbor Formation to a mean of 0.63 for 2 samples from the A-lignite. The electrical conductivity of samples in Group II was 842 micromhos/cm and the pH was 7.6. There is a slight tendency toward an increase in conductivity and pH with increasing sodium content. This increase in sodium, conductivity, and pH is roughly related to stratigraphic position. The sample with the highest conductivity, pH, and sodium content is in the lowest unit, the E-interval. The samples with the lowest conductivity, pH, and sodium content are in the A-interval, A-lignite, and A-lignite, respectively.

The distribution of analyses in Group II is shown in figure 3.6.12-18. Except for 2 samples from sandy valley fills south of Dunn Center and along Spring Creek, all samples of this relatively fresh $Ca(HCO_3SO_4)$ type water were collected in the northern part of the area high in the stratigraphic section. They reflect recharge through calcareous glacial sediment of the Coleharbor Formation and sandy sediment in the upper part of the Sentinel Butte Formation.

Group III consists of 34 samples, with a mean $Na\text{-}HCO_3$ composition of 49-47, from 4 units, the Coleharbor Formation, Dunn Center bed, E-lignite, and J-lignite. The sodium content varies from a mean of 47 for 7 samples from the E-lignite to 61 for a single sample from the J-lignite. The bicarbonate content varies from a mean of 42 for 7 samples from the Coleharbor Formation to a mean of 50 for 7 samples from the E-lignite. The mean electrical conductivity and pH of this $(CaNa)(SO_4HCO_3)$ type water are 1535 micromhos/cm and 7.5, respectively. As in Group II, there is a slight tendency toward an increase in pH and conductivity with an increase in sodium.

Analyses in this group are concentrated in 2 areas, in the north-central part of the area and in the central part of the area along the partly buried meltwater channel beneath the proposed plant site (fig. 3.6.12-19). The analyses in the northern part of the project area are generally from wells situated along the small stream valley that flows southeastward to join Spring Creek. They are thus lower in the landscape than the wells in Group II which are generally located on the higher divide areas east and west of this drainage. Like the analyses in Group II, these analyses are from wells high in the stratigraphic section. The higher sodium and sulfate content of analyses in Group III is believed to reflect recharge through the floor of valleys eroded below the upland level. In these valleys the thin veneer of calcareous glacial sediment has been removed, so a continued supply of Ca^{2+} ions is not present. As is discussed below, gypsum is concentrated by surface water in depressional areas producing a source for sulfate ions.

Group IV consists of 2 analyses each from the F- and G-intervals. The mean $Na\text{-}HCO_3$ composition is 72-38, making the water a $Na(SO_4HCO_3)$ type. The conductivity ranges from 1616 to 2039 with a mean of 1828 micromhos/cm. The pH is 7.4.

There are too few analyses in this group to permit any meaningful generalizations about their distribution or origin.

Group V consists of 18 analyses of $CaSO_4$ type water from 4 stratigraphic units, Coleharbor Formation, A-lignite, Dunn Center bed, and H-lignite. The mean $Na\text{-}HCO_3$ composition of the group is 22-21, but individual values range from a mean of 10-16 for 2 samples from the Coleharbor Formation to a mean of 33-21 for 6 samples from the A-lignite. The mean electrical conductivity and pH are 1211 and 7.1, respectively. Nine samples from the Dunn Center bed and 1 from the H-lignite had pH values of 6.7 and 6.6, respectively.

The distribution of analyses in Group V is very similar to that in Group III (fig. 3.6.12-20). Most of the analyses are from the center of the northern part of the area along the small stream valley that flows southeastward into Spring Creek. A small group of samples occurs in the central part of the area along the buried valley west of the proposed plant site. In general, samples from Group V are from a higher

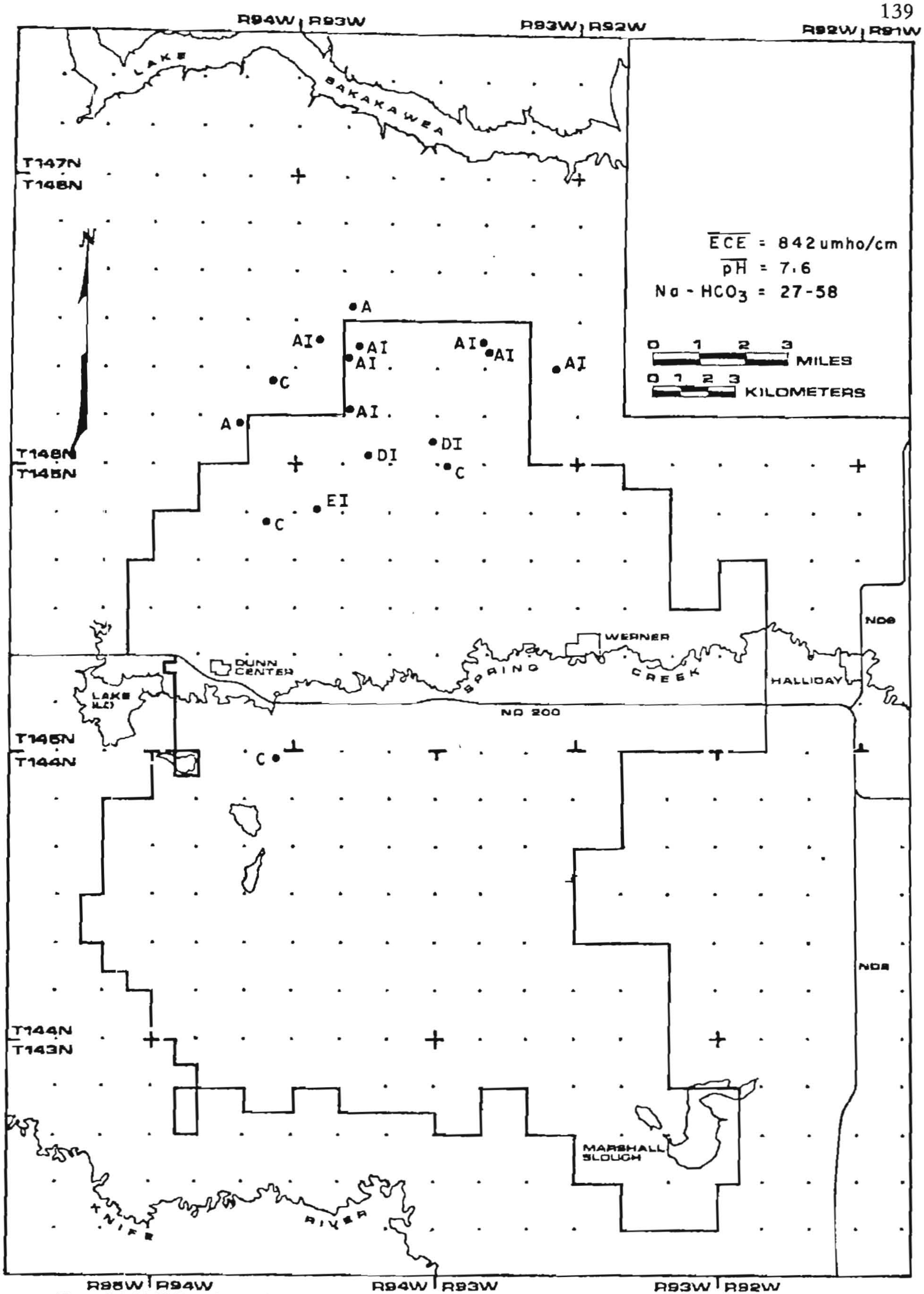


Figure 3.6.12-18 Location and stratigraphic position of groundwater samples in chemical analysis group II, Dunn Center area. See figure 3.6.12-17 for explanation of symbols.

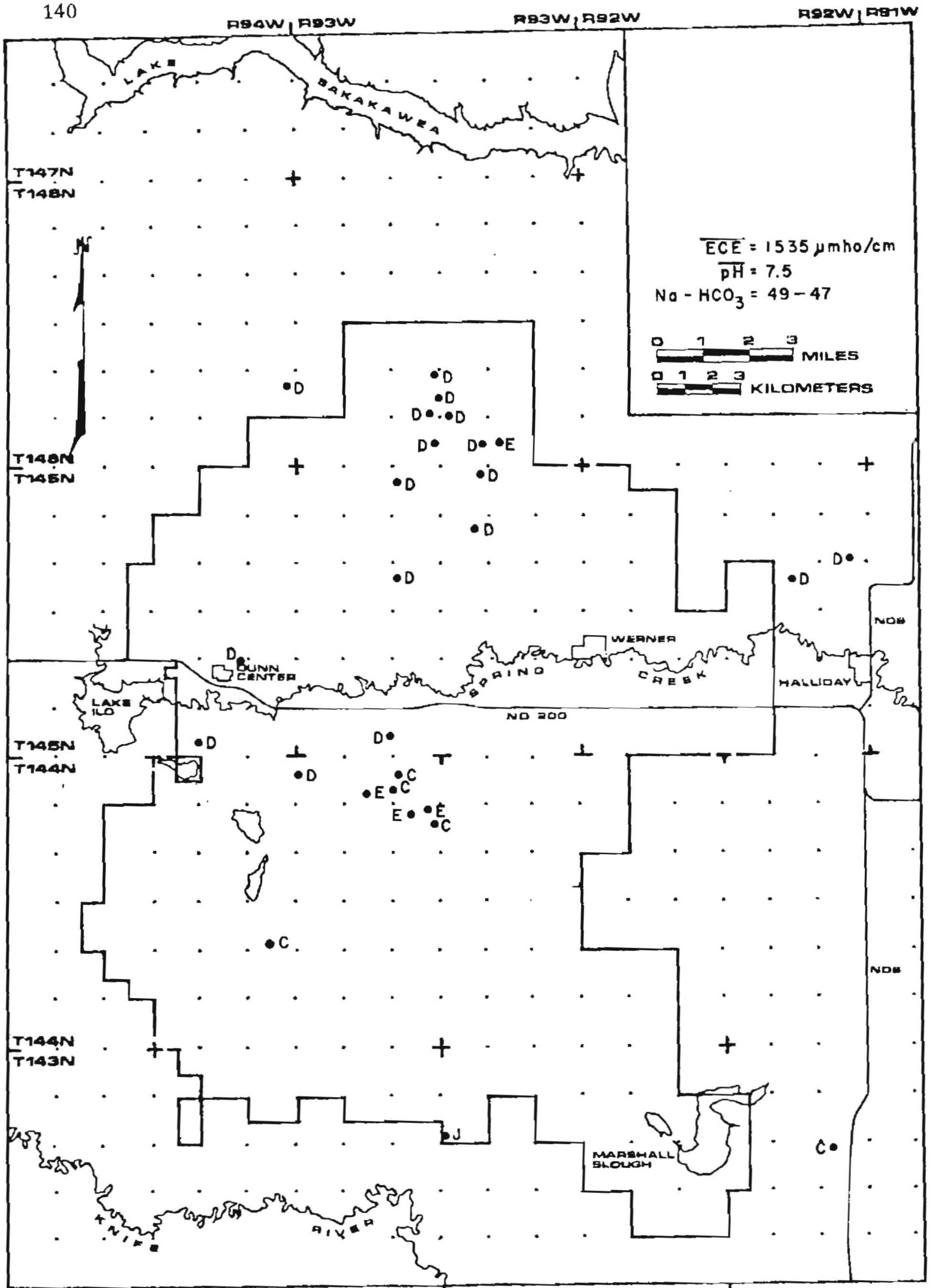


Figure 3.6.12-19 Location and stratigraphic position of groundwater samples in chemical analysis group III, Dunn Center area. See figure 3.6.12-17 for explanation of symbols.

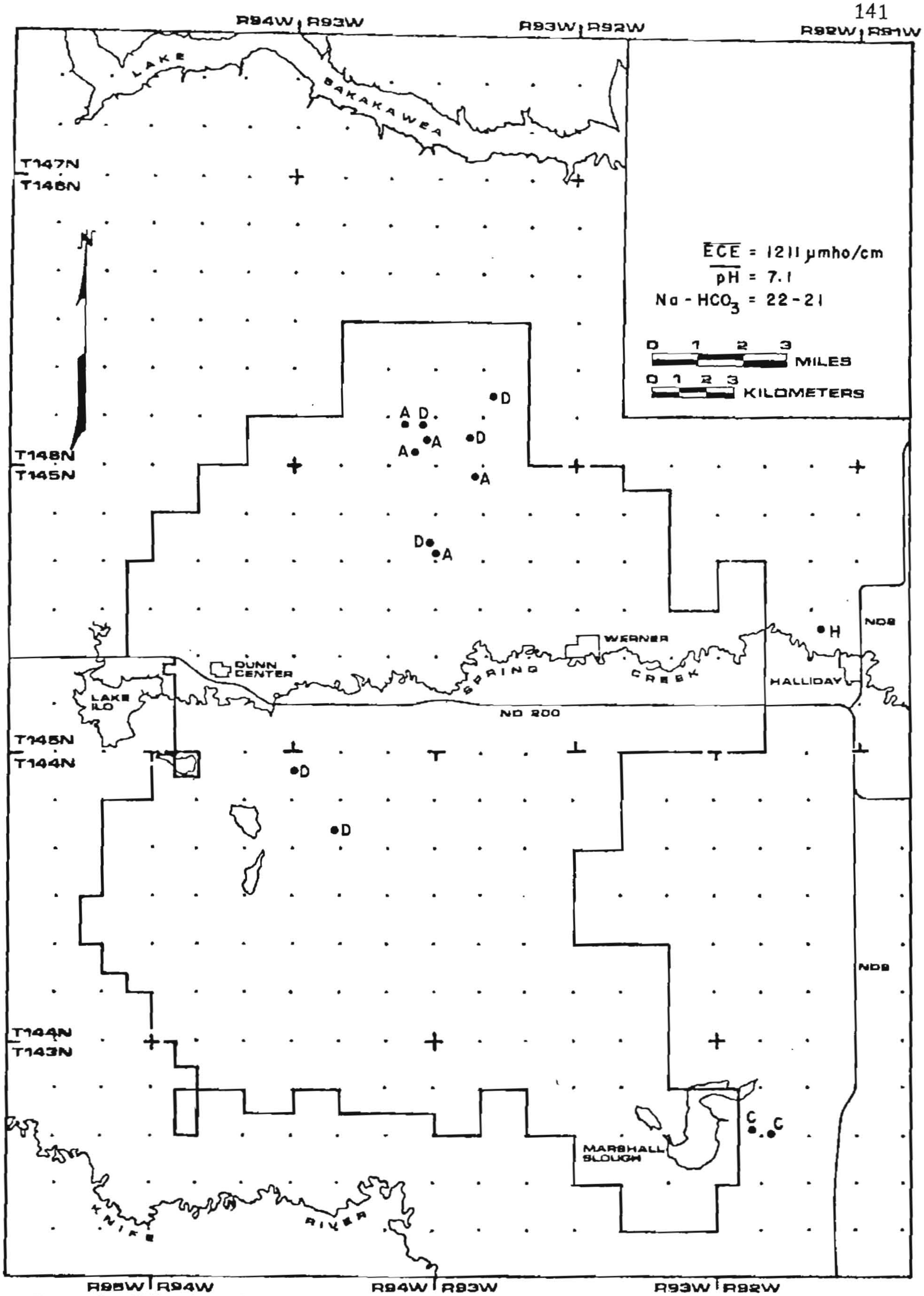


Figure 3.6.12-20 Location and stratigraphic position of groundwater samples in chemical analysis group V, Dunn Center area. See figure 3.6.12-17 for explanation of symbols.

stratigraphic position than those in Group III in the same area (figs. 3.6.12-19 and -20). On the basis of these observations, the analyses from Group V appear to represent water within the same origin and history as those in Group III. Those in Group V are shallower and have been recharged more recently than those in Group III. They reflect a build-up of gypsum in the valley floors over time.

Set II contains 9 samples in Group VI. They consist of (CaNa) SO_4 type water from the Coleharbor Formation, G-interval, I-interval, and J-lignite. They are characterized by a mean Na-HCO_3 composition of 42-31, mean electrical conductivity of 2453 micromhos/cm, and a mean pH of 7.5. They form a group of medium conductivity, low to medium pH waters. These samples have been separated from those in Group V because of their mean conductivity, which is greater than 2000 micromhos/cm.

The higher sodium content of the samples in Group VI relative to Group V may reflect the absence of excess calcium ions because of the absence of calcareous glacial sediment in the southern part of the area, where these samples are concentrated (fig. 3.6.12-21). It is more likely, however, that it reflects greater cation exchange during recharge through the silty and clayey sediment that is more abundant in the Sentinel Butte Formation in the southern part of the area.

Set III is composed of 15 analyses from a single group, Group VII. These analyses are from the Coleharbor Formation, C-lignite, B-lignite, A-interval and lignite, E-interval, and F-interval and lignite. These analyses are characterized by high salinity, mean electrical conductivity of 6100 micromhos/cm, and a medium pH of 7.7. The group ranges from a composition of $CaSO_4$, a Na-HCO_3 content of 19-02, for 1 sample from the C-lignite to $NaSO_4$, a mean Na-HCO_3 content of 87-16, for 2 samples from the E-interval. The mean Na-HCO_3 content of the group is 62-14, a $(NaCa)SO_4$ type water.

Most of the analyses in this group are from the central part of the project area. A few are located near Lake Ilo, along Spring Creek and its tributaries, and near Marshall Slough (fig. 3.6.12-22). Nearly all these samples are from shallow wells situated in areas where leakage of evaporitic surface water into the aquifer is possible. The analyses near Lake Ilo, the projected plant site, and Marshall Slough are in areas where ^{18}O and T data indicate that evaporitic surface water is penetrating into aquifers (secs. 3.6.9, 3.6.10, 3.9). A number of analyses are from the A-lignite, near its outcrop south and southeast of the proposed plant site (fig. 3.6.12-22). It is not known whether these analyses reflect an increase in salinity near a groundwater discharge area (zone II, fig. 2.4.2-1) or recharge of saline surface water for areas of temporary ponding in side-slope positions (zone III, fig. 2.4.2-1).

Set IV consists of a small group of 6 analyses in Group VIII from the B-lignite, A-interval, Dunn Center bed, and H-interval. These samples are characterized by high salinity, mean electrical conductivity of 3344 micromhos/cm, and high pH of 8.2. The mean Na-HCO_3 composition of this group of $Na(SO_4HCO_3)$ type water samples is 91-45. This group differs from Group VII by having a lower salinity, higher pH, sodium, and bicarbonate content.

These samples have a distribution similar to that of Group VII and probably also represent recharge of slightly evaporated surface water.

The largest set of analyses make up Set V, which consists of 154 analyses in 3 groups (fig. 3.6.12-17). The set is characterized by medium salinity. Mean electrical conductivity was 2315 micromhos/cm, and a high pH of 8.2. The mean Na-HCO_3 composition of the set is 90-60. Composition of waters in the set ranges from $Na(HCO_3SO_4)$, with a mean Na-HCO_3 composition of 86-50 from Group IX, to $NaHCO_3$, with a mean Na-HCO_3 composition of 96-83 for Group XI. The pH generally tends to increase as the bicarbonate content increases.

Group IX consists of 88 analyses from the Coleharbor Formation, A-interval and lignite, Dunn Center bed and interval, E-interval and lignite, H-lignite and J-lignite. The mean Na-HCO_3 content of the $Na(HCO_3SO_4)$ type water making up

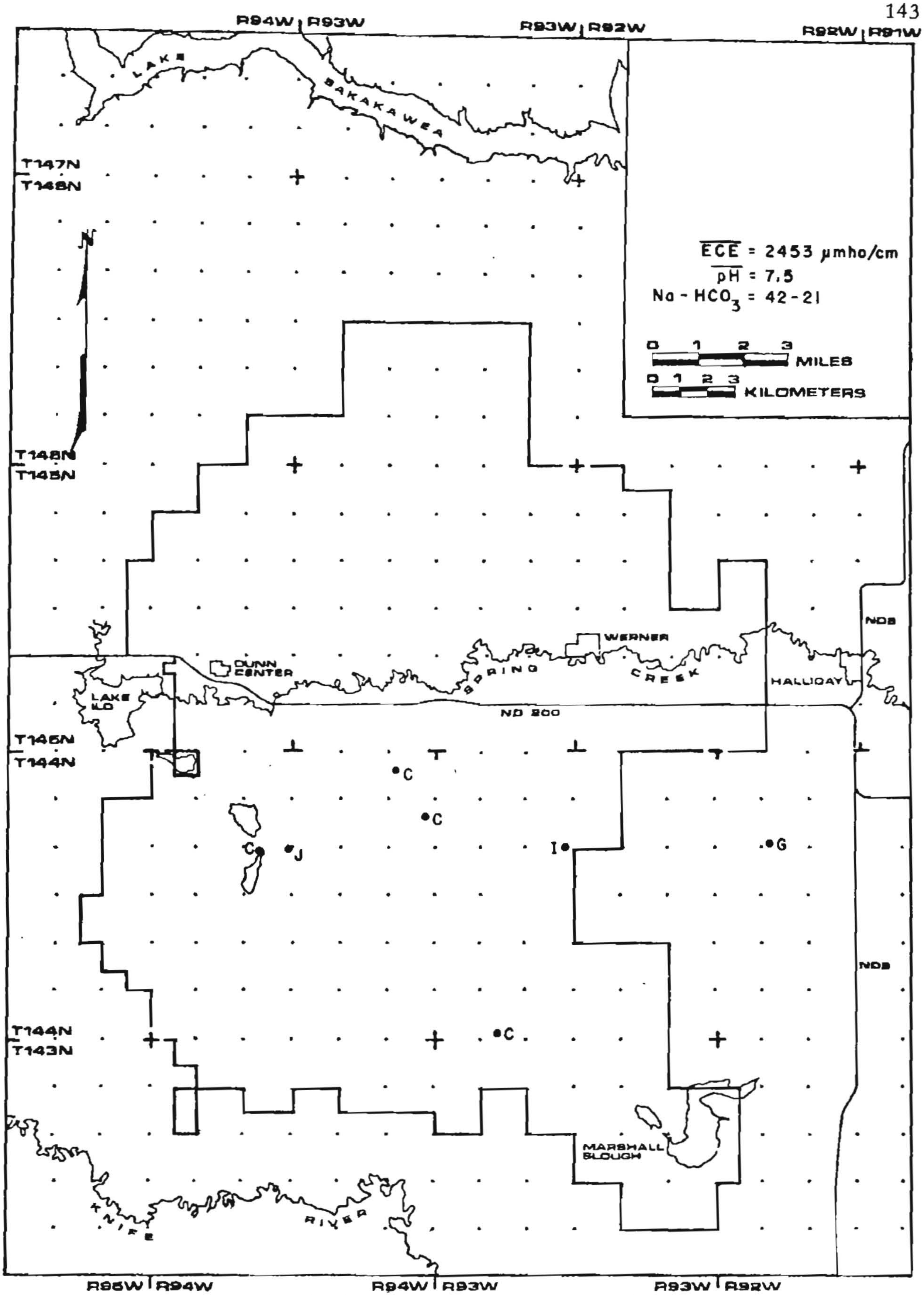


Figure 3.6.12-21 Location and stratigraphic position of groundwater samples in chemical analysis group VI, Dunn Center area. See figure 3.6.12-17 for explanation of symbols.

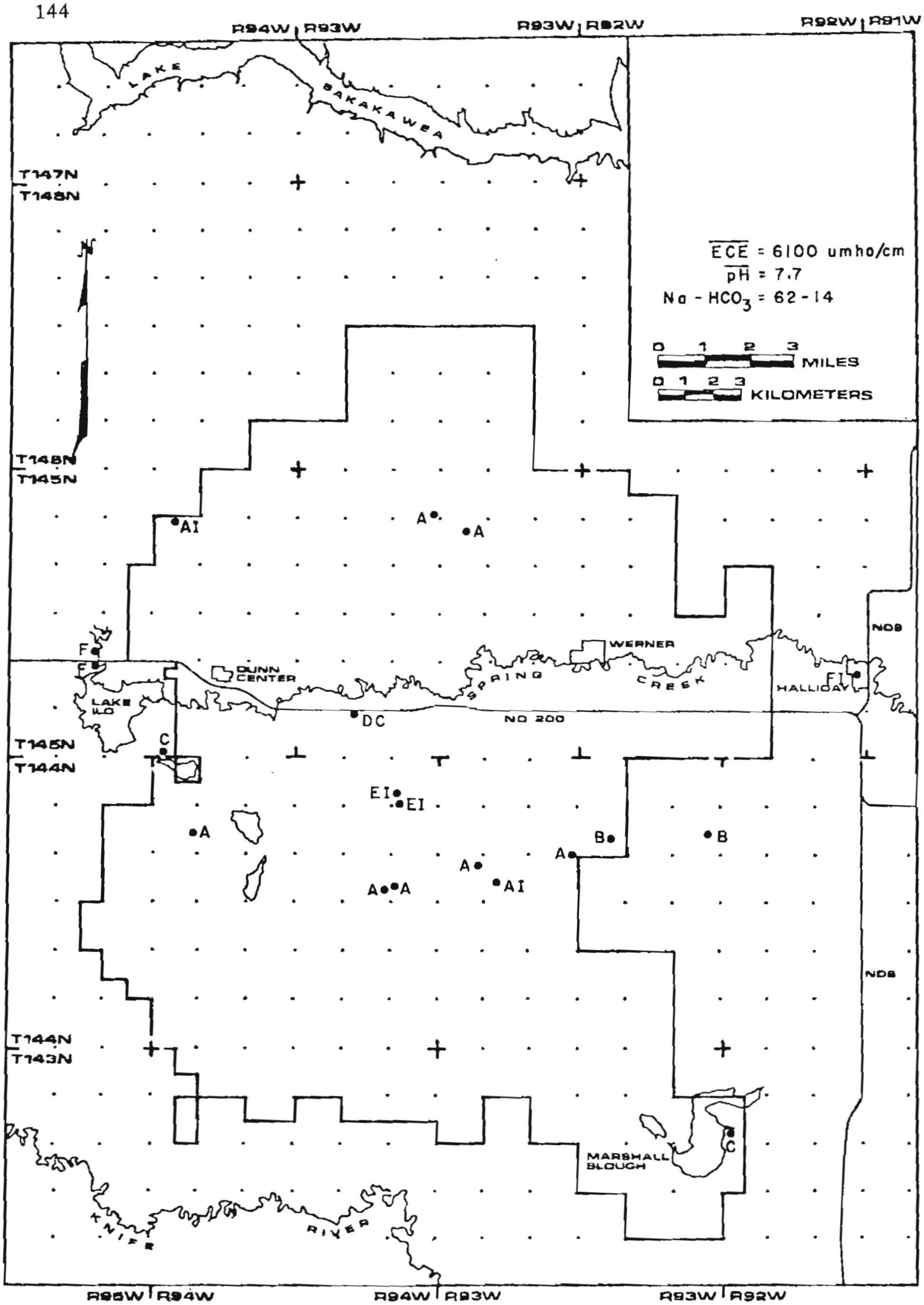


Figure 3.6.12-22 Location and stratigraphic position of groundwater samples in chemical analysis group VII, Dunn Center area. See figure 3.6.12-17 for explanation of symbols.

this set is 86-50. The electrical conductivity has a mean value of 2296 micromhos/cm and the mean pH is 8.1.

Samples in this group are spread throughout the project area (fig. 3.6.12-23). Many samples are concentrated along the Spring Creek valley, the buried meltwater channels southeast of Lake Ilo, southeast of the proposed plant site, and around Marshall Slough, and along the tributary to Spring Creek that flows southeastward from the north-central part of the project area. The distribution of these samples in Group IX is very similar to that of samples in Group III. Group IX differs from Group III in having a higher sodium content and greater salinity and pH. The waters in Group IX are believed to have the same origin as those in Group III differing only in that they were recharged through silty and clayey sediment permitting greater ion exchange of Na^+ for Ca^{2+}. Other samples occur in settings in the southern part of the area analogous to those in Group II in the northern part of the area. These samples in Group IX reflect recharge through upland sites underlain by silt and clay in the upper part of the Sentinel Butte Formation.

Group X consists of 32 analyses of $Na(HCO_3SO_4)$ type water from the F-interval and lignite and the I-interval. The mean Na-HCO_3 content of these analyses is 95-61. The mean electrical conductivity is 2412 micromhos/cm and the mean pH is 8.4.

The analyses in Group X are concentrated along buried meltwater channels beneath and southeast of the proposed plant site and southeast of Lake Ilo and along Spring Creek between Dunn Center and Werner in the area where wells in the F-lignite flow at the surface (fig. 3.6.12-24). These analyses are believed to reflect water that has encountered sufficient silt and clay for nearly all the Ca^{2+} ions to have been replaced by ion exchange with Na^+ ions. The concentration of analyses of Group X along meltwater trenches reflects recharge through the low lying areas where sulfate is concentrated by surface water (sec. 3.10). The significance of the sulfate in the flowing wells is not known.

Group XI consists of 34 analyses of $NaHCO_3$ type water, which had a mean Na-HCO_3 composition of 96-83, from the A-lignite, Dunn Center bed, G-interval, H-lignite, J-lignite, and H-interval and lignite. The mean conductivity was 2274 micromhos/cm and the mean pH was 8.5.

These analyses are distributed, more or less uniformly throughout the project area (fig. 3.6.12-25). The absence of analyses in this group in the northern part of the area reflects the absence of wells in the deeper part of the flow system. These analyses generally reflect water that was recharged beneath upland areas where sulfate concentrations were not especially great. The water has passed through sufficient silt and clay for nearly all the Ca^{2+} ions to be replaced by ion exchange by Na^+ ions (sec. 3.10).

3.6.13 Summary of Groundwater-Flow System

The Dunn Center area extends from the upland divide between the drainage basins of the Knife River and Spring Creek across nearly the entire Spring Creek valley to within about 2 miles of the drainage divide with the Little Missouri River. Most of the project area is characterized by downward moving groundwater and therefore is a groundwater recharge area. Even the floors of the major glacial meltwater valleys cutting across the project area are groundwater recharge areas characterized by downward hydraulic gradients. Only in limited areas along the bottom land of Spring Creek is the hydraulic gradient upward.

The hydraulic conductivity of the lignite and sand beds that comprise the aquifers in the area is several orders of magnitude greater than that of the silt and clay confining beds. As a result, the groundwater-flow system has a strong anisotropy characterized by nearly vertical flow, which is nearly everywhere downward, in the confining beds, and nearly horizontal flow, toward the nearest outcrop, in the aquifers. Most of the material making up the Sentinel Butte Formation above the Dunn Center bed in the project area is silt. As a result, over most of the area the rate of groundwater

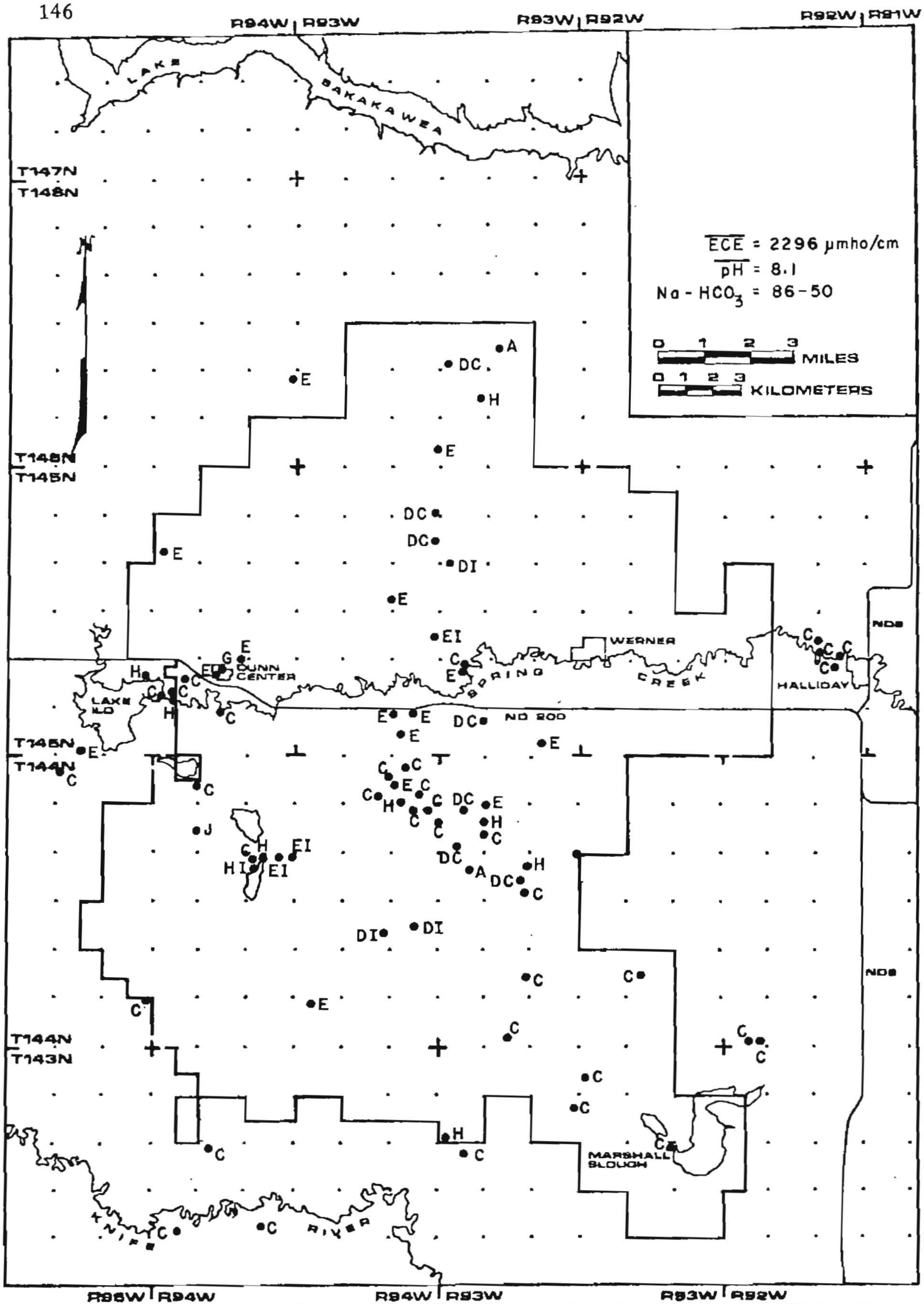


Figure 3.6.12-23 Location and stratigraphic position of groundwater samples in chemical analysis group IX, Dunn Center area. See figure 3.6.12-17 for explanation of symbols.

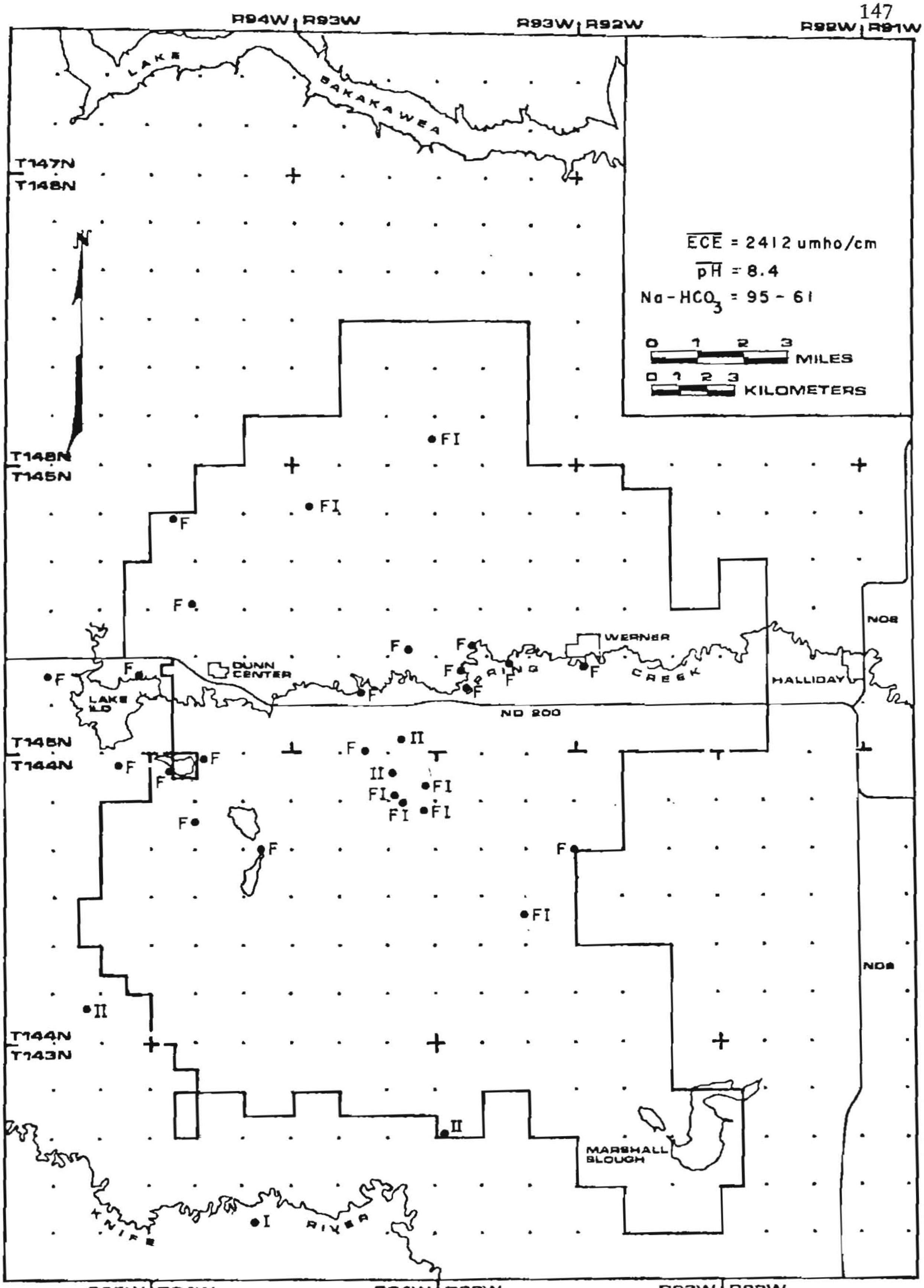


Figure 3.6.12-24 Location and stratigraphic position of groundwater samples in chemical analysis group X, Dunn Center area. See figure 3.6.12-17 for explanation of symbols.

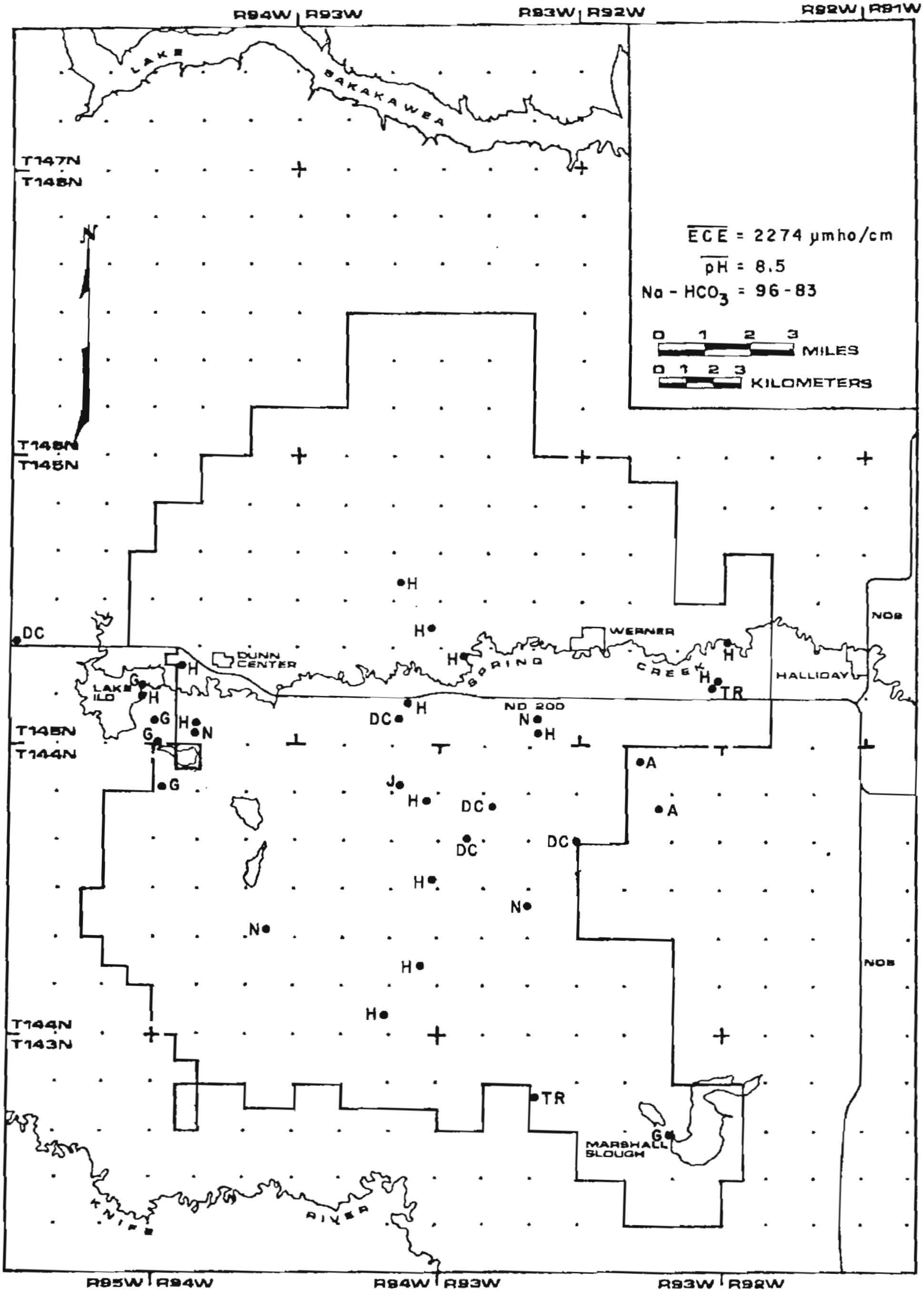


Figure 3.6.12-25 Location and stratigraphic position of groundwater samples in chemical analysis group XI, Dunn Center area. See figure 3.6.12-17 for explanation of symbols.

recharge is slow. In most of the area, the small amount of water that percolates downward is removed from the system by lateral migration along lignite beds, which lie above the Dunn Center bed, to springs and seeps at their line of outcrop. Most of this water is then lost by evapotranspiration or as runoff. A small proportion of this water reenters the groundwater-flow system through the floors of the major glacial-meltwater valleys.

In some parts of the area, nearly the entire thickness of the overburden above the Dunn Center bed consists of sand. In these places, groundwater recharge is much more effective. The rate of downward flow is greater and greater quantities of water are delivered deeper into the system. Most of this water is also discharged within the Spring Creek basin by lateral flow in and seepage from the lignite beds that outcrop in the area. Because of the greater recharge rate in these areas underlain by sand, more water is delivered to the Dunn Center bed than can be discharged in the area. Some of this water flows eastward down the regional gradient, and some moves downward toward deeper aquifers below the Dunn Center bed. Because these deeper aquifers, lignite and sand beds in the Sentinel Butte Formation, do not outcrop in the project area, groundwater flow is northward toward the Little Missouri valley, southward toward the Knife River valley, and eastward toward the regional discharge area along the Missouri River.

In general, the hydraulic head in the permeable fill in the glacial-meltwater channels is higher than in the adjacent aquifers in the Sentinel Butte Formation. However, only in the area around Lake Ilo on the western edge of the project area is there evidence that groundwater is flowing from the valley fill sediment into aquifers in the Sentinel Butte Formation. In this area, ^{18}O and $^{3}H(T)$ data indicate that aquifers as much as 150 feet below the Dunn Center bed are being recharged with lake water that has flowed downward through the valley fill sediment.

Eight major and three minor groups of water types have been delineated on the basis of major-ion chemistry. Each group occurs in a certain setting and reflects a different recharge history.

Three groups dominate the shallow groundwater regime in the northern part of the project area. Group II consists of very fresh $Ca(HCO_3SO_4)$ type water that has recharged primarily through uplands underlain by calcareous glacial sediment and sandy sediment in the upper part of the Sentinel Butte Formation. Group V consists of moderately fresh $CaSO_4$ type water that was recharged through low areas in the landscape surrounded by calcareous glacial sediment and sandy sediment in the upper part of the Sentinel Butte Formation. Group III consists of $(CaNa)(SO_4HCO_3)$ type water that is slightly more saline than the water in Group V. The water in Group III is found in the same locations as that in Group V except that it is slightly deeper in the system. It is believed to reflect the same recharge history.

Three major and one minor groups dominate the shallow groundwater regime in the southern and central parts of the project area. Group VI is made up of $(CaNa)\ SO_4$ water that is moderately saline. This water recharged through low areas where gypsum was concentrated by surface water and then through silt and clay. Group VI is analogous to Group V in the southern part of the area. Group IX consists of $Na(HCO_3SO_4)$ type waters that are moderately saline. This group represents water that was recharged through uplands underlain by silty and clayey sediment of the Sentinel Butte Formation, analogous to Group II in the north, and through valley bottom sites underlain by silt and clay, analogous to Group III in the north. Group VII and VIII are highly saline $(NaCa)SO_4$ and $Na(SO_4HCO_3)$ type waters, respectively, that represent recharge to shallow aquifers of evaporitic surface water. The samples of Group VII were more strongly evaporated than those in Group VIII.

Two groups of analyses are found in the deeper part of the groundwater regime. Group X consists of moderately saline $Na(HCO_3SO_4)$ type water that reflects recharge through the lowlands in which gypsum has been concentrated by surface water. Group XI consists of moderately saline $NaHCO_3$ water. Some of the water in this group, such as that in the N-lignite, was recharged outside the project area sufficiently long ago that its present chemistry may reflect little about its origin. The same may be true for other samples from the J-lignite and H-lignite. Alternatively these latter samples and those from higher in the section that fall in this group may reflect recharge through uplands that contained very little gypsum followed by flow through enough silt and clay to alter their cation content to its present high sodium content.

3.7 Groundwater Use and Supplies

About half a dozen water wells in the Dunn Center area are completed in the Fox Hills or Hell Creek aquifers. These include the municipal water well in Halliday, the newly completed and as yet not producing municipal water well in Dunn Center, and several flowing stock wells north of the project area in the breaks along the Little Missouri River valley. The rest of the producing water wells in the Dunn Center area are completed in coal or sand beds in the upper part of the Sentinel Butte Formation or in sand or gravel of the Coleharbor Formation.

The wells completed in the Coleharbor Formation and each of four intervals in the Sentinel Butte Formation are summarized on a series of maps, figure 3.7-1, Coleharbor Formation, figure 3.7-2, A-lignite and above, figure 3.7-3, Dunn Center bed and interval, figure 3.7-4, E-interval and F-interval including the lignites, and figure 3.7-5, G-interval and H-interval including the lignites. Table 3.7-1 summarizes the wells completed in each of these intervals and indicates the number of stock, domestic, and dual purpose wells in each.

Table 3.7-1. *Summary of water wells in the Dunn Center area by stratigraphic position and water use.*

Stratigraphic Unit	Domestic Wells	Stock Wells	Dual-Purpose Wells	Total Wells in Use	Percent of Total Wells
Coleharbor Formation	2	5	2	9	5.5
C-Interval and Lignite	–	2	–	2	1.2
B-Interval and Lignite	–	2	1	3	1.8
A-Interval	1	11	3	15	9.2
A-Lignite	5	10	4	19	11.7
Dunn Center Interval	4	6	–	10	6.1
Dunn Center Bed	12	29	14	55	33.7
E-Interval and Lignite	2	9	8	19	11.7
F-Interval and Lignite	5	7	5	17	10.4
G-Interval and Lignite	2	1	–	3	1.8
H-Interval and Lignite	2	5	2	9	5.5
I-Interval and Lignite	–	–	1	1	0.6
J-Interval and Lignite	–	1	–	1	0.6
Total	35	88	40	163	

Estimated water usage in the Dunn Center area is summarized on table 3.7-2. The individual requirements for water usage were derived from tables presented by Klausing (1974, p. 60) and Armstrong (1971, p. 78). The population figures were estimated from data for Dunn County. The Dunn Center project area comprises 172 square miles, about 8.1% of the area of Dunn County. The agricultural census data for the county (Price and Vossen, 1975) were reduced to 8.1% of the county values. The population of the county, determined from the 1970 census, was decreased by the population of the towns in the county to determine the rural population. This figure was reduced to 8.1%, and the population of Dunn Center and Werner were added to this figure to give an estimate of the population of the project area that is using shallow groundwater.

Table 3.7-2. *Estimated groundwater use in the Dunn Center area.*

Use	Individual Requirements (gpd)	Population in Project Area	Daily Use (gpd)
Domestic	70-100	412	28,840-41,200
Cattle	15	9,070	136,050
Dairy Cows	35	202	7,070
Hogs	5	389	1,945
Sheep	1.5	194	291
Chickens	0.1	825	82.5
			174,278.5-186,638.5

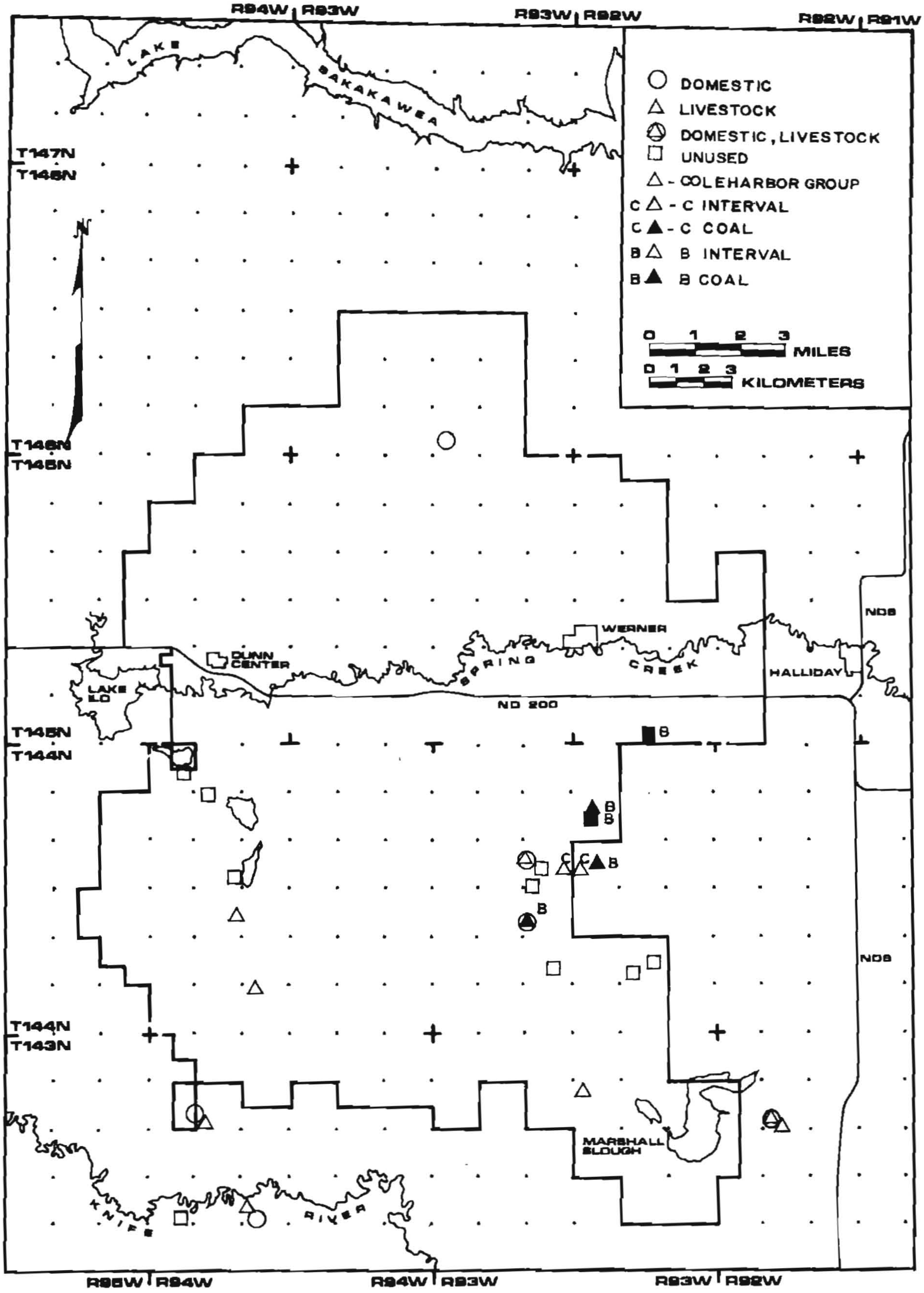


Figure 3.7-1 Map of wells producing water from aquifers in the Coleharbor Formation and B- and C-lignites and intervals in the Dunn Center area.

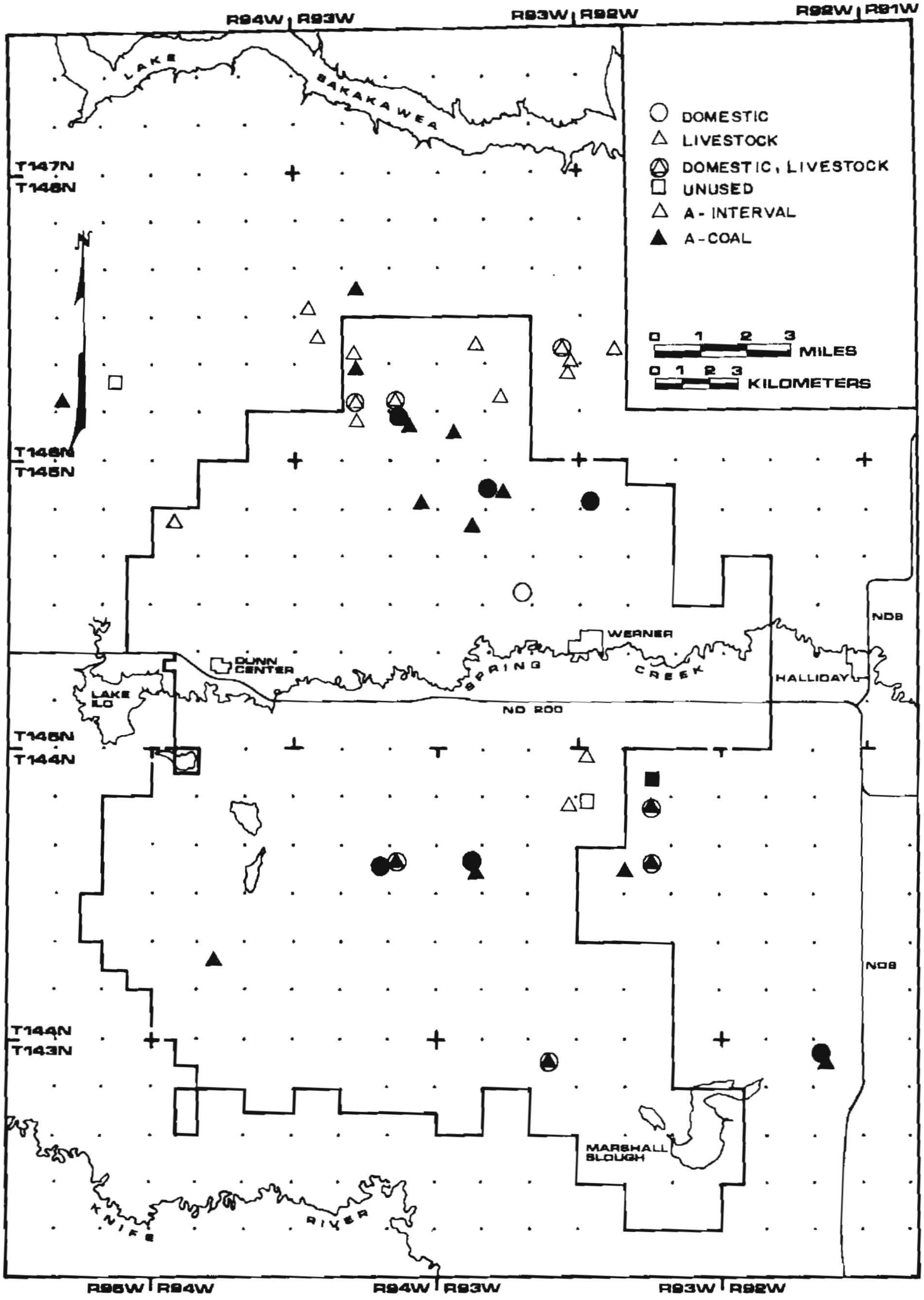


Figure 3.7-2 Map of wells producing water from in the A-interval and A-lignite in the Dunn Center area.

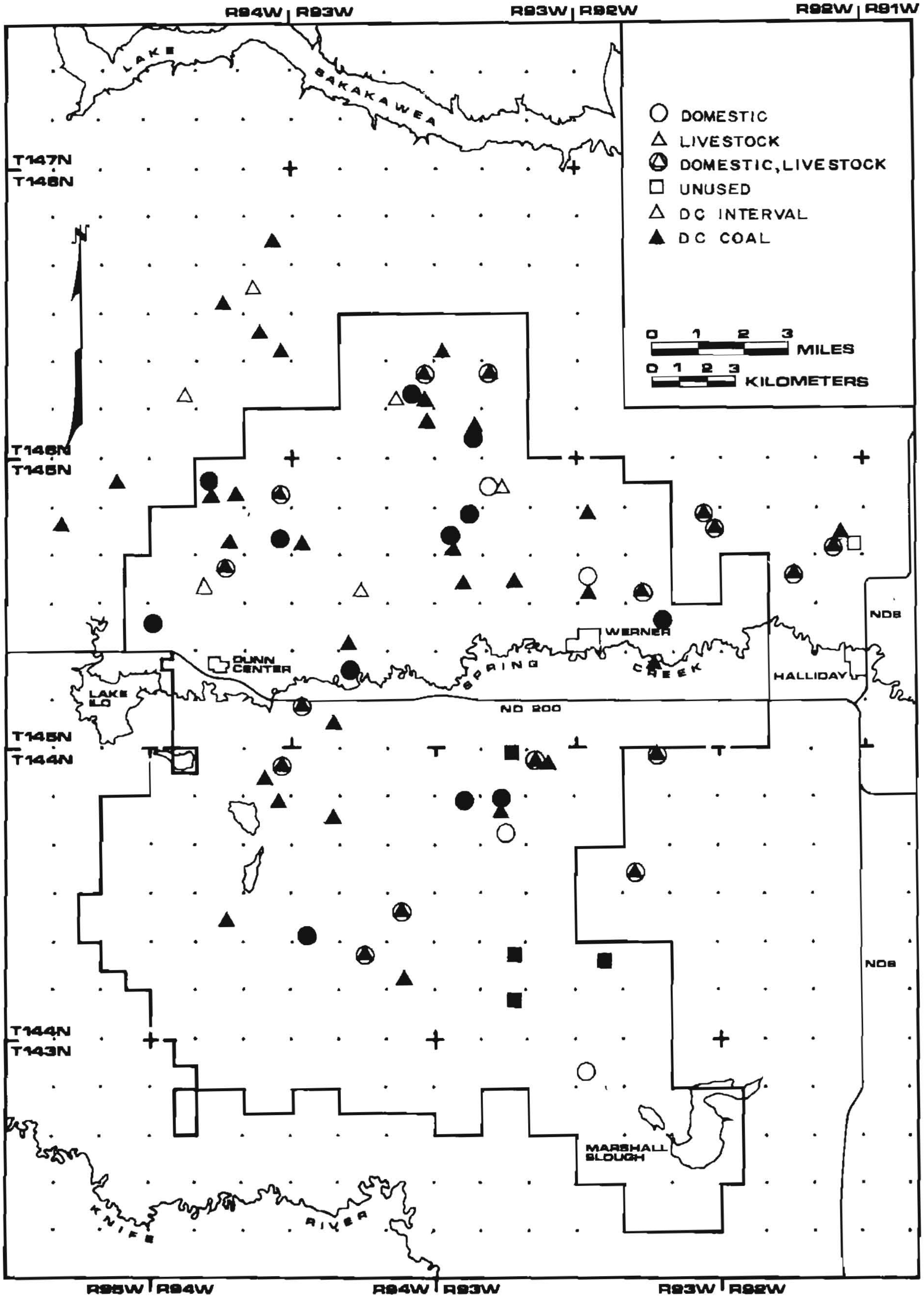


Figure 3.7-3 Map of wells producing water from the Dunn Center bed and interval in the Dunn Center area.

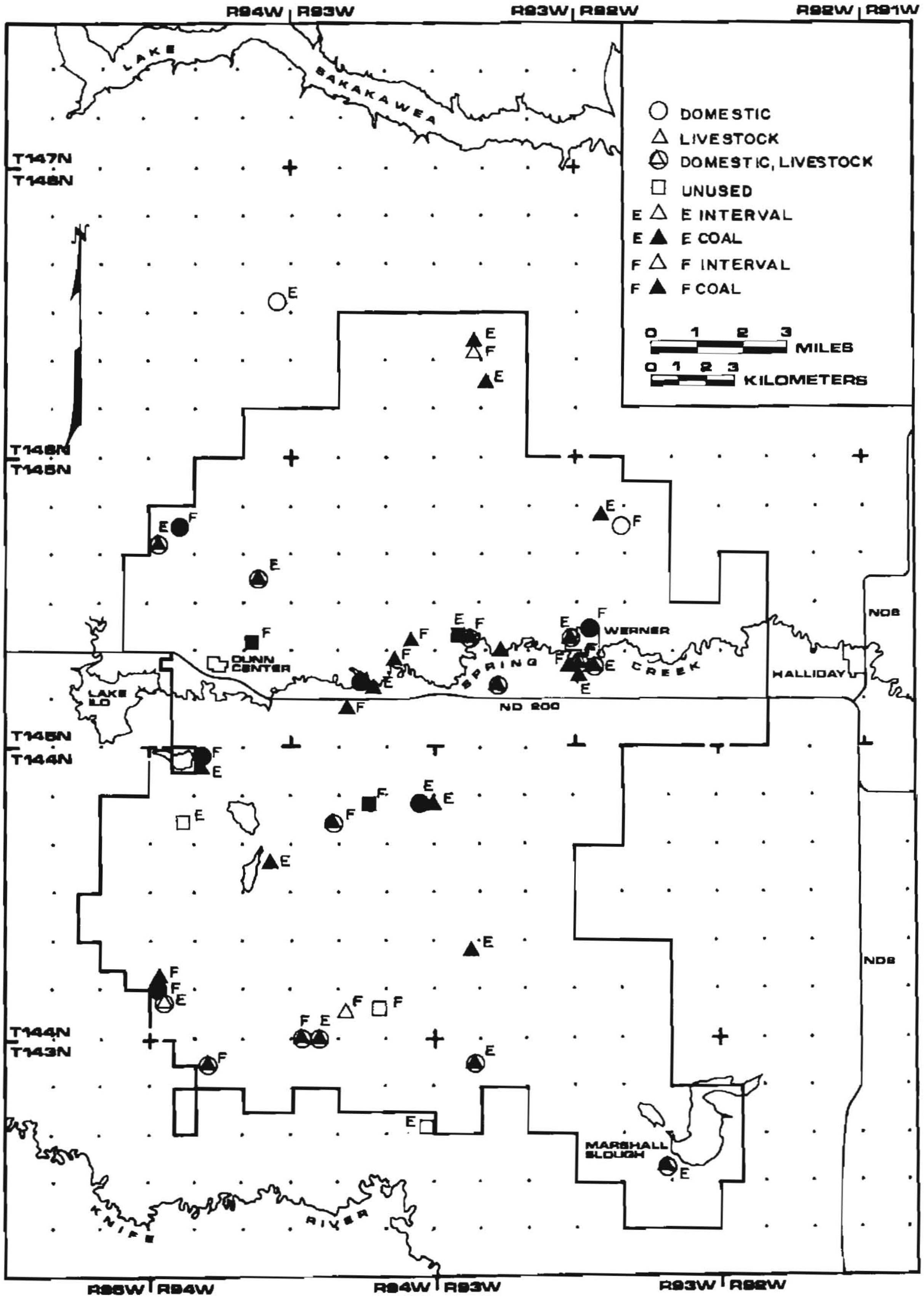


Figure 3.7-4 Map of wells producing water from the E- and F-intervals and lignites in the Dunn Center area.

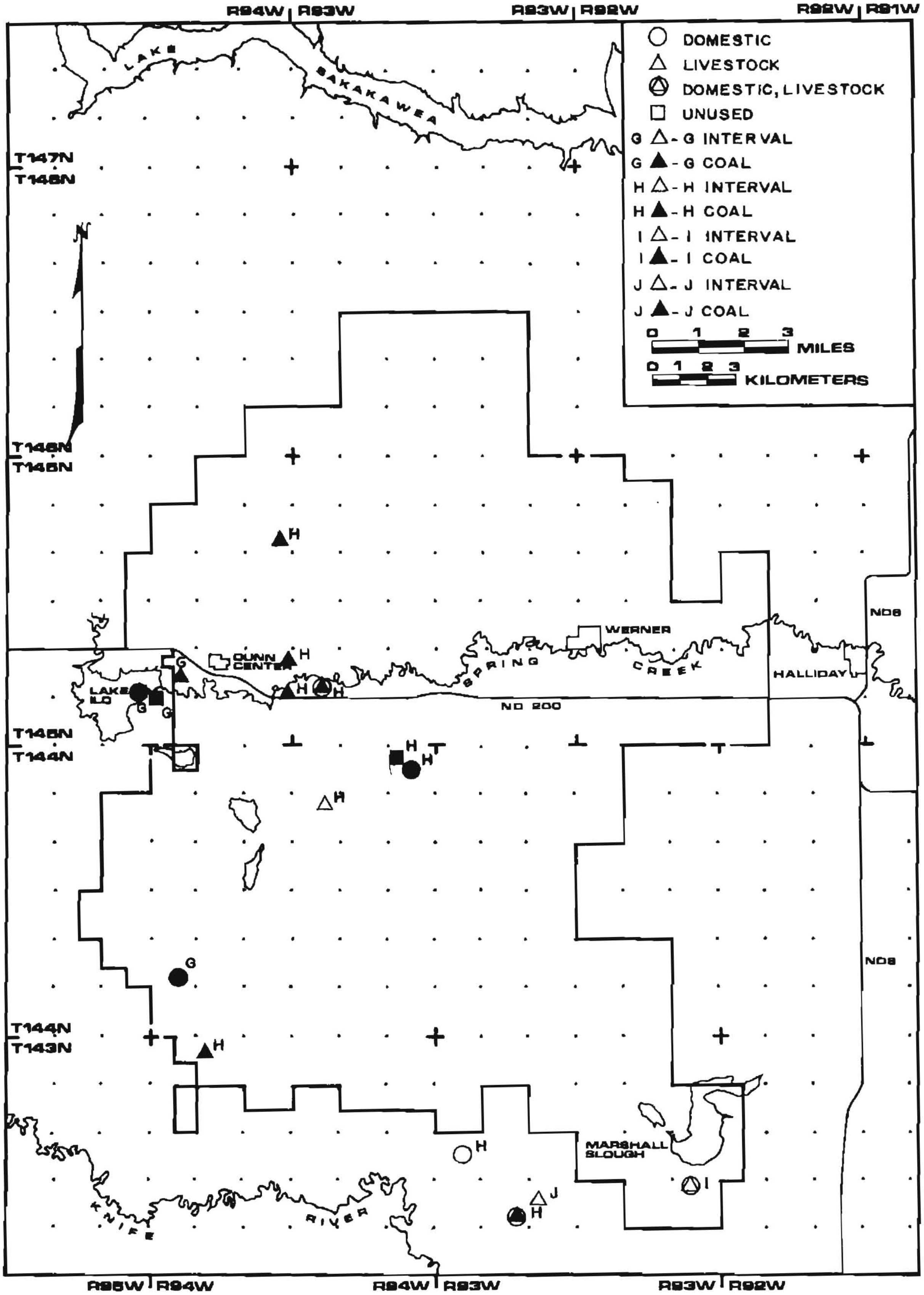


Figure 3.7-5 Map of wells producing water from the G-, H-, I-, and J-intervals and lignites in the Dunn Center area.

These population figures were then multiplied by the daily water use figures to give the estimates of total groundwater consumption presented in table 3.7-2.

3.8 Groundwater Quality

In this section, the results of the chemical analyses of samples from UND, Water Commission, and farm wells are appraised in terms of the use suitability of the water. Chemical analyses of Water Commission and farm wells provided by the U.S. Geological Survey are also used as part of the data base. All of the data are listed, along with information on the wells and stratigraphic position, by Moran and others (1976, app. C-I, IV, V, XI). Fossum (1976) discusses the water quality aspects of the area in greater detail. The data are summarized in stratigraphic groupings in table 3.6.12-1.

The drinking water standards set by the U.S. Public Health Service (1962) are used to appraise the water chemistry in terms of its suitability for human consumption. The drinking water standards are summarized in table 3.8-1. In terms of drinking water quality, the distinctive features of the groundwater in the Sentinel Butte Formation are (1) almost all well samples have sulfate concentrations considerably above the recommended limit of 250 mg/1, (2) the total dissolved solids are almost invariably above the recommended limits of 500 mg/1, (3) many well samples have manganese concentrations that exceed the recommended limit of 0.05 mg/1, (4) a few farm well samples have nitrate concentrations that exceed the recommended limit of 45 mg/1, (5) a significant number of samples exceed the recommended limit of 0.7 mg/1 at 10°C for fluoride, and (6) all other dissolved constituents for which data are available are below the recommended limits. It should be noted that the comments on manganese and fluoride are based only on the chemical data made available from the U.S. Geological Survey and six UND analyses of farm wells. However, it appears that these analyses are sufficient to at least draw attention to the significant occurrence of manganese and fluoride excess but not sufficient to adequately indicate the areal extent and stratigraphic control on the occurrence. Except for fluoride and nitrate, the other constituents that exceed the recommended limits generally do not seriously limit the use of the water for drinking water purpose. The recommended limits are usually interpreted as a guideline to suggest that if alternative drinking water supply that is closer to or within the limits is available, it would be more suitable for use on the basis of these water quality considerations. In a very large part of the American and Canadian Interior Plains Region, farm wells yield water that exceeds the recommended sulphate and total dissolved solids limits. The Dunn Center area is in no way unique in this regard. According to Camp (1963) the low limit placed on manganese in the Drinking Water Standards has no health significance and is a result of properties that relate to manganese precipitate problems in water distribution systems. The occurrence in some wells of fluoride and nitrate concentrations that exceed the recommended limits is more significant. Excess fluoride, according to the U.S. Public Health drinking water standards "shall constitute grounds for rejection of the supply." Nitrate concentrations that exceed the recommended limits present a health hazard to infants. The cause of high

Table 3.8-1. *Summary of U.S. Public Health Service (1962) standards for drinking water quality.*

Constituent	Recommended Limit 1962
Total Dissolved Solids	500
Fluoride	0.8-1.7^c
Manganese	0.05
Iron	0.3
Chloride	250
Sulfate	250
Nitrate	45

c=Dependent on annual average maximum daily air temperature over not less than a 5-year period.

nitrate concentrations in well water in the Dunn Center area is poor well construction. The source of the nitrate is normally animal or human wastes that cause contamination of surface water or soil water with subsequent leakage into poorly constructed wells along the outside of the well casing. Some shallow dug wells have direct entry through leaky well covers. The general absence of high nitrate concentrations in the natural groundwater flow system is established by the results from the UND wells which indicate no nitrate values above 6.8 mg/1.

In terms of sulfate concentration, the Bullion Creek and Fox Hills-Hell Creek aquifers contain water that is below the maximum limits for drinking water recommended by the U.S. Public Health Service, and therefore in this regard is generally of better quality than Sentinel Butte or Coleharbor water. However, the fluoride concentrations in these deep aquifers on the basis of the limited data available is generally above the recommended limits. The two Fox Hills wells near the study area (located 3 miles north of the study area and at Halliday) have fluoride concentrations of 3.7 and 6.7 mg/l, which is greatly above the recommended limit of 1.7 mg/l at 10°C. Fluoride concentrations at these levels may cause mottled enamel in children's teeth. Bone changes may be expected when water containing more than 8 mg/l is consumed over long periods of time (Camp, 1963).

The Public Health Service Drinking Water Standards give no consideration to the suitability of water for livestock, irrigation, or industrial uses. Industrial use factors will not be covered in this discussion, but limited discussion of the water chemistry with respect to livestock consumption and agricultural use may be appropriate. With regard to suitability for livestock use, sulfate is the only major limiting factor with respect to groundwater in the Dunn Center area. The laxative effect of water with high sulfate concentrations can significantly inhibit livestock productivity. Sulfate concentrations below about 100 mg/l are generally regarded as having no major influence on livestock productivity. Because the groundwaters of the Coleharbor, Sentinel Butte, Bullion Creek, and Fox Hills-Hell Creek aquifers have relatively high electrical conductivity and very high sodium concentrations, the waters generally rate as poor or unsuitable for irrigation on the U.S. Department of Agriculture (1954) rating scheme. This rating scheme is based primarily on the sodium adsorption ratio of the waters, which increased with increasing Na concentration.

3.9 Surface Water-Groundwater Interactions

3.9.1 Introduction

In this section, the available information on surface water-groundwater interactions is summarized in terms of both hydrologic and water-quality considerations. Some of the data used here have been referred to in preceding sections.

The significant surface water bodies in or very near the study area are Lake Ilo, Marshall Slough, and Spring Creek. There are several other minor surface water regimes in the area. These include the sloughs north and south of UND sites 26 and 27, and some small pothole sloughs in the northern upland.

3.9.2 Lake Ilo

In section 3.6 it was indicated on the basis of water level data from the UND observation well network and Water Commission wells that the hydraulic gradients in the vicinity of Lake Ilo have downward components. This statement is based on water level readings in the shallow wells at UND sites 44, 47, and 43. The locations of UND wells, Water Commission wells, and sampled farm wells in the vicinity of Lake Ilo are shown in figure 3.9.2-1, which indicates that these three sites are located very close to the shore of Lake Ilo. Each of the sites has two observation wells. The stratigraphic positions of the wells and representative water levels are shown in figure 3.6.4-14. The downward gradients have been identified by comparing the water levels in the shallow wells to the water level of Lake Ilo, which varied from 2190 to 2189 feet

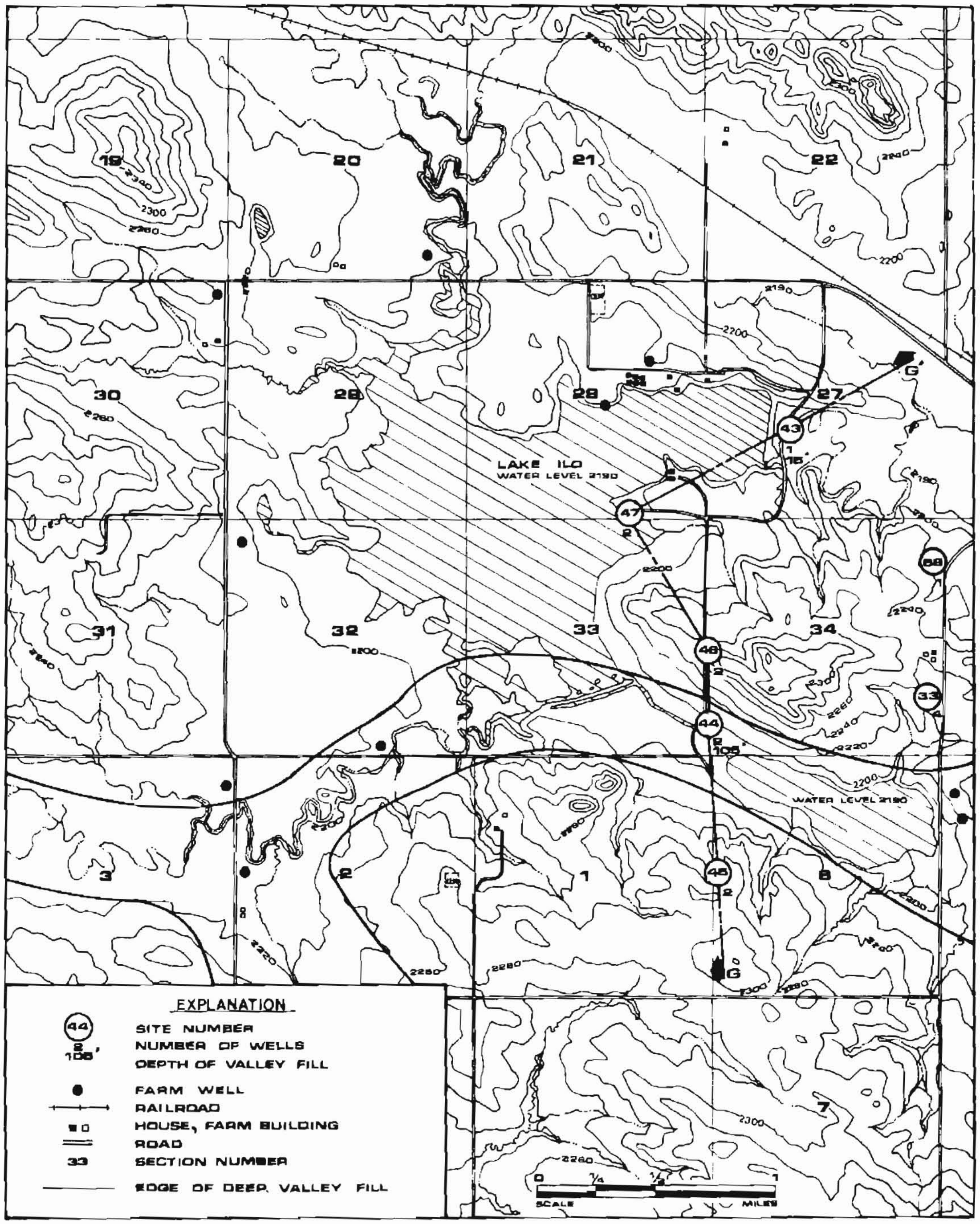


Figure 3.9.2-1 Map of UND, Water Commission, and farm wells near Lake Ilo.

above mean sea level during the study period. Because the lake levels are higher than the water levels in the shallow wells, downward flow from the lake into the groundwater zone is indicated, at least on the eastern side of the lake where the three well sites are located.

An indication of whether or not downward gradient components extend deeper into the groundwater-flow system can be obtained by comparing the water levels in the shallow and deeper wells at each of the three sites. At site 44, the water level in the deep well (112 feet) in the G-lignite just below the base of the valley fill (fig. 3.6.4-14) varied between 0.7 and 3.0 feet above the level in the shallow well during the observation period of October and November. There is, therefore, a reversal in the vertical-flow component at depth at this site. At site 47, the deep well (146 feet) also has water levels that are higher than the shallow well at this site, by as much as 7 feet during the observation period. The levels in the deep well are even higher than the lake level by 2 to 3 feet. At site 43 the deep well (38 feet) is Water Commission Well 4733. Its level varied from 2 feet above to the same level as the shallow well. At sites 45 and 46, however, which are located within a half mile of the lake, but considerably above the lake, the levels in the shallow wells are above the lake and the levels in the deep wells (205 feet and 191 feet below ground surface) are much below lake level.

It is concluded from the hydraulic head data from the five well sites along cross section G-G' that the flow is downward and outward from the lake into the shallow groundwater zone and that at greater depth the flow pattern is complex. Much of the leakage from the lake into the shallow groundwater regime is by way of lignite beds that crop out in the lake. Because of structural warping, both the Dunn Center bed and the E-lignite crop out below lake level at one place or another. Rapid leakage from the lake into deeper aquifers occurs through the buried glacial meltwater channel that extends beneath the lake (figs. 3.6.4-14, 3.5.1-2). Water moves downward through the permeable sand and gravel of the valley fill and then laterally into sand or the B- and F-lignites and possibly, in some places, into the G-lignite. The H-lignite does not appear to be connected to Lake Ilo and appears to have hydraulic heads above lake level.

Since there are no observation wells west, north, and south of the lake it is not possible to comment directly on hydraulic head distribution in these areas. Indirect information is provided, however, from ^{18}O and tritium data. The locations of farm wells near the lake that were sampled and analyzed for these isotopes are indicated in figure 3.9.2-1. The results of these analyses are listed in table 3.9.2-1, some of which have been referred to previously in section 3.6. Table 3.9.2-1 indicates that there are farm wells north of Lake Ilo (No. 75), south (Nos. 68, 69, and 70) and southeast (81 and 98) that yield water at least part of which has originated in Lake Ilo, in the streams that flow into Lake Ilo, or in the sloughs near Lake Ilo. This conclusion is based on the ^{18}O and ^{3}H data for these wells. The ^{18}O values are all heavier than the normal groundwater (i.e., heavier than -14 per mille) and most of the samples contain high ^{3}H concentrations. All of the wells indicated above are relatively shallow and therefore only establish the movement of surface derived water into the shallow groundwater zone. Two deeper farm wells that are close to the lake (Nos. 60 and 72) have ^{18}O values in the normal groundwater range and a third well in the same area (No. 61) has very strongly evaporitic water which is definitely derived from Lake Ilo. At the eastern end of the slough that forms a southeastern extension of the lake, one of the two farm wells that were sampled in this area (Nos. 81 and 98) is at a depth of 133 feet and has slightly evaporitic water and no detectable ^{3}H. The shallow farm well nearby has strongly evaporitic water and high tritium. Of the UND wells along cross section G-G' that were sampled, only the deep well at site 46 and the shallow well at site 43 have evaporitic water.

In summary, the isotope data indicate that surface water from Lake Ilo and associated water regimes seep downward into the groundwater-flow system and that

Table 3.9.2-1. *Results of oxygen-18 and tritium analyses of samples collected during 1975 from UND wells and farm wells located near Lake Ilo. See figure 3.9.2-1 for location of wells.*

Location	Owner	Date	Depth (ft)	Strata	Oxygen-18	Tritium
Wells with isotope results indicating water derived at least in part from Lake Ilo or adjacent surface water regimes.						
144-94-05 BBB	Fritz, F.	10-28-75	133	F-Lignite	-13.5	Nil
144-94-05 BBC	Fritz, F.	10- 3-75	20	E-Lignite	-10.0	192±14
144-95-02 CBC	Mittlestad, R.	10- 8-75	?	?	-12.9	Nil
145-94-20 DDC 2	Saetz, J.	10-10-75	40	F-Lignite	-12.1	252±13
145-94-27 BCC	Lake Ilo	8-22-75	130	G-Lignite	- 9.4	130±12
	Public Pump	10- 8-75			- 9.2	15±6
145-94-27 CAB	UND 43-1	10-15-75	17	Coleharbor	- 9.8	—
145-94-30 AAD	Hutchinson, D.	10-16-75	20	Coleharbor	-14.8	86±10 N.D.
145-93-21 DCC 1	Murphy, C.	10- 8-75	22	E-Lignite	-13.3	21±8
145-93-21 DCC 2	Murphy, C.	10- 8-75	15	E-Lignite	-13.8	99±13
145-94-34 CAB	UND 46-1	10-27-75	190	G-Lignite	-13.4	—
145-94-34 CCC	UND 44-2	10-16-75	140	Coleharbor	-14.1	—
Wells with isotope results indicating water that is not derived from Lake Ilo or adjacent surface water regimes.						
144-94-06 CBB	UND 45-1	10-29-75	205	G-Lignite	-15.5	—
145-94-20 DDC 1	Saetz, J.	10-10-75	31	F-Lignite	-16.2	26±9
145-94-20 DDC	Saetz, J.	10-10-75	30	F-Lignite	-15.7	73±9 N.D.
145-94-28 ACD	Wagner, L.	10- 9-75	83	F-Lignite	-15.9	41±14 N.D.
145-94-28 DCD 1	UND 47-1	10-16-75	146	H-Lignite	-16.2	—
145-94-28 DCD 2	UND 47-2	10-16-75	61	F-Lignite	-15.9	—
145-94-28 DDB	Lake Ilo Natl. Wildlife	8-22-75	150	G-Lignite	-16.2	Nil
145-94-30 AAD	Hutchinson, D.	10-16-75	106	F-Lignite	-16.0	19±12 N.D.

its depth of penetration deeper into the groundwater regime is highly variable from place to place. Some of the relatively deep wells that show isotopic evidence of evaporitic effects are located in the Sentinel Butte Formation. This indicates that seepage from the lake into the valley fill aquifers of the Coleharbor Formation can move at least to some extent into the more regional flow system in the sand and lignite aquifers in the Sentinel Butte Formation.

The main chemical characteristics of Lake Ilo water are included in table 3.9.2-2, which indicates that, compared to groundwater typical of aquifers in the Coleharbor Formation and the Sentinel Butte Formation, the major ion concentrations and total dissolved solids in Lake Ilo are relatively low. The electrical conductivity in Lake Ilo varies between 650 and 800 micromhos. The water in Lake Ilo has significantly lower conductivity, dissolved solids, and concentration of Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-}, and SO_4^{2-} than the Little Missouri River, the Knife River, and Spring Creek (table 3.9.2-2). Considering that Lake Ilo is a shallow water body with extensive marshlands along its periphery and with very limited surface outflow, and that it is located in a region of relatively high potential evaporation from the open water bodies and high evapotranspiration from marshlands, the low conductivity and major ion concentrations may at first

Table 3.9.2-2. *Comparison of major chemical characteristics of water from Lake Ilo, Knife River, Little Missouri River, and Spring Creek during the period 5-27-75 to 10-7-75.*

	Dates (1975)	Number of Samples	Spec. Cond. (umhos)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	HCO_3 (mg/l)	CO_3 (mg/l)	Cl (mg/l)	SO_4 (mg/l)	Total Dissolved Solids (mg/l)	Flow (cfs)
Knife River (Manning)	5-27 10-7	5	1754	94	33	330	9.5	655	0.0	3.5	484	1285	7.0
Knife River (Marshall)	5-27 10-27	5	1948	93	21	377	10.6	673	7.2	3.3	540	1435	43.2
Little Missouri River (Watford City)	5-27 10-7	5	1641	117	22	295	12.5	333	9.5	9.7	636	1273	518.6
Lake Sakakawea	6-17 10-29	7	984	70	12	151	6.9	215	0.0	6.4	331	697	—
Spring Creek (Werner)	5-27 10-7	5	1471	119	23	239	10.5	452	4.6	2.9	446	1107	9.9
Spring Creek (Halliday)	5-27 10-7	5	1320	114	22	207	10.1	426	4.9	3.0	396	953	31.2
Lake Ilo (Spillway)	5-27 10-7	5	709	58	7	131	10.4	275	2.0	2.1	160	583	—
Lake Ilo (Marshland)	5-27 10-7	5	653	47	6	149	12.4	354	2.3	0.9	133	566	

appear anomalous. These conditions are consistent, however, with the conclusion that the lake is situated in a groundwater recharge area. In a simple form, the water budget equation for the lake for a specified time interval can be expressed in the form:

Precipitation on Lake + Surface
Inflow=Evapotranspiration
+ Outflow @ Lake Ilo
Dam + Groundwater Seepage.

The lake remains relatively dilute because (1) surface water is the only significant inflow, (2) the surface water inflow is relatively dilute, and (3) the inflow is adequate to keep the lake sufficiently flushed to maintain low concentrations of major ions even though the evapotranspiration is relatively high.

3.9.3 Marshall Slough

The other significant shallow water body in the project area is Marshall Slough, located in the extreme southeastern part of the area. The geologic setting of Marshall Slough is similar to that of Lake Ilo in that it is situated in a broad topographic valley that is filled with relatively extensive and thick sediment of the Coleharbor Formation. The topography and hydrogeologic setting of Marshall Slough are shown in figure 3.9.3-1, which indicates that there is one UND well site (No. 39) and three Water Commission wells (4622, 4623, and 8228) near Marshall Slough. The wells indicate that the slough is situated in an area of downward hydraulic head components and, therefore, that there is downward seepage from the slough into the groundwater-flow system. The hydrogeologic cross section in figure 3.9.3-1 indicates that the slough is underlain by about 150 to 250 feet of silt and clay overlying a sand and gravel aquifer. If this silt and clay unit is continuous beneath the slough, the loss of water from the lake by groundwater seepage will be relatively small, even though the downward gradient components are not small. The map of the potentiometric surface of the lower permeable unit of the valley fill (fig. 3.5.1-2) suggests that groundwater flows laterally in the valley fill from the northern channel and southeastern channels beneath the lake and then follows the channel northeastward away from the lake. The velocities, fluxes, and influence of the slough on the channel flow cannot be

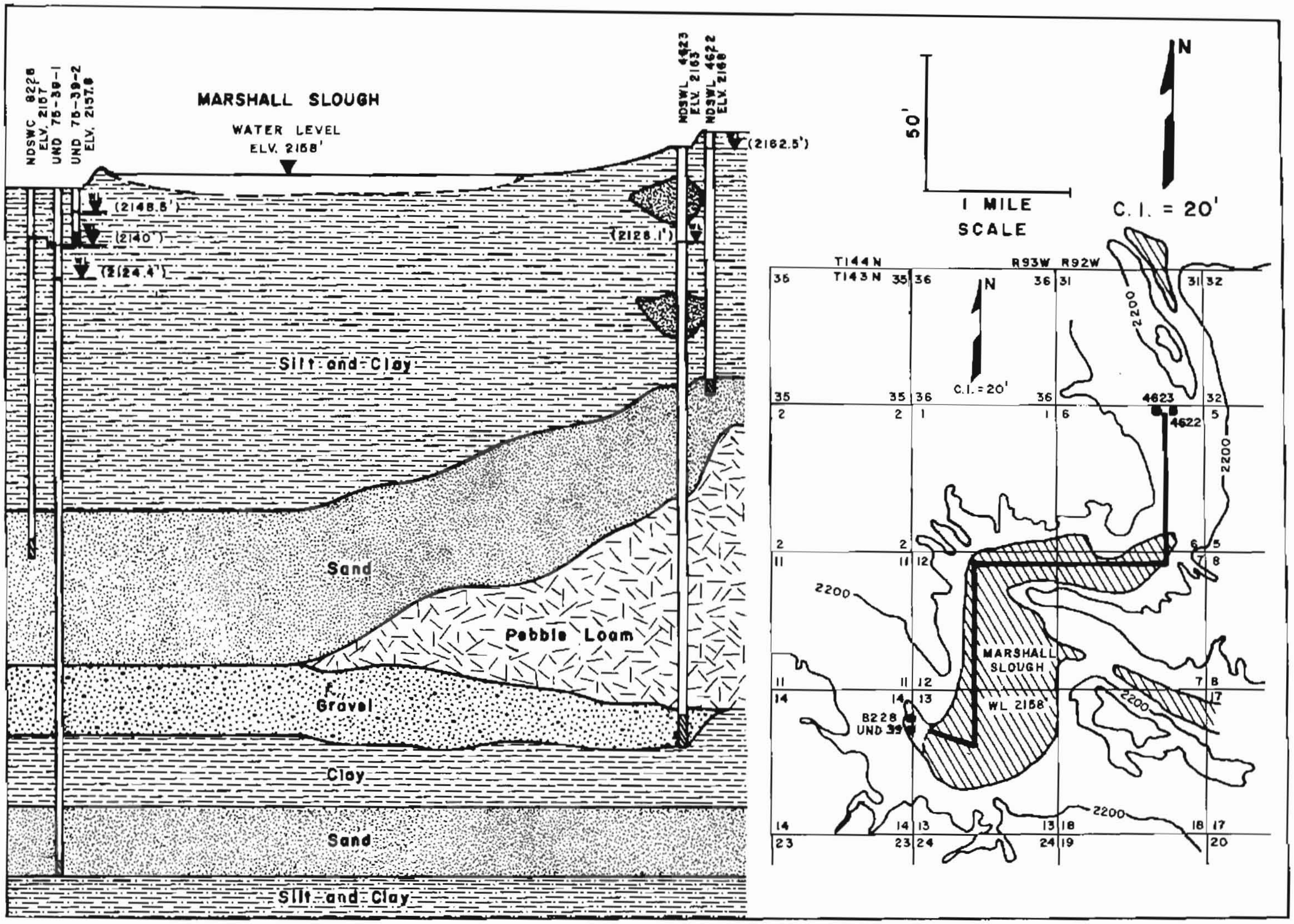


Figure 3.9.3-1 Hydrogeologic conditions near Marshall Slough, spring 1976.

determined with the existing data.

A sample from the shallow well at UND site 39, with intake interval from 15 to 20 feet below ground surface, gave a value of -10.7 per mille ^{18}O. This value is in the strong evaporitic range and indicates that water derived from Marshall Slough occurs in the shallow groundwater zone. No ^{18}O data was obtained from deeper observation wells, and no farm wells suitable for sampling were located in the valley fill near Marshall Slough.

3.9.4 Spring Creek

The only major permanent stream flowing through the project area is Spring Creek. The surface hydrology of this stream is discussed by Mason (1976). Two UND observation well sites (Nos. 32 and 34) are situated within 50 feet of Spring Creek. Site maps, stratigraphy, and hydraulic head distributions at these two sites are shown in figures 3.9.4-1 and -2. The water levels in all of the wells except the deep well (191 feet) at site 34 are above the level in Spring Creek adjacent to the sites (fig. 3.9.4-1). This indicates that there is upward groundwater flow into the stream bed and into the shallow water-table zone adjacent to the stream. The muddy drill water in the deep well at site 34 was blown out on October 12 and 23 and again on November 7, but clean water conditions in the well were not attained. The water level has risen very slowly since November 17 and by February had not yet reached static level. It is likely that the level will eventually rise above stream level.

At site 32, the water levels in the two deepest wells (120-foot well in F-lignite and 166-foot well in H-lignite) are above ground surface (fig. 3.9.4-2). The 120-foot well has the highest water level, which indicates that groundwater flows upward from the F-lignite toward the water-table zone and downward from the F-lignite toward the H-lignite. In other words, seepage that discharges to the Spring Creek lowland in the vicinity of site 32 is derived from the portion of the flow system above the F-lignite even though deeper aquifers are artesian in this area. The well inventory identified numerous flowing wells (i.e., wells with static levels above ground surface, either flowing or capped) located in the valley of Spring Creek within the project area. This suggests that the artesian conditions observed at site 32 are probably representative of much of the Spring Creek lowland.

The hydraulic head distribution and general groundwater-flow directions beneath the valley of Spring Creek are included on the regional cross section A-A' in figure 3.6.4-8, which indicates that the seepage zone in and above the E-lignite that contributes groundwater to the valley of Spring Creek is supplied by flow from the south and from the north or northwest. To the south, the source of the relatively high hydraulic heads in the aquifers in the seepage zone is the valley fill in the proposed plant site area. This buried valley intersects the Dunn Center bed and the E- and F-lignites. Because of the higher hydraulic head in the valley fill, groundwater flows northward from the valley fill through these aquifers to the discharge zone beneath the Spring Creek lowland. The Dunn Center bed discharges groundwater in its outcrop zone near the edge of the valley floor. The E-lignite has a flow divide beneath the valley. It is not clear from the hydraulic head data whether northward flow from the valley fill through F-lignite encounters a flow divide beneath the valley of Spring Creek or continues toward the outcrop area at the Little Missouri valley. Groundwater flow in the Dunn Center bed and E-lignite toward Spring Creek from the northwest originates from the areas in the northern part of the study area. Although the Spring Creek lowland is an extensive discharge area, the actual upward groundwater flux from the E-lignite to the stream bed and water-table zone in the valley is probably relatively small because of the silt and clay beds that occur above this aquifer.

Five flowing wells near Spring Creek were sampled for isotope analyses (UND site 32-1, 2 and farm wells 21, 23 and 24). ^{18}O was determined on all of the samples and one sample (32-1) was analyzed for ^{3}H. The results are included in table 3.9.4-1. The wells are all in the depth range of 100 to 166 feet below ground surface and are located in the F- and H-lignites.

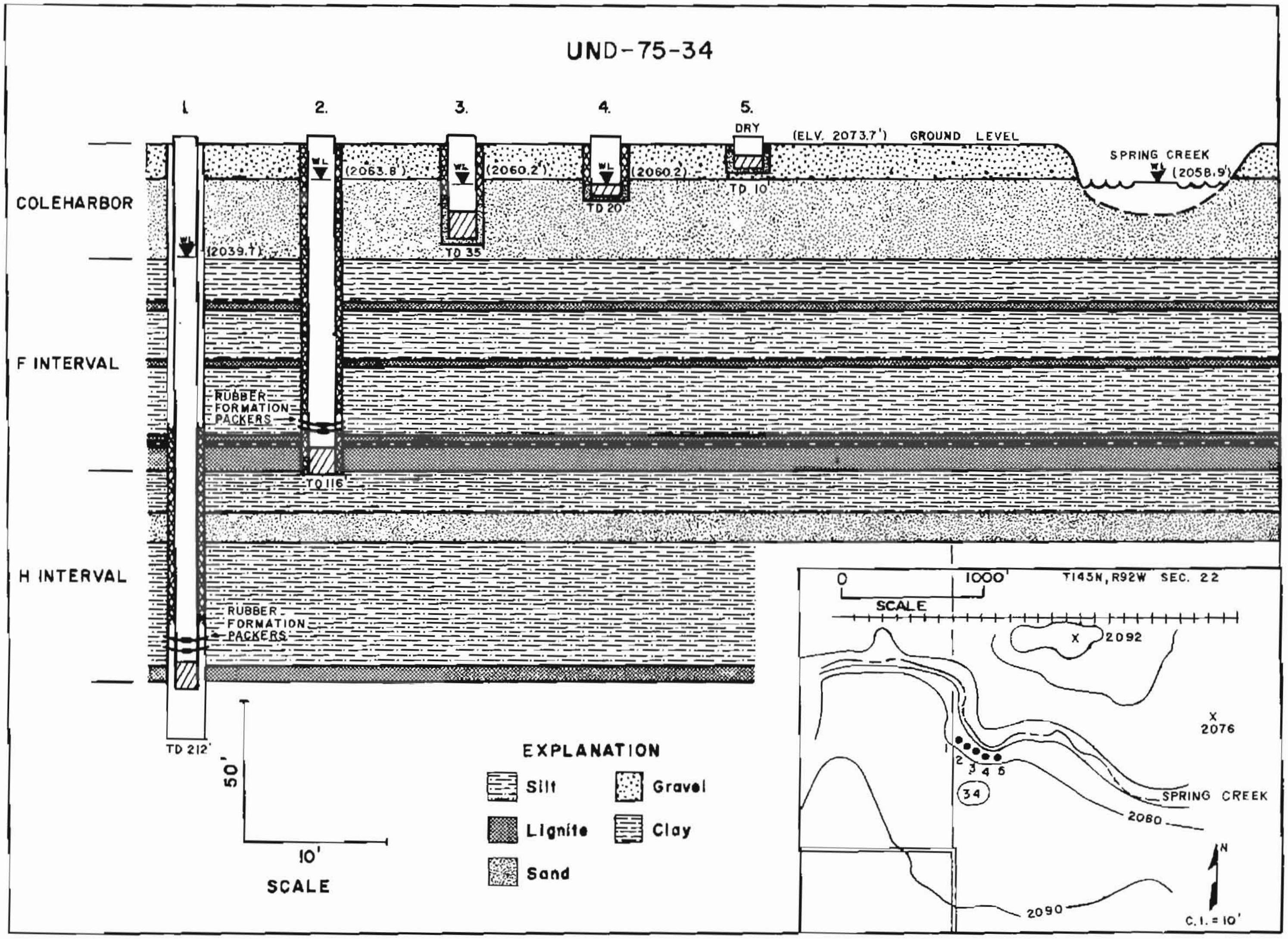


Figure 3.9.4-1 Hydrogeologic conditions near Spring Creek at UND site 34, spring 1976.

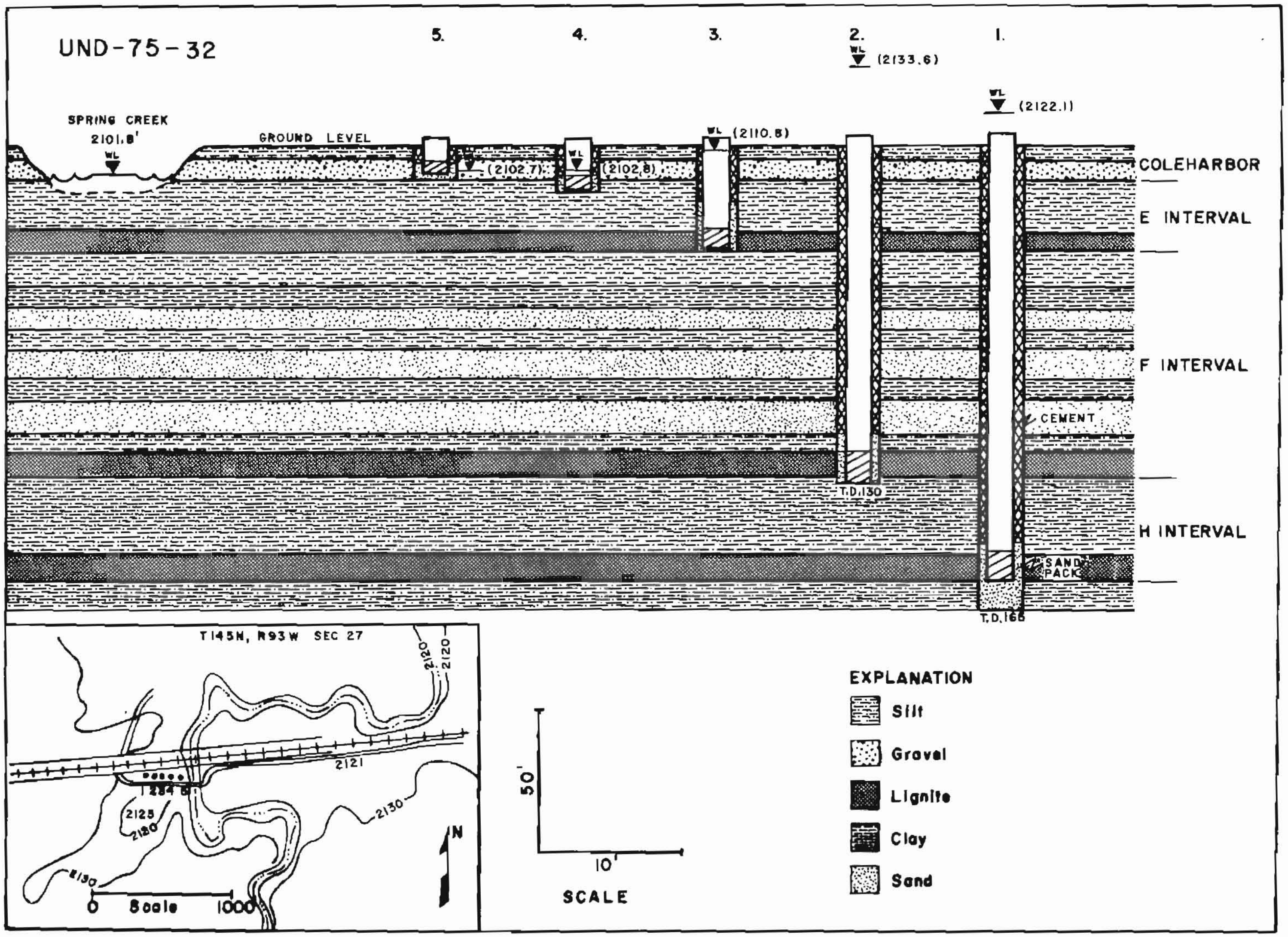


Figure 3.9.4-2 Hydrogeologic conditions near Spring Creek at UND site 32, spring 1976.

Table 3.9.4-1. *Results of oxygen-18 and tritium analyses of samples from farm wells and UND wells near Spring Creek.*

Location	Owner	Date	Depth (ft)	Strata	Oxygen-18	Tritium
145-92-25 ABA	Town-Halliday	5-24-75	1510-1555	Fox Hills	-17.0	Nil
145-92-30 BBB	Goetz	5-24-75	100	F-	-16.6	121±49 N.D.
145-93-27 ABC	UND 32-1	10- 1-75	140-165	H-lignite	-16.5	Nil
	UND 32-2	10- 1-75	105-120	F-lignite	-16.4	117±16 N.D.
	UND 32-3	10- 1-75	27-37	E-lignite	-15.7	—
	UND 32-4	10- 1-75	11-16	Coleharbor	-15.5	—
145-93-29 BCA 2	Lynch, G.	5-24-75	60-70	DC & E-lignite	-16.2	Nil N.D.
145-93-30 CDB 2	Pelton, W.	10- 1-75	117-130(F)	F & H-lignite	-16.7	Nil N.D.
145-94-27 BCC	Lake Ilo Park	8-22-75	130	G-lignite	- 9.2	130±12
	Public Well	10- 8-75	130		- 9.4	15±6
145-94-27 CAB	UND 43-1	10-15-75	7-17	Coleharbor	- 9.8	—
145-94-28 ADB 2	Kittelson, O.	10- 8-75	127-140	H-lignite	-16.1	Nil
145-94-28 DCD	UND 47-1	10-16-75	141-146	H-lignite	-16.2	—
	UND 47-2	10-16-75	51-61	F-lignite	-15.9	—
145-94-28 DDB	Lake Ilo Natl. Wildlife Hdqtr.	8-22-75	150	G-lignite	-16.2	Nil
145-94-34 CBB	UND 46	10-27-75	181-191	G-lignite	-13.4	—

The ^{18}O values for all five wells are in the range of 16.2 to 16.5. Considering that the analytical precision of measurement is approximately ±-.15 per mille, the range of the flowing well ^{18}O values is very small, and indicates that the water is derived from the same source area or similar types of source areas. As indicated previously in section 3.6, the ^{18}O concentrations in the valley fill that occur beneath the proposed plant site are typically in the range of -13.3 to -15.9 per mille. The ^{18}O values in the Sentinel Butte Formation in and above the F-lignite in the areas south and west of Spring Creek are typically lighter than -15.8 and generally heavier than -17 per mille. The ^{18}O data, therefore, suggest that the valley fill is probably not an important source of water to the groundwater zone that discharges in the Spring Creek lowland, even though the hydraulic head data suggest that the valley fill is a potential source. Presumably the northward seepage from the valley fill is limited by permeability constraints.

Tritium analysis of a sample from UND 32-1, located in the H-lignite beneath Spring Creek, showed no detectable ^{3}H. The groundwater in the shallower aquifers beneath the Spring Creek lowland may be very young. Additional ^{3}H analyses would be necessary to evaluate this possibility.

The water chemistry of Spring Creek is compared to Lake Ilo water and groundwater in the Spring Creek area in table 3.9.4-2. Table 3.9.4-3 shows the variations in Spring Creek water chemistry and flow discharge during the period of 4/26/75 to 10/7/75. Table 3.9.4-2 indicates that Spring Creek water has total dissolved solids between Lake Ilo water and the groundwater. All three of these waters have Na^+, SO_4^{2-} , and HCO_3^- as the dominant ions. The chemical data are consistent with the interpretation that during non-snowmelt periods the water in Spring Creek in the downstream part of the project area is primarily a mixture of Lake Ilo water, with lower major-ion concentrations, and groundwater seepage from the zone in and above the F-lignite, that has higher major-ion concentrations. The small ephemeral tributaries that feed minor amounts of water to Spring Creek during part of the non-snowmelt period can be viewed as groundwater contributors since their water is derived from spring flow and other seepage zones. During periods of high rainfall intensity it would be expected that rapid surface runoff from gullies and rills would produce inflow to Spring Creek and to the tributaries that feed Spring Creek. This would dilute the concentrations in Spring Creek and would

Table 3.9.4-2. *Comparison of average water chemistry of Spring Creek and Lake Ilo for the period of 5-27-75 to 10-7-75 with chemistry of samples from farm wells and UND wells near Spring Creek.*

Location	Owner	Date	Well Depth or Intake Interval (ft)	Aquifer	Spec. Cond. (umhos)	pH	Temp. (°C)	Total Hardness (mg/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Fe (mg/l)	HCO$_3$ (mg/l)	CO$_3$ (mg/l)	Cl (mg/l)	SO$_4$ (mg/l)	NO$_3$ (mg/l)	TDS (mg/l)	Stand. Error (percent)
145-95-25 ABA 7	Town-Halliday	5-24-75	1510-1555	FH	2410	8.2	17	12	3.5	0.9	590	1.7	0.6	1190	0.0	240	0.4	1.0	1480	- 0.6
145-92-30 BBB	Goetz	8- 4-71	100	F(L)	2180	8.3	8	10	2.9	0.7	560	2.7	0.0	1170	0.0	3.5	254	1.0	1450	0.1
145-93-21 CDD	Lynch, G.	5-24-75	100(F)	F(L)	1850	8.1	11	12	4.8	0.0	493	3.7	0.0	861	0.0	2.7	370	0.0	1275	- .3
145-93-22 DCA 1	Hausauer, P.	8-22-75	130(F)	F(L)	1812	8.4	—	10	4.0	0.0	426	4.3	—	828	2.6	2.8	300	—	—	- 2.9
145-93-27 ABC 1	UND 32-1	10- 1-75	140-165(F)	H(L)	1897	8.1	—	16	6.0	0.2	516	5.0	—	944	0.0	10	230	0.1	—	5.4
145-93-27 ABC 2	UND 32-2	10- 1-75	99-120(F)	F(L)	2051	8.2	—	20	7.2	0.5	562	5.0	—	1049	0.0	2.0	200	0.7	—	7.7
145-93-27 ABC 3	UND 32-3	10- 1-75	19-37	E(L)	2077	7.9	—	152	32	17	500	9.0	—	783	0.0	3.5	604	0.6	—	- 1.0
145-83-27 ABC 4	UND 32-4	10- 1-75	9-17	CH	1666	8.0	—	352	80	37	300	9.0	—	659	0.0	3.0	456	0.6	—	0.2
145-94-26 BDA 2	DC Motors	10-10-75	115	G(L)	1722	8.1	—	32	8.0	2.9	622	5.0	—	710	0.0	3.5	773*	—	—	*
145-94-27 BCC	Lake Ilo Park	8-22-75	130	G(L)	922	7.0	—	216	46	24	218	7.5	—	410	0.0	21	342	—	—	*
145-94-27 CAB	UND 43-1	10-15-75	5-17	CH	1487	8.0	—	316	64	38	468	4.3	—	720	0.0	4.5	330	0.0	—	-18
145-94-28 ABB	DC Cemetery	10-10-75	133	G(L)	2114	6.0	—	552	213	5.0	236	9.5	—	34	0.0	11	993*	—	—	*
145-94-28 ADB 2	Kittelson, O.	10- 8-75	127-140	H(L)	3323	8.3	—	60	16	4.9	556	3.0	—	1020	3.6	3.5	415	—	—	*
145-94-28 DCD 1	UND 47-1	10-16-75	117-155	H(L)	1897	8.5	—	16	4.4	1.2	910	4.8	—	966	7.2	2.5	320	0.1	—	27
145-94-28 DCD 2	UND 47-2	10-16-75	50-63	F(L)	1846	8.2	—	82	24	5.3	876	7.5	—	739	0.0	2.5	456	0.4	—	30
145-94-28 DDB	Lake Ilo NWR	8-22-75	150	G(L)	1812	8.3	—	13	5.2	0.0	516	4.8	—	914	0.0	4.5	210	—	—	7.9
145-93-24 DCC	Spring Creek (Werner)	5-27 to 10- 7-75	—	—	1471	8.1	19	417	119	23	239	11	2.6	461	4.5	2.9	446	0.1	1107	3.9
145-92-22 ADA	Spring Creek (Halliday)	5-27 to 10- 7-75	—	—	1320	8.2	18	376	114	22	207	10	5.1	436	4.0	3.0	396	0.1	953	3.3
145-94-27 CDB	Lake Ilo (Spillway)	5-27 to 10- 7-75	—	—	709	7.8	19	168	58	7.3	131	10	8.3	278	2.0	2.1	160	0.1	583	8.1
145-94-33 DDD	Lake Ilo (Marshland)	5-27 to 10- 7-75	—	—	653	8.3	18	363	47	5.8	149	12	—	368	2.3	0.9	133	0.1	566	3.8

(CH)=Coleharbor
(FH)=Fox Hills
F(L)=F-Lignite
H(L)=H-Lignite
DC(L)=DC-Lignite
E(L)=E-Lignite
G(L)=G-Lignite
I(L)=I-Lignite

*Value calculated by subtraction

Table 3.9.4-3. *Variations in major ion chemistry and flow discharge in Spring Creek at Werner and Halliday during the period of 4-26-75 to 10-7-75.*

	Date	Flow (cfs)	Spec. Cond. umhos	pH	Total Suspended Solids mg/l	Total Dissolved Solids mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	HCO_3 mg/l	CO_3 mg/l	Cl mg/l	SO_4 mg/l	NO_3 mg/l
Spring Creek at Werner	4-26-75	260	490	8.2	155	362	26	10	87	9.2	192	0.0	0.8	75	
	5-27-75	15	1150	7.6	88	834	55	36	197	10.0	314	0.0	1.8	310	0.3
	7- 8-75	6	1130	8.4	49	937	106	12	208	10.6	403	10	1.5	346	0.0
	8- 5-75	3	1580	8.5	42	1231	139	17	265	10.4	497	13	3.3	476	0.0
	9-16-75	16	1708	7.8	1	1251	197	5	258	11.6	472	0.0	3.0	530	0.0
	10- 7-75	10	1617	8.2	3	1283	174	28	265	9.8	530	0.0	5.0	570	0.1

	Date	Flow (cfs)	Spec. Cond. umhos	pH	Total Suspended Solids mg/l	Total Dissolved Solids mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	HCO_3 mg/l	CO_3 mg/l	Cl mg/l	SO_4 mg/l	NO_3 mg/l
Spring Creek at Halliday	4-26-75	370	375	8.2	171	281	26	11	58	8.2	131	0.0	1.8	54	—
	5-27-75	25	1300	8.0	69	987	76	39	211	9.6	381	0.0	3.0	380	0.2
	7- 8-75	30	710	7.7	106	452	62	8	95	10.6	243	0.0	<1.0	224	0.2
	8- 5-75	2	1530	8.5	84	1159	131	19	255	9.9	490	14	4.3	476	0.0
	9-16-75	51	1441	8.3	11	961	153	8	211	9.7	462	0.0	2.5	390	0.0
	10- 7-75	48	1617	8.4	71	1206	143	37	262	10.8	504	10	5.0	510	0.0

produce a transient chemical regime not included in the generalized interpretation presented above.

Without numerous observation well sites along many transects of the Spring Creek lowland, it is not possible to develop detailed interpretations of the hydrodynamic interactions between the creek and the groundwater regime. However, a general impression of the plausibility of the interpretation that groundwater is a major source water to the creek can be obtained using the Darcy equation with data from UND site 32 and data on hydraulic conductivity and gradient in the Dunn Center bed.

The upward seepage flux from the E-lignite across the silt unit, which underlies the alluvial gravel that connects to the stream, is estimated using information shown in figure 3.9.4-2. The head drop across the 18-foot-thick silt bed is approximately 8 feet. With a representative hydraulic conductivity of 10^{-6} cm/sec for the silt, the Darcy equation yields 1.46×10^{-8} ft^3 per second per square foot of discharge area. Per half mile width of valley floor and per mile length of valley, this seepage discharge to the water-table zone in the shallow alluvial fill is 0.20 cubic feet per second per mile or 2.8 cfs for the reach from Lake Ilo to Halliday.

The Dunn Center bed crops out in the valley of Spring Creek, either just above the valley floor or adjacent to the alluvial fill, for most of the distance from Lake Ilo to Halliday. The flow from the Dunn Center bed into Spring Creek can be calculated using the Darcy equation. We assume values of hydraulic gradient of 65 feet/mile to 25 feet/mile, determined from figure 3.6.4-2. A value of hydraulic conductivity of 5×10^{-3} to 1×10^{-2} cm/sec is used. This value seems reasonable for the Dunn Center bed on the basis of data summarized in figures 3.5.2-1 and 3.5.3-1. A thickness of 9 feet, which is about half the thickness of the Dunn Center bed, is used. This figure is based on the assumption that where the Dunn Center bed is above the valley fill it is nearly dry and where it is below the valley fill it is nearly saturated. Plugging these values into the Darcy equation gives a flux of 0.38 to 0.07 cfs per mile or 5.37 to .98 cfs for the reach from Lake Ilo to Halliday. Assuming a recharge area of about 150 square miles for the Dunn Center bed through this reach, this flux requires an average recharge of just under 0.5 inches per year. Thus, these ratios of groundwater seepage into Spring Creek seem quite reasonable.

Since the length of the stream valley

from the Lake Ilo Dam on the western boundary of the project area to Halliday east of the project area is approximately 14 miles, it is evident that as much as 10 cfs of seepage water are probably feeding the stream bed and the shallow alluvial gravels adjacent to the stream bed. These estimates assume, of course, that the hydrogeologic data from UND site 32 and other assumptions used above can be generalized to an extensive area of the stream valley, which is an oversimplification; however, the occurrence of flowing wells along much of the valley and the data from UND site 34 suggest that the generalizations are not unreasonable as a basis for demonstrating the plausibility of the interpretation that groundwater seepage between Lake Ilo Dam and Halliday is the main source of streamflow during much of the non-snowmelt part of the year.

On the basis of streamflow data presented by Mason (1976), it is evident that groundwater discharge plays a significant role in the total flow of Spring Creek during non-snowmelt periods. During the period from mid-July to October 1975, from 75 to 80 percent of the discharge at the Halliday gauging station entered the stream between Werner and Halliday. The average increase in flow during this period was 26 cfs. Although precipitation during this period was not great, there were several rainfall events that contributed at least part of this flow by direct runoff from surface streams. In addition to this direct runoff and the groundwater discharge directly into Spring Creek from the Dunn Center bed and E-lignite, several tributaries to Spring Creek receive groundwater seepage from the Dunn Center bed and the A-, B-, and C-lignites. For example, the small unnamed creek that flows from the north into Spring Creek east of Werner receives seepage from the A-lignite. Using data from figures 3.6.4-1 and 3.5.2-1 in the Darcy equation gives the following results, assuming that about half the total thickness of the A-lignite, about 10 feet, is saturated:

$$q = KA \text{ grad } h$$

$$q = \frac{(5 \times 10^{-2})(.20)(4.5)(5280)}{(30.48) \quad \times \quad (5280)}$$

$$= 0.737 \text{ cfs.}$$

Multiplying by 2, to take into account the two sides of the valley, gives a seepage of about 1.48 cfs. Observations in the field and on aerial photographs indicate that other small tributaries of Spring Creek are clearly fed by springs in lignites above the Dunn Center bed, although no quantitative data on flow from these springs are available.

Using the data and assumptions above, it has been shown that as much as 9.65 cfs of water are contributed to Spring Creek between Lake Ilo and Halliday from direct groundwater seepage and from a seepage-fed tributary. These sources alone accounted for about 25 percent of the total flow in Spring Creek between mid-July and October, 1975.

3.9.5 Other Areas

Although Lake Ilo, Marshall Slough, and Spring Creek are the only major surface water systems in or adjacent to the study area, there are some other surface-water regimes that are relatively minor but of some interest with respect to surface water groundwater interactions. There are two relatively permanent sloughs near UND site 27, one to the north and one to the south. The north slough occupies about 280 acres and the south slough about 120 acres, although the actual extent of the water surface varies greatly seasonally and with longer-term climatic trends. The sloughs are situated on a valley floor underlain by more than 100 feet of sediments of the Coleharbor Formation. At UND site 27 between the two sloughs, there is a small downward gradient component in the upper 20 to 30 feet of valley fill sediments (fig. 3.6.4-13) which indicates that the sloughs are probably situated in a recharge area. The upper 20 to 30 feet of valley-fill sediments at sites 26 and 27 are composed primarily of silt. If the silt extends beneath the two sloughs, it would be expected that, because of low permeability, the sloughs would not interact very strongly with the sand aquifer in the valley fill beneath the silt. Because the slough appears to be situated in a groundwater recharge area, it would be expected that during series of abnormally dry years the water levels would decline considerably and probably go to dryness on some occasions.

In the hilly terrain in the extreme northern part of the project area, there are numerous relatively permanent pothole sloughs that occupy less than one acre each. A few of these sloughs are as much as 5 to 10 acres in area. Data from UND site 8 and farm wells in the area indicate that the water table in this area is very deep, generally more than 60 to 80 feet below ground surface. It is evident, therefore, that these sloughs are separated from the groundwater zone by a thick unsaturated zone and therefore do not interact directly with the groundwater-flow system. It is likely that fine-grained mucky sediments that form the slough bottom deposits, and pebble-loam of the Coleharbor Formation that underlies the slough sediment, have relatively low permeability and greatly restrict the downward seepage of water from the sloughs into the groundwater-flow system. It was indicated in section 3.6 that the ^{18}O values from the shallow well at UND site 8 and a shallow farm well in the area are very light and therefore show no indication of having been influenced by seepage of evaporitic slough water. Aerial photographs taken show that in July, 1958, nearly all of these sloughs were dry enough that they were used for hay.

3.10 Geochemical Evolution of the Groundwater

3.10.1 General Chemical Characteristics of the Groundwater

The distinctive characteristics of nearly all water in the Sentinel Butte Formation, excluding a few local shallow zones where the water has either not traveled far enough to acquire appreciable dissolved solids or where evapotranspiration has caused excessive dissolved solids are: pH values generally in the range of 7.5 to 9.0 with values between 7.9 and 8.5 most common, electrical conductivity values typically between 1 500 and 4 000 micromhos, HCO_3^- concentrations typically between 500 and 1500 mg/l, SO_4^{2-} values typically in the range of 200 to 2000 mg/l, Ca^{2+} values typically less than 100 mg/l, and Mg^{2+} values typically less than 50 mg/l, and K^+ values typically less than 30 mg/l. In terms of water classification according to the dominant ions, the Sentinel Butte Formation contains $Na(HCO_3SO_4)$ and $Na(SO_4HCO_3)$ type groundwater.

3.10.2 Conceptual Geochemical Model

For a conceptual geochemical model to adequately explain the dominant chemical characteristics of the groundwater in the Sentinel Butte Formation it must be able to produce alkaline pH values, electrical conductivities in the appropriate range, and Na^+, HCO_3^-, and SO_4^{2-} as the dominant ions.

The usual explanation for high Na^+ concentrations in groundwater in continental sedimentary terrain is ion exchange, which is a particularly reasonable mechanism for the Sentinel Butte system since there are extensive zones of sediments that include appreciable clay-sized particles with moderate to high cation exchange capacities. There is no apparent source of appreciable Na^+ concentrations from soluble sodic minerals.

Because of the difference in valence charge, clay minerals have a tendency to attract divalent cations to their exchange sites in preference to monovalent cations. The exchange process for aqueous solutions with the two competing cations, Na^+ and Ca^{2+}, can be expressed as

$$2Na^+ + Ca^{2+}(ad) \rightleftharpoons Ca^{2+} + 2Na^+(ad), \quad (1)$$

where the suffix (ad) denotes cations adsorbed on the surface or interlayer positions of clay particles. For equilibrium conditions the law of mass action can be applied to exchange reactions,

$$K_{Na\text{-}Ca} = \frac{[Ca^{2+}]\ [Na^+(ad)]^2}{[Na^+]^2\ [Ca^{2+}(ad)]} \qquad (2)$$

where $K_{Na\text{-}Ca}$ is the thermodynamic equilibrium constant for the reaction as written above, and the square brackets represent activities. A common procedure in the development of the mass-action theory for application to cation exchange processes is to assume that the activities of an absorbed cation is equal to its mole fraction (i.e., $[Na^+(ad)] = N_{Na^+}$ and $[Ca^{2+}(ad)] = N_{Ca^{2+}}$). This assumption was originally suggested by Vaneslow (1932) and has been used by others such as Bolt

(1967), Babcock (1963), Babcock and Schultz (1963), and Jensen and Babcock (1972). Eq. (2) can then be rewritten as

$$K^* = \frac{Ca}{Na^2} \frac{(Ca^{2+})}{(Na^+)^2} \frac{N^2{}_{Na}}{N_{Ca}} \qquad (3)$$

Where Ca and Na represent the activity coefficients of Ca and Na, the quantities in parentheses are the cation concentrations in molality or molarity (these concentration units are equivalent for the salinity range of interest in this study), and N denotes mole fraction of adsorbed cation. K* is referred to as the selectivity coefficient or selectivity function, depending on whether it varies significantly over a large range of values for the ratio N_{Na}/N_{Ca}. For the Na-Ca exchange pair, K* is much less than unity because Ca^{2+} is the strongly preferred cation. To make direct quantitative use of Eq. (3), it would be necessary to obtain K* values from laboratory tests on samples from the particular stratigraphic zones under consideration. Although this has not been done, Eq. (3) can be used qualitatively.

The question of what happens when groundwater passes into or through stratigraphic units that have significant cation exchange capacity will now be considered. For a given material, the equilibrium ratio of $(Ca^{2+})/(Na^+)$ depends on the ionic strength of the groundwater and on the parameter $N_{Na}2/N_{Ca}$, which is determined by the hydrologic and hydrochemical history of the deposit. Ionic strength, I, is determined by the concentrations of major ions in the water, according to the relation

$$I = \tfrac{1}{2}\sum m_i z_i{}^2 \qquad (4)$$

where m denotes molality and z the valence. For Dunn Center groundwater the ionic strength relation can be approximated as

$$I = \frac{(Na^+)}{2} + 2(Mg^{2+}) + 2(Ca^{2+}) + \frac{(HCO_3{}^-)}{2} + \frac{(Cl^-)}{2} + 2(SO_4{}^{2-})$$

which yields values for Dunn Center water typically in the range of 0.01 to 0.1. Values for γ_{Ca} and γ_{Na} can be obtained from the Debye-Huckel equation which relates I directly to individual ion activity coefficients. This relation is described by Garrels and Christ (1965) and Berner (1971) and others. For Dunn Center groundwater, the following values are representative: γ_{Ca} 0.6 and γ_{Na} 0.85. A representative value for $\gamma_{Ca}/\gamma_{Na}2$ in Eq. (3) is therefore about 0.7 which for the purpose of this analysis can be taken as unity. To proceed with a parameter analysis, a K* value of 0.1 will be assumed. Eq. (3) therefore becomes

$$\frac{(Ca^{2+})}{(Na^+)^2} \simeq \frac{0.1N^2{}_{Na^+}}{N_{Ca}} \qquad (6)$$

The following calculations of exchange equilibria are presented in order to illustrate how an ion exchange relation such as Eq. (6) can influence the cation concentrations in groundwater. Consider a situation where Ca^{2+} and Na^+ are adsorbed in equal concentrations on the cation exchange sites of clay particles in which case $N_{Na} = 0.5$ and $N_{Ca} = 0.5$, and $N^2{}_{Na}/N_{Ca} = 0.5$. From Eq. (6) the equilibrium relation becomes

$$(Ca^{2+}) \approx (Na^+)^2/20 \qquad (7)$$

Therefore if groundwater with a concentration of 1×10^{-3}m Ca^{2+} (40 mg/1 and 1×10^{-3}m Na^+ (23 mg/1) enters the clay stratum, Ca^{2+} will exchange for Na^+ on the clay particles until the equilibrium condition expressed in Eq. (7) is satisfied. This will occur when the Ca^{2+} concentration in the water is reduced to $.45 \times 10^{-6}$m and the Na^+ concentration is increased to 3×10^{-3}m. Eq. (1) indicates that for each mole of Ca^{2+} that goes onto the clay, 2 moles of Na^+ must go into solution. Even if K* is assigned a value much closer to unity, the exchange reaction will cause nearly all of the Ca^{2+} in solution to be exchanged for Na^+.

This exchange process would, of course, increase N_{Ca} and decrease N_{Na}, but because the concentrations of adsorbed cations are large compared to the cation concentrations in most groundwater, many hundreds or thousands of pore volumes of groundwater would have to pass through the clay before the $N^2{}_{Na}/N_{Ca}$ term increases significantly. To rationalize this statement one needs only to consider that cation exchange capacities (CEC) for sediments with moderate to high clay contents are almost invariably in the range of 1 to 100 milliequivalents per 100 grams of dry sediment. If a porosity of 0.33 and an average specific gravity of solids of 2.65 are assumed as representative of the sediment, it can be shown that under saturated conditions (i.e., below the water table), 1 litre of groundwater is in contact with 2 650 grams of solids. If the CEC is 50 meq/100g, one litre of water would be in contact with solids that have a total of 1325 meq of exchangeable cations. If, as in the case of the hypothetical groundwater considered above, there are equal mole fractions of Na^+ and Ca^{2+} on the exchange sites, one litre of water would be in contact with a total of $668x10^{-3}$ moles of Na^+ and $334x10^{-3}$ moles of Ca^{2+} on the exchange sites of the clay. Therefore if, as in the above example, $.9995x10^{-3}m$ of Ca^{2+} are exchanged for $1.999x10^{-3}m$ of Na^+ to achieve equilibrium when the groundwater enters the pore volume and displaces the pre-existing water, the N^2_{Na}/N_{Ca} term is changed only very slightly. If groundwater with the specified concentration continues to flow through the clay stratum, the exchange process will continue to modify the (Ca^{2+}) (Na^+) ratio until the adsorbed cations attain mole fractions such that the right side of Eq.(6) equals the value of $(Ca^{2+})/(Na^{2+})$ that exists for the incoming groundwater. If the cation concentrations in the input water remain constant over time, the mole fractions of adsorbed cations will eventually adjust so that ion exchange does not alter the groundwater chemistry as it passes through the clay.

The high Na^+ concentrations, which are so characteristic of groundwater in the Dunn Center area, cannot be derived from cation exchange processes unless large concentrations of a counter ion such as Ca^{2+} and/or Mg^{2+} are available in solution. Since some of the strata in the Sentinel Butte Formation have significant amounts of carbonate minerals [this is described in more detail in section 3.10.3, based on analytical data given by Moran and others (1976, app. C-II)]; calcite and/or dolomite are logical sources for Ca^{2+} and Mg^{2+} ions. The study by Royse (1967) of the sedimentological characteristics of the Sentinel Butte Formation in western North Dakota indicates that calcite is much more abundant than dolomite in sediments of this formation. In the development of our conceptual geochemical model, we will therefore proceed on the basis that calcite is the dominant carbonate-mineral source of Ca^{2+} in the groundwater. The calcite dissolution reaction can be expressed as

$$CaCO_3 + H_2CO_3 \longrightarrow Ca^{2+} + 2HCO_3^- \quad (8)$$

Groundwater in the Sentinel Butte Formation in the Dunn Center area has HCO_3^- concentrations generally in the range of 500 to 1200 mg/l ($8.2x10^{-3}$ to $17.9x10^{-3}$ moles/litre). If we assume that calcite dissolution has generated all of the HCO_3^-, it is apparent from Eq. (8) that one-half the number of moles/litre of Ca^{2+} also must have gone into solution ($4.1x10^{-3}$ to $8.9x10^{-3}$ m/l Ca^{2+}). If the Ca^{2+} derived from calcite dissolution is exchanged for Na^+ on clay particles, $8.2x10^{-3}$ to $17.9x10^{-3}$ m/l (145 to 411 mg/l) of Na^+ would occur in the groundwater. It is evident from figures 3.6.12-1 and 3.6.12-7 and table 3.6.12-1, however, that most samples from wells in the Sentinel Butte Formation have Na^+ concentrations that are higher than the upper limit of this range. There also remains the problem of accounting for the high SO_4^{2-} concentrations in the groundwater.

The most reasonable mechanism to account for the high SO_4^{2-} concentrations and the excess Na^+ is the dissolution of gypsum. This process can be represented by the reaction,

$$CaSO_4\ 2H_2O \longrightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \quad (9)$$

Ca^{2+} going into solution from gypsum would be accompanied by exchange for Na^+ on the clay particles. Each mole of Ca^{2+} from dissolution of gypsum would therefore produce 2 moles of Na^+ in solution. As indicated previously, SO_4^{2-} concentrations in groundwater of the Sentinel Butte Formation are generally in the range of 200 to 2000 mg/1. If all of this SO_4^{2-} was derived by gypsum dissolution with the Ca^{2+} exchanged entirely for Na^+, the corresponding Na^+ concentrations in the groundwater would be accompanied by 96 to 958 mg/l of Na^+ in solution. Addition of Na^+ produced in this manner to the Na^+ obtained by ion exchange accompanying calcite dissolution produces the total Na^+ concentrations that are typical of groundwater in the Sentinel Butte Formation.

A reasonable working hypothesis to account for the major chemical characteristics of groundwater in the Sentinel Butte Formation can therefore be summarized as follows: CO_2 charged water from rain and snow melt infiltrates below ground surface where it dissolves calcite and gypsum accompanied by exchange of Ca^{2+} for Na^+ to produce $Na(HCO_3SO_4)$ and $Na(SO_4HCO_3)$ type groundwater. Whether HCO_3^- or SO_4^{2-} is the anion depends on the relative amounts of calcite and gypsum that dissolved.

Since the minerals pyrite and marcasite, both of which have the composition FeS_2, are relatively abundant in many of the strata in the Sentinel Butte Formation, the possibility that oxidation of these minerals produces significant SO_4^{2-} concentrations should be evaluated. The oxidation reaction can be expressed as (Stumm and Morgan, 1970),

$$\underline{FeS_2}+\frac{15}{4}O_2+\frac{7}{2}H_2O \longrightarrow \underline{Fe(OH)_3}+2SO_4^{2-}+4H^+$$

where the underlined components are solid phases. Water at 10°C at equilibrium with the earth's atmosphere only contains 11 mg/l of dissolved O_2. Therefore, water from rain or snow melt that infiltrates below ground surface contains so little dissolved oxygen that the amount of SO_4^{2-} that could be produced by this process would be very small. For example, 11 mg/l represents only 0.34×10^{-3} m/l. Eq. (10) indicates that for each mole of O_2 that is consumed in the oxidation of FeS_2 to SO_4^{2-}, 0.53 moles of SO_4^{2-} are produced. Consumption of 11 mg/l of O_2 would therefore produce only 17 mg/l of SO_4^{2-}, which is a very small amount compared to the total SO_4^{2-} concentrations in the groundwater. Although it is very unlikely that oxidation of FeS_2 is a mechanism that contributes much SO_4^{2-} directly to the groundwater, it is probable that this process plays a major role in the origin of gypsum, which is subsequently dissolved by infiltrating water that contributes to groundwater recharge. The role of FeS_2 in the genesis of gypsum is discussed in more detail in section 3.10.4.

We will now consider whether or not the observed pH values for the groundwater are consistent with the geochemical model. The acid in groundwater, which normally is the main cause of dissolution of calcite (a dolomite), is carbonic acid (H_2CO_3). Carbonic acid is produced by hydrolysis of gaseous carbon dioxide.

$$CO_2(g)+H_2O \rightleftharpoons H_2CO_3 \qquad (11)$$

The mass - action expression for this reaction is

$$K_{CO_2}=\frac{[H_2CO_3]}{P_{CO_2}} \qquad (12)$$

where K_{CO_2} is the equilibrium constant, P_{CO_2} is the partial pressure of carbon dioxide, and the square brackets denote activities. H_2CO_3 is a polyprotic acid, with two dissociation reactions,

$$H_2CO_3 \rightleftharpoons H+HCO_3^- \qquad (13)$$

$$HCO_3 \rightleftharpoons H^++CO_3^{2-} \qquad (14)$$

The equilibrium expressions for these reactions are

$$K_{H_2CO_2}=\frac{[H^+]\,[HCO_3^-]}{[HCO_3^-]} \qquad (15)$$

$$K_{HCO_3^-}=\frac{[H^+]\,[CO_3^{2-}]}{[HCO_3^-]} \qquad (16)$$

Pure water in equilibrium with carbon dioxide of the earth's atmosphere ($P_{CO_2}=10^{-3.5}$) has an equilibrium pH of 5.6 at 10°C (this result can be obtained following the calculation procedures outlined in Garrels and Christ (1965) or Stumm and Morgan (1970). If calcite dissolves in pure water in equilibrium with the P_{CO_2} of the earth's atmosphere, the Ca^{2+} and HCO_3^- concentrations will be 22 and 70 mg/l respectively and the pH will be 8.4.

Equilibrium will occur when the expression

$$K_{Cal}=[Ca^{2+}]\,[CO_3^{2-}] \qquad (17)$$

is satisfied. K_{Cal} is the equilibrium constant for calcite at the temperature of interest. If Ca^{2+} is removed from solution by exchange with Na^+ on clay particles, calcite will continue to dissolve so that the activity product $[Ca^{2+}]\,[CO_3^{2-}]$ will equal K_{Cal}. If the exchange reaction is relatively fast compared to the calcite dissolution reaction Ca^{2+} will decrease and CO_3^{2-} must therefore rise to high values. Considering Eq. (16) in terms of Le Chatellier's Principle indicates that as a result of a rise in CO_3^{2-}, H^+ will decrease and HCO_3^- will increase. If the reactions occur under conditions where the atmospheric P_{CO_2} is maintained, H_2CO_3 will remain constant (Eq. (12)). If water containing atmospheric P_{CO_2} values infiltrates below the water table, P_{CO_2} will decrease as dissolution occurs because H_2CO_3 is consumed in the dissolution process (Eq. (8)). This hypothetical evolution sequence will result in groundwater with (1) P_{CO_2} less than the earth's atmospheric value (i.e., less than $10^{-3.5}$) and (2) pH values above 10 or 11. pH values this high are not consistent with the values for groundwater in the Dunn Center area, which have pH values generally between 7.5 and 9.0. From investigations of soil water and groundwater in numerous areas in North America and elsewhere, it is generally accepted that the water in the soil zone becomes charged with dissolved CO_2 partial pressures in the soil zone is decay (oxidation) of organic matter in the A and B horizons and root respiration. Therefore, water that infiltrates downward through the unsaturated zone normally contains relatively high concentrations of H_2CO_3, which is available for strong dissolution of calcite or dolomite if these minerals are encountered as the water moves along its flow paths.

If pure water becomes charged with CO_2 at partial pressures of $10^{-2.5}$ to 10^{-1}, which would be reasonable for unsaturated zone conditions where soil profiles with organic matter occur, and then dissolves calcite under conditions where the gaseous CO_2 partial pressures are maintained (referred to as open system conditions), equilibrium pH values will be in the range of 6.6 to 7.7 at 10°C, and the equilibrium HCO_3^- concentrations will be 192 to 610 mg/l. These pH and HCO_3^- values are lower than those characteristic of groundwater in the Sentinel Butte Formation. If exchange of Ca^{2+} for Na^+ on minerals occurs, the HCO_3^- concentrations and pH will rise as calcite continues to dissolve in order to maintain the equilibrium condition expressed in Eq. (17). If the Ca-Na exchange only occurs below the water table, then the calcite dissolution that accompanies the exchange process will consume H_2CO_3 as indicated in Eq. (8) and the P_{CO_2} will decline (Eq. (12)). Since the P_{CO_2} values calculated by WATEQ, a computer program developed by Truesdell and Jones (1974), from pH and HCO_3^- data obtained from analyses of water samples are typically in the range of 10^{-3} to 10^{-4}, it is reasonable to expect that these processes do, in fact, occur below the water table. This hypothesis will now be tested using a more quantitative approach.

Consider a situation where water with $P_{CO_2}=10^{-1.5}$ atm dissolves calcite to equilibrium under open system conditions. This will result in a pH of 7.0, $HCO_3^-=384$ mg/l and $Ca^{2+}=252$ mg/l. If 240 mg/l of Ca^{2+} are exchanged for Na^+ under closed system conditions (i.e., below the water table) and if the water returns to a saturated condition with respect to calcite (Eq. (17)), the equilibrium conditions will be as follows: $Ca^{2+}=12$ mg/l, $HCO_3^-=600$ mg/l, $Na^+=213$ mg/l, pH=7.9, and $P_{CO_2}=10^{-2.15}$. If gypsum then dissolves in the water to the extent that many hundreds of milligrams per litre of SO_4^{2-} occur in solution, the Na^+ concentration will rise much higher because of exchanges with the gypsum-derived Ca^{2+}, and the HCO_3^- and pH values will rise somewhat because of the decrease in activity coefficients of Ca^{2+} and CO_3^{2-} caused by the ionic strength effect. As more calcite dissolves, the P_{CO_2} will decrease further. This semi-quantitative line of reasoning indicates that it is feasible to generate the characteristic chemical features of groundwater in the Sentinel Butte Formation through the combination of calcite and gypsum dissolution and cation exchange, with important stages occurring both above and below the water table.

This geochemical model is consistent with the ^{13}C content of groundwater in the Sentinel Butte Formation. For example, Wigley (1975) indicates that water that dissolves calcite at 10°C and $P_{CO_2}=10^{-1.5}$ under open system conditions can be expected to have an equilibrium ^{13}C content of about -17 per mille. If, as in the case of the example calculated above, ion exchange maintains the Ca^{2+} concentration of 12 mg/l and calcite dissolution causes equilibrium to be re-established under closed system conditions, the ratio of open system derived carbon to total inorganic carbon will be 384/600. If, as would be expected, the average ^{13}C content of the calcite is 0 per mille, the ^{13}C value for the groundwater after the closed system dissolution will be (384/600)x(-17 per mille)=-11 per mille, which is within the range of ^{13}C values for groundwater in the Sentinel Butte Formation (table 3.6.11-1).

Calculations using the computer program WATEQ (developed by Truesdell and Jones, 1974) indicate that groundwater in the study area is almost invariably undersaturated with respect to gypsum. When gypsum is in contact with water in an undersaturated state it dissolves rapidly. The fact that the groundwater is undersaturated with respect to gypsum and the lack of a large general increase in SO_4^{2-} and Na^+ deeper in the flow system and along flow trends are indications that gypsum is generally absent deeper in the flow system. Where it is present shallower in the system, the mineral concentrations must be extremely small, much below detection using x-ray diffraction methods. It seems reasonable to conclude that the evolution of groundwater towards higher major ion concentrations is severely restricted by the scarcity of gypsum.

The following calculation will serve to illustrate how very minute amounts of gypsum can influence the chemistry of the groundwater. For calculation purposes consider a 1 cm^3 sample of geologic material with a porosity of 33 percent and a gypsum content of 0.03 percent. Using an average specific gravity of the solids of 2.67, the sample will have a bulk dry weight of 1790 mg of which 0.54 mg are gypsum. If the entire gypsum content of the solids dissolves, the 0.33 cm^3 of void space filled with water will contain the 0.54 mg of gypsum, or in other words 1600 mg/litre of dissolved gypsum. The SO_4^{2-} concentration of this water would be 1130 mg/litre. This illustrates that gypsum concentrations in the solids at levels far below detection using normal methods will produce high SO_4^{2-} concentrations when brought in contact with groundwater.

Calculations using WATEQ yield supersaturation values for nearly all UND well samples with respect to calcite. It is more likely, however, that the groundwater is at or very near equilibrium. The calculated supersaturation levels are probably caused by a slight amount of degassing of the water during sampling which would produce higher pH values than the in situ groundwater.

In some situations, it might be expected that an oxidizing zone would exist above the water table, an intermediate zone of slightly oxidizing or slightly reducing conditions near the water table (slightly above or slightly below) and reducing conditions at greater depth below the water table. For the Dunn Center area there is insufficient geochemical data available to enable the subsurface environment to be subdivided in these categories. The available data indicate, however, that strongly reducing conditions generally do not occur in the Sentinel Butte Formation. This conclusion is based on the occurrence of abundant SO_4^{2-} in all aquifers. In the pH environment of these aquifers reduction of SO_4^{2-} would produce HS^- and H_2S. H_2S is detectable by smell to levels as low as about 10^{-8} atm. There is no evidence of significant H_2 occurrence in farm wells or UND wells in the area. In addition, reducing conditions would be expected to produce methane gas, CH_4. To the best of our knowledge methane is not present in noticeable concentrations in wells in the Dunn Center area. Studies of the methane contents of selected wells in the Dunn Center area, which are currently in progress, indicate that methane is not present in significant minute amounts. From thermodynamic considerations it is evident that SO_4^{2-} can exist as the stable dissolved sulfur species in alkaline groundwater under redox conditions that are slightly to moderately anaerobic. These conditions, therefore, are expected to exist in the Sentinel Butte aquifers, except possibly at some of the shallowest recharge locations where aerobic conditions may exist.

3.10.3 Occurrence of Calcite and Exchangeable Cations

For the geochemical model described above to operate, at least some of the strata in the Sentinel Butte Formation must have (1) significant amounts of calcite, (2) significant amounts of gypsum, and (3) clay minerals with appreciable cation exchange capacity and adequate adsorbed concentrations of Na^+ on the exchange sites. We will now consider whether or not there is evidence independent of the groundwater chemical data that indicates that these four conditions actually exist.

Samples of cores from the Sentinel Butte Formation obtained during the UND test drill program were analyzed by the Department of Soil Science at North Dakota State University and by Montana Testing Lab Incorporated for the following parameters; texture, total percent carbonate-mineral content, cation exchange capacity, sodium adsorption ratio, and chemical composition of water extracts from standard water-saturated paste samples, including specific conductance pH, and major-ion concentrations. Not all samples were analyzed for all of these parameters.

Measurements of pH, Ca^{2+}, $SO_4{}^{2-}$, and $HCO_3{}^-$ on soluble extracts from soil paste samples prepared in the standard manner are difficult or impossible to relate to the carbonate-mineral or gypsum content of the solid material in the sample. Drying of the soil sample prior to addition of distilled water will cause precipitation of calcite ($CaCO_3$) and gypsum ($CaSO_42H_2O$) in the sample. The calcite will dissolve when the sample is mixed with distilled water, thereby causing the pH of the water to rise and significant concentrations of Ca^{2+} and $HCO_3{}^-$ to go into solution.

Aerated distilled water in equilibrium with the earth's atmospheric $CO_2(P_{CO_2}=10^{-3.5}$ atm) has a pH of approximately 5.7. If this water is mixed with a dry calcareous soil sample under aerated conditions (i.e., with exposure to air), it is capable of dissolving approximately 83 mg/l of calcite. If the effects of other chemical interactions are neglected, the water after dissolution will have a pH of approximately 8.4 and approximately 70 mg/l of $HCO_3{}^-$ and 23 mg/l of Ca^{2+} (Garrels and Christ, 1965; Stumm and Morgan, 1970). If the Ca^{2+} concentration is regulated to very, very low concentrations because of the Na^+-Ca^{2+} exchange reaction, more calcite can be dissolved in the soil paste water. This will cause higher equilibrium pH values and higher Ca^{2+} concentrations. If, however, there is insufficient quantity of calcite or dolomite in the sample to provide sufficient Ca^{2+} and $HCO_3{}^-$ concentrations to attain equilibrium, the water extract from the soil paste will have lower pH, Ca^{2+}, and $HCO_3{}^-$ values. Since Ca^{2+} is affected by ion exchange, the diagnostic parameters are pH and $HCO_3{}^-$. With this theoretical background, the results of the soil paste tests are now appraised.

One hundred thirty-two core samples from a total of fifteen boreholes were analyzed using the soluble extract procedure (Moran and others, 1976, app. C-II). Forty-one percent of the samples have extract pH values equal to or greater than 8.4. Of the 132 samples analyzed for soluble extract composition, 85 were analyzed for total carbonate content of the solids by weight loss resulting from mixture with acid. Fifty percent of these samples have detectable carbonate mineral contents. The carbonate mineral contents were determined by NDSU by means of the gasometric method (U.S. Salinity Laboratory Staff, 1954) which has a lower limit of detection of approximately 0.5 to 1 percent.

The water extract pH data and carbonate-mineral content data indicate rather conclusively that at least some of the strata in the Sentinel Butte Formation have significant amounts of carbonate mineral material, most of which is probably calcite rather than dolomite.

Core samples which do not have detectable carbonate mineral content and which have soil extract pH values less than about 8.4 may have essentially no significant carbonate mineral content. Of the 85 samples for which there are both types of data, forty percent are in this category. It must be concluded from the groundwater chemistry data, however, that nearly all of the groundwater in the

Sentinel Butte Formation has at some time during its flow history come into contact with strata containing significant carbonate mineral content. If this were not the case, significant members of well samples with anomalously low pH and HCO_3^- values would have been observed during the course of our investigation. It should be kept in mind, however, that if groundwater dissolves calcite during its passage through a calcareous bed and then flows into a non-calcareous zone, the water will maintain its high pH and HCO_3^- concentrations during its period of flow through the non-calcareous zone.

Eighteen of the core samples that were analyzed for cation exchange capacity by Montana Testing Laboratory Incorporated had a CEC range from 3 to 42 milliequivalents per 100 grams of dry sample. There is sufficient cation exchange capacity, therefore, to provide a relatively large reservoir of exchangeable cations on colloidal particles in the sediments of the Sentinel Butte Formation.

3.10.4 Origin of Calcite, Gypsum, and Exchangeable Sodium

Hypotheses will now be developed to account for the origin of the exchangeable Na^+ and of the gypsum of the strata of the Sentinel Butte Formation. It was indicated above based on a parameter analysis of Eq. (3) that the mole fraction ratio N_{Na}/N_{Ca} must rise to a high value before the $Ca^{2+} \longrightarrow Na^+$ exchange becomes ineffective or is reversed. Sedimentological evidence indicates that the deposits of the Sentinel Butte Formation were laid down in fresh-water fluvial and possibly deltaic environments (Royse, 1967; Jacob, 1976). Although it is not possible to determine what the chemistry of the fluvial environment was at the time of deposition, we will proceed with some speculation in this regard.

It is very unlikely that the Na^+ that is being exchanged for Ca^{2+} in the present groundwater-flow system was adsorbed on the colloidal clay particles at the time of deposition of the sediments of the Sentinel Butte Formation. The drainage basin that supplied the waters and sediments to the fluvial and deltaic environments appears to have been composed predominantly of sedimentary rocks. If there were significant amounts of calcite or dolomite in the source rocks, the drainage water would likely have had molar ratios of Na^+/Ca^{2+} that were less than unity. The fact that many of the strata in the Sentinel Butte Formation have appreciable carbonate mineral contents (mostly calcite) is evidence that suggests that the drainage basin contained carbonate rocks that provided calcareous sediment to the streams and deltaic systems. There is the possibility, however, that the calcareous material in the Sentinel Butte Formation was precipitated from circulating groundwater at some later time. The ^{13}C data from groundwater in this formation suggest that the carbonate minerals were derived from erosion of marine carbonate rocks; however, more conclusive information will be obtained from ^{13}C analyses of the carbonate minerals rather than the water. These studies are in progress.

Even if we assume that the drainage basin was largely devoid of carbonate rocks to supply calcareous sediment, analogy with present day chemical environments in fluvial systems indicates that it is very unlikely that the Na^+/Ca^{2+} ratio would have been greater than about 3 to 5. Freshwater rivers, streams, and deltas in non-arid environments normally contain cations with individual species concentrations in the range of 10^{-4} to 10^{-2} moles per litre. Because (1) in fresh continental waters the selectivity coefficient K^* for the Na-Ca exchange reaction (Eq. (3)) is characteristically less than unity, (2) the Na^+/Ca^{2+} molar ratio is characteristically not very large, and (3) activity coefficient ratio is close to unity, it is evident from Eq. (3) that clays deposited in most fluvial or deltaic environments will have nearly all of the cation exchange sites loaded with Ca^{2+}. Since Ca^{2+} has a much stronger affinity for the adsorption sites of clay particles, the only way that the adsorption sites can become preferentially loaded with Na^+ is by immersion of the sediment in an aqueous solution with a large Na^+ excess. If there is very little Na^+ on the exchange surfaces of clay minerals, and if Ca^{2+} rich groundwater is passing through the material, the exchange reaction represented by Eq. (1) will, within a relatively small number of pore volume replacements, achieve equilibrium with respect to the incoming groundwater. When equilibrium is achieved, the process of ion exchange will no longer be capable of modifying the cation concentrations in the incoming groundwater. If, on the other hand, the cation exchange sites initially have a high percentage of Na^+ and if the incoming groundwater has Ca^{2+} as the predominant cation at concentrations of only a few millimoles per litre or less, many hundreds of pore volumes of groundwater would have to pass through the clayey materials before the mole fractions of adsorbed cations will have attained equilibrium with respect to the incoming water. If the groundwater flowing into the cation exchange zone has a constant composition, and if the cation exchange zone is relatively homogeneous with respect to its exchange properties, a zone in which the mole fractions of adsorbed cations have attained equilibrium with respect to the incoming groundwater will gradually expand in the flow direction. If the input conditions remain relatively constant for long periods of time, the strata with cation exchange capabilities will eventually attain equilibrium and henceforth be incapable of modifying the cation chemistry through exchange processes.

Except for the northern part of the Dunn Center area, groundwater in even the shallow parts of the Sentinel Butte Formation has high Na^+/Ca^{2+} molar ratios. This condition reflects the very sluggish nature of the groundwater-flow system. High Na^+/Ca^{2+} ratios will not persist for very long in areas where groundwater circulation is relatively rapid and/or where cation exchange capacities are relatively small. If the cation exchange capacity is small, the reservoir of exchangeable Na^+ on the adsorption surfaces must also be small.

In the geochemical model that we have used to account for the $Na(HCO_3SO_4)$ and $Na(SO_4HCO_3)$ waters that are so characteristic of the Sentinel Butte Formation, CO_2 charged groundwater dissolves calcite to equilibrium. This contributes Ca^{2+} and HCO_3^- to the water and raises the pH. Gypsum dissolution contributes more Ca^{2-} and raises the SO_4^{2-} concentration to hundreds of milligrams per litre. Cation exchange on clays replaces most of the Ca^{2+} with Na^+. The selectivity coefficient (Eq. (3)) for the Mg^{2+}-Ca^{2+} exchange reaction is typically between 0.6 and 0.9 (Jensen and Babcock, 1972). The very small amounts of Cl^- probably came from a variety of minor sources. The calcite dissolution, gypsum dissolution, and cation exchange reactions probably occur simultaneously in some parts of the system and possibly in sequence in other areas, depending on the local stratigraphy and flow-system conditions.

The key factor that controls the extent to which the hydrochemical system will evolve is the presence of gypsum. As indicated in section 3.10.2, calculations indicate that almost without exception, groundwater samples from the Sentinel Butte Formation are considerably undersaturated with respect to gypsum. This means that if the groundwater encounters any gypsum, dissolution will occur. Equilibrium with respect to gypsum will be attained if there is sufficient gypsum present so that dissolution can proceed until there are several thousand milligrams per litre of Ca^{2+} in solution. The exact equilibrium concentrations will depend on the temperature and ionic strength of the groundwater (Cherry, 1968). It is well known that gypsum dissolves in water relatively quickly. For example, laboratory experiments indicate that equilibrium is normally attained within a matter of minutes or hours (Kemper, et al., 1974). It is reasonable to conclude, therefore, that groundwater in the Sentinel Butte Formation is generally lacking in gypsum. There must have been enough gypsum to supply observed SO_4^{2-} concentrations (this requires only minute amounts) but not enough for the system to attain the higher concentrations that would establish equilibrium. If the sediments of the Sentinel Butte Formation contain even minute concentrations of gypsum extending very far below ground surface, then the SO_4^{2-} concentrations should become greater as the water moves deeper into the flow system; therefore, after flowing far enough the water would attain equilibrium concentrations. Since there are no major systematic increases in SO_4^{2-} concentrations far below the water-table zone, we must conclude that gypsum is generally absent in most of the strata of the Sentinel Butte Formation.

Another question now arises: If gypsum is generally absent, but if calcite is generally present along with high Na^+ content clays, what controls the equilibrium pH and the equilibrium concentrations of Ca^{2+}, Na^+, and HCO_3^- in the groundwater? The two controlling equilibrium relations are

$$K^* = \frac{[Ca^{2+}]}{[Na^+]^2} \frac{N^2_{Na}}{N_{Ca}} \tag{18}$$

$$K_C^1 = \frac{[Ca^{2+}][HCO_3^-]^2}{[H_2CO_3]} \tag{19}$$

Eq. (18) is equivalent to Eq. (3) and Eq. (19) is the mass-action expression for Eq. (8). It can also be derived by combining Eqs. (15), (16), and (17) where $K_C^1 = K_C K_{H_2CO_3}/K_{HCO_3}$. If CO_2-charged water infiltrating through the unsaturated zone dissolves calcite to equilibrium under open system conditions and subsequently interacts with clay minerals below the water table, the temperature and soil P_{CO_2} will determine the equilibrium pH and Ca^{2+} and HCO_3^- concentrations attained above the water table. Below the water table the equilibrium will be controlled by the P_{CO_2} that exists when the water moves into the saturated zone (i.e., the initial P_{CO_2}) and on the N_{Na}/N_{Ca} ratio of adsorbed cations that exists when the new water passes into and through the clayey zone. As Ca^{2+} is removed by exchange with Na^+ calcite will dissolve. If the Na-Ca exchange reaction occurs more rapidly than the calcite dissolution reaction, which is what would normally be expected, Ca^{2+} in solution would be maintained at low concentrations as calcite dissolution proceeds towards equilibrium. As dissolution occurs, H_2CO_3 will decrease (see Eq. (8)), and HCO_3^- will increase; and, therefore, the equilibrium condition expressed in Eq. (18) will be readily achieved if a sufficient quantity of $CaCO_3$ is present in the sediment. In total, therefore, the equilibrium pH, Ca^{2+}, HCO_3^- CO_3^{2-} and Na^+ values that will be produced by this sequence of events will be determined by the P_{CO_2} of the unsaturated zone, the temperature, K*, K_C^1, and the initial N_{Na}/N_{Ca} ratio.

If some gypsum dissolution occurs in the unsaturated zone before calcite has dissolved to equilibrium, calcite solubility will be depressed by the common-ion effect. If gypsum dissolution occurs after calcite equilibrium has been reached, but before cation exchange becomes significant, the water will become supersaturated with respect to calcite (i.e., Ca^{2+} in Eq. (18) increases while the other terms remain fixed) and calcite precipitation will occur. If gypsum dissolution occurs after the water has dissolved calcite and reached equilibrium with respect to the Na-Ca exchange reaction, SO_4^{2-} concentrations will rise, and, even though most of the additional Ca^{2+} would be exchanged for Na^+, the N_{Na}/N_{Ca} ratio on the clay mineral adsorption sites would have to rise slightly. The effect of this rise combined with the increase in ionic strength which decreases the activity coefficients (i.e., $[Ca^{2+}] = \gamma_{Ca} \cdot (Ca^{2+}) \rightarrow [HCO_3^-] = \gamma_{HCO_3} \cdot (HCO_3^-)$ etc.), would cause slightly increased concentrations of Ca^{2+} and HCO_3^- in the groundwater. The water would then be slightly supersaturated with respect to calcite. This would lead to precipitation of very small amounts of calcite.

As groundwater moves along its flow paths, the adjustment processes described above occur. The exact position of equilibria relations will, of course, be affected by the local geologic and hydrologic conditions. The purpose of this discussion has been to outline a conceptual geochemical framework that is consistent with the characteristic chemical properties of the groundwater on a regional scale.

From the above analysis we are left with the question of how and when did the Na^+ that is adsorbed on the clay minerals originally enter the sediments of the

Sentinel Butte Formation. In the same context it is also appropriate to consider the origin of the small but significant amounts of gypsum that supply the SO_4^{2-} concentrations and Ca^{2+} for exchange with Na^+. Gypsum could not have been deposited in the freshwater fluvial or deltaic environments in which the sediments of the Sentinel Butte Formation were deposited, nor could gypsum (or anhydrite: $CaSO_4$) have persisted in the water if it had been eroded from gypsiferous source areas. Gypsum is sufficiently soluble so that highly brackish or saline water is required for its persistence or formation as a mineral precipitate.

The origins of the adsorbed Na^+ and of the gypsum are, of course, problematic. The sediments of the Sentinel Butte Formation were laid down approximately 50 million years ago. The present hydrologic regime in the Dunn Center region has presumably existed only since deglaciation of the area about 13 000 years ago, an almost insignificant amount of time compared to the total length of time during which groundwater has circulated through the strata of the Sentinel Butte Formation. The present groundwater-flow system, which is characterized by downward flow through aquitards and lateral flow towards the major valleys, provides no mechanism for introduction of larger amounts of Na^+ into the system.

Some time prior to the existence of the Little Missouri valley, the Sentinel Butte and Golden Valley Formations were appreciably thicker than at present. Based on sediment thickness and the elevation of the Killdeer Mountains, it is reasonable to expect that the surface of the Dunn Center area was buried beneath at least 1000 feet and possibly as much as 3000 feet of sediment. Given burial of this type, a different landscape than at present, and many tens of millions of years, a groundwater-flow system that carried Na^+ rich water was probably established at some period. This flow system was probably analogous to that in the Cannonball, Ludlow, Hell Creek, and Fox Hills Formations in this area at the present time. This would have caused the adsorption sites on clay minerals to become loaded with Na^+ in preference to other cations. The present groundwater-flow regime is in the process of removing Na^+ from the clays, but because the flow rates are so slow, Na^+ has continued to occur in major amounts.

Although we consider them to be less reasonable than those presented above, there are other hypotheses that could account for the adsorbed Na^+. At some time after deposition of the sediments of the Sentinel Butte Formation, there may have been a marine invasion of the area. Since there is no evidence of marine sediments above the Sentinel Butte Formation, this mechanism is considered improbable. When the Dunn Center area was glaciated, ice load stress on the subglacial strata may have caused saline water in strata such as the Pierre Formation and in aquifers below to be squeezed up into shallower zones. This water would most likely have had a high Na^+ content. However, if glacial squeezing actually did cause saline water to flow upward, it is unlikely that the water would have flowed upward as far as the Sentinel Butte Formation. The water would probably have entered some of the more permeable deep aquifers such as the Fox Hills and Hell Creek Formations and traveled laterally, rather than continue to move upward through numerous overlying aquitards. Another hypothesis is that marine interstitial water was squeezed upward out of the sediment of the Cannonball Formation as deposition of overlying sediments caused consolidation of this sediment. The sediment of the Cannonball Formation was deposited in a marine environment (Cvancara, 1976); however, it is less than 300 feet thick and therefore would not have been able to supply very large volumes of Na^+ rich water even if consolidation did cause some upward flow.

The small amounts of gypsum that contribute SO_4^{2-} to the groundwater may have been introduced into the strata of the Sentinel Butte Formation as precipitates formed during (1) the circulation of the brackish or saline water that contributed the Na^+ to the clay minerals, or (2) during circulation of some other brackish or saline water. There is another explanation, however, which seems to be more reasonable.

The chemical reaction represented in Eq. (10) indicates that oxidation of FeS_2 (pyrite or marcasite) can produce SO_4^{2-} in solution. As indicated previously, there is insufficient dissolved oxygen in rain or snow melt to produce more than about 17 mg/l of SO_4^{2-}, if oxidation occurs below ground surface as recharge water infiltrates towards the water table. Many lines of evidence (sec. 3.6.6) indicate that nearly all water that infiltrates below ground surface in the Dunn Center area and in most other areas of western North Dakota evaporates or evapotranspires before it infiltrates deep enough to recharge the water-table zone. It is only the exceptional rainfall or snow-melt events or combination of events that cause groundwater recharge. It is likely, therefore, that much of the water that infiltrates through the solum while carrying sufficient oxygen to cause oxidation of FeS_2 is evaporated or evapotranspired before it reaches the water table. If this water encounters FeS_2 before it is lost by evapotranspiration it will become more acidic as a result of H^+ production. It will also contain as much as about 17 mg/l of SO_4^{2-}. If the water comes into contact with calcite ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$), the acidity caused by H^+ production (i.e., H_2CO_3) from CO_2 and by FeS_2 oxidation would cause dissolution of these minerals. The infiltrating water would then be characterized by Ca^{2+} and possibly Mg^{2+} as the dominant cations and by HCO_3^- and SO_4^{2-} as the dominant anions. If these major ions then become concentrated because of evapotranspiration, the residual water would precipitate gypsum and calcite in zones above the water. The water in the pore spaces need not go to dryness for these mineral precipitates to form. Supersaturation with respect to calcite would occur after only a slight amount of evapotranspiration has occurred. Considerable concentration would have to take place before gypsum would precipitate.

The roots of vegetation draw water from the solum and in many areas from below the solum. Some of the types of prairie grasses that occur in the Dunn Center area can send roots as deep as 11 feet below ground surface (personal communication, Dr. V. Facey, professor of botany, UND). The rootlets of grass and other vegetation act as semi-permeable membranes. As water is drawn from the porous medium into the transmission channels in the interior of the rootlet, the membranes that comprise part of the rootlet walls are capable of acting as selective filters, thereby preventing most of the major ions from being transported into the main root channels as water moves up to the leaves. In general, it is expected that the process of evapotranspiration will remove water from the soil and subsoil zones and leave most of the salts behind. Evapotranspiration as well as evaporative vapor transport processes, therefore, would both tend to produce major-ion increases that would occur as the water content of infiltrating water is reduced.

The gypsum precipitated as the end result of the FeS_2 oxidation and evapotranspiration processes will be available in the unsaturated zone as a source of Ca^{2+} and SO_4^{2-} to infiltrating water that on later occasions passes downward through the soil. Since it is only very infrequently that appreciable amounts of water travel all the way through the unsaturated zone to the water table, the gypsum that precipitated during many FeS_2 oxidation and evapotranspiration cycles would provide large Ca^{2+} and SO_4^{2-} concentrations to the water recharging the groundwater zone. If this mechanism is in fact the main source of the SO_4^{2-} in the groundwater, major SO_4^{2-} concentrations would be typical of shallow groundwater as well as deeper groundwater and major increases in SO_4^{2-} concentration with depth would not occur. These features are consistent with the observed occurrence of SO_4^{2-} in groundwater of the Sentinel Butte Formation.

A second source of SO_4^{2-} ions in the groundwater in the Dunn Center area is suggested by the distribution of gypsum in the shallow groundwater. In section 3.6.12 and 3.6.13 a strong parallel between high gypsum content and recharge through low areas, especially valley floors, was noted. It is possible that this reflects subaerial weathering of sulfide particles and concentration of SO_4^{2-} in low-land areas by surface-water transportation.

As was shown above, pyrite and marcasite are commonly present in sediment of the Sentinel Butte Formation. When these sediments are eroded by running water, the pyrite and marcasite are exposed to the air. Because adequate oxygen is present in this case, the sulfide can be readily oxidized to a sulfate. The sulfide grains can be moved down slope physically as bed load and suspended load in streams and the sulfate can be moved as dissolved load. Except during spring runoff and during extremely heavy, local rainfall events none of the small streams draining the project area reach Spring Creek or the Knife River. Rather, they reach local depressions or valley floors, drop their sediment load, and infiltrate into the floor of the valley or evaporate. Sulfide grains in the sediment load are then exposed once again to the atmosphere and are further oxidized. Dissolved sulfate is either carried into the ground, where the water infiltrates, or is left on and just below the surface as gypsum, where the water evaporates. When the valley floor becomes wet again, the gypsum would be dissolved and could infiltrate in sites where infiltration is favored.

This process could account for the concentration of higher sulfate values along the partly buried meltwater valleys that are evident as deep as in the F- and H-lignites. It can also account for the very high sulfate values in the highly saline samples that appear to represent direct recharge from evaporitic surface waters.

3.10.5 Groundwater Below the Sentinel Butte Formation

Although there are not many chemical analyses of samples from wells in the Bullion Creek Formation, the few that there are (table 3.6.12-1) indicate that the groundwater in this formation is $NaHCO_3$ type water with SO_4^{2-} concentrations generally much lower than the SO_4^{2-} values in groundwater in the Sentinel Butte Formation. There are no Fox Hills wells currently operating in the study area (a well in the Fox Hills Formation at the town of Dunn Center has been installed but is not yet operational). A Fox Hills well located just three miles north of the area and one located in the town of Halliday two miles east of the study area have $NaHCO_3$ type water with SO_4^{2-} concentrations below 10 mg/l. This suggests that in the Dunn Center region very low SO_4^{2-} values are probably typical of Fox Hills-Hell Creek groundwater. East of Dunn County in Mercer, Oliver, and McLean Counties, the SO_4 concentrations in the Fox Hills-Hell Creek aquifer are very low (Croft, 1973; Klausing, 1974). In a regional study west of the Dunn Center area, Hamilton (1970) also observed very low SO_4^{2-} values in this aquifer.

The low SO_4^{2-} concentrations in these deeper zones indicates that (1) SO_4^{2-} is being lost through processes of SO_4^{2-} reduction or (2) SO_4^{2-} is generally absent from the geologic materials through which the groundwater in these formations flows. If SO_4^{2-} reduction is the cause of the paucity of SO_4^{2-} significant levels of H_2S gas should be a characteristic feature of the groundwater. H_2S gas, which is often referred to as rotten egg gas, is detectable by smell to levels as low as about 10^{-8} atm of partial pressure. Well water that smells of H_2S is good evidence of SO_4^{2-} reduction. The smell of H_2S was not present in water from the UND wells in the Bullion Creek Formation nor was it present in the two Fox Hills-Hell Creek wells that were sampled in the Dunn Center area. Although Croft (1973) suggests that the very low SO_4^{2-} concentrations in the Fox Hills-Hell Creek aquifer may be due to SO_4^{2-} reduction, he makes no mention of H_2S occurrence in this aquifer. If appreciable amounts of H_2S occur in this aquifer, it would be expected that this gas would be an important factor limiting the use of water obtained from the aquifer.

The process of SO_4^{2-} reduction can be represented as follows (Stumm and Morgan, 1970).

$$SO_4^{2-} + CH_2O + 6H^+ \longrightarrow H_2S + CO_2 + 3H_2O \qquad (20)$$

CH_2O is a simple carbohydrate used in this equation to represent whatever organic matter is involved in the oxidation process. For SO_4^{2-} reduction to occur in an anaerobic aqueous environment a compound must be oxidized (i.e., there must be an electron doner). Organic matter is normally expected to be the electron doner. The result of organic matter oxidation is an increase in P_{CO_2} and H_2CO_3 and a decrease in pH. If calcite or dolomite are present, this will cause dissolution of these minerals, thereby raising the HCO_3^-, Ca^{2+} and Mg^{2+} concentrations. If the Ca^{2+} and Mg^{2+} are exchanged for Na^+ on the adsorption sites of clay minerals, the end result of the process of SO_4^{2-} reduction will be higher Na^+ HCO_3^-, and pH values.

If high SO_4^{2-} content water flowing downward through the Sentinel Butte Formation is a major source of water feeding the Bullion Creek Formation, and if the SO_4^{2-} is then lost by reduction processes within the strata of the Bullion Creek Formation, we would expect to observe exceptionally high HCO_3^- concentrations and widespread H_2S smell in Bullion Creek wells. Bullion Creek wells do not exhibit such features, and it is reasonable to conclude that water in the Bullion Creek Formation in the Dunn Center area has been derived mainly from lateral inflow rather than from downward seepage from the Sentinel Butte Formation. There is also the possibility that significant amounts of Bullion Creek water are derived by upward seepage from the Fox Hills Formation.

4.0 IMPACTS OF THE PROPOSED DUNN CENTER PROJECT ON THE GEOLOGIC AND GEOHYDROLOGIC ENVIRONMENT

The following section is a brief summary of the conclusions of a more extensive impact assessment reported by Moran and others (1976).

4.1 Effects on Water Levels in Wells

Throughout most of the area of the proposed AMAX Dunn Center No. 1 mine, the Dunn Center bed and A-lignite are beneath the regional water table. In limited areas, the B-lignite is also saturated. The process of mining will cause groundwater to flow through the lignite beds toward the mine where it will discharge into the excavation in springs and seeps. This will result in a decline in the potentiometric surface in the lignite beds, which in turn will produce an increase in downward seepage from the confining beds. This will ultimately result in a decline in the regional water table adjacent to the mined area. The effect of these declines in potentiometric surface will be to cause a decline in water level in wells, which are completed in lignite beds that outcrop in the walls of the excavation. Water level in lignite beds beneath the Dunn Center bed is not expected to be affected by mining.

The area of the proposed AMAX Dunn Center No. 1 mine is bounded on the west, north, and east by deeply eroded, partly filled glacial meltwater valleys. These valleys effectively limit the distance out from the mine that wells will experience a decline in water level. On the west and north, the Dunn Center bed outcrops above the floor of the valley so all effects on water levels will end at the valley wall. On the east, the Dunn Center bed is bounded by saturated, highly permeable material in the valley fill. On the basis of our study, it appears that the valley fill sediment can supply all the water that will seep into the mine without experiencing a significant decline in head.

The deeply eroded glacial meltwater valleys that bound the mine area on the south are more distant from the mine, and water levels in wells between the mine and these valleys, several miles to the south, will decline. The magnitude of water-level decline in a well is a function of the distance from the mine, the time since mining began, the amount of water-level decline at the edge of the mine, the storage coefficient and transmissivity of the lignite, and the hydraulic conductivity of the overburden on the lignite. On the basis of the values of these variables that we have determined or estimated in the Dunn Center area, we believe that water-level decline in wells will probably be less than 5 feet at a distance of two miles from the mine. In most places, drawdown will probably be one foot or less at a distance of 2 miles. In most places, drawdown of 10 feet or more will probably be restricted to a distance of about 0.5 mile from the highwall.

Following the reclamation, the water level in areas that have been mined will begin to rise. Once mining stops the water level in wells south of the mine will also begin to return toward their former level.

4.2 Effects on Surface Water Regime

The proposed project should have no impact on either Lake Ilo or Marshall Slough. Both lakes are located in groundwater recharge areas and neither is fed by significant amounts of groundwater. In addition, Lake Ilo is situated such that it would not receive seepage from the mine area.

Spring Creek receives groundwater discharge that passes through the Dunn Center bed in the area of the proposed AMAX Dunn Center No. 1 mine. The mine would prevent this water from reaching Spring Creek. We estimate that this could represent a maximum decrease of about 1.7 cubic feet a second in the flow of Spring Creek, about 10 percent of the groundwater discharge that reaches Spring Creek from within the Dunn Center project area.

4.3 Effects on Groundwater Chemistry

The estimation of chemical quality of groundwater in the cast overburden following reclamation is extremely difficult. The chemical system is very complex and contains numerous variables, many of which can only be estimated with the available data. On the basis of the data available, it seems likely that the chemical quality of the groundwater in the cast overburden may be similar to the lower-quality water that occurs in the overburden at present. It may be, that in significant areas of the cast overburden, the chemical quality of the water will be quite good.

The same uncertainty exists with respect to the chemical quality of groundwater in cast overburden in which gasifier ash has been disposed. The data available suggest that the chemical quality may be as low or lower than the poorer water in the overburden at present. This conclusion is very tentative, and the final water quality may well be considerably better.

4.4 Effects on Post-Mining Water Supply

Even if the water in the cast overburden is of low chemical quality, adequate groundwater supplies can be developed in the mined area to permit the reestablishment of an agricultural economy. Aquifers beneath the Dunn Center bed will be unaffected by the mining and wells can be completed in them. These materials are generally not as permeable as the shallower lignite and sand aquifers. As a result more wells will be required in order to produce the same amount of water as at present.

REFERENCES

AMAX Coal Co., DC-1 Task Force, March 15, 1976, Environmental Mining and Reclamation Plan for Proposed Lignite Mine and Gasification Plant in Dunn County, North Dakota.

Armstrong, C. A., 1971, Groundwater resources of Burke and Mountrail Counties: North Dakota Geological Survey, Bull. 55, pt. III, 86 p.; North Dakota State Water Commission, County Groundwater Studies 14, pt. III, 86 p.

Babcock, K. L., 1963, Theory of the chemical properties of soil colloidal systems at equilibrium: Hilgardia, v. 34, p. 417-542.

Babcock, K. L., and Schulz, R. K., 1963, Effect of anions on the sodium-calcium exchange in soils: Soil Society of America Proc., v. 27, p. 630-631.

Back, W., and Hanshaw, B. B., 1965, Chemical hydrogeology: *in*, Advances hydroscience: v. 1, p. 49-109.

Barnes, I., and Clarke, F. E., 1964, Geochemistry of ground water in mine drainage problems: United States Geological Survey Prof. Paper 63-A, 6 p.

Barnes, I., Stuart, W. T., and Fisher, D. W., 1964, Field investigations of mine waters in the northern anthracite field, Pennsylvania: United States Geological Survey Prof. Paper 73-B, 8 p.

Benson, W. E., 1952, Geology of the Knife River area, North Dakota: United States Geological Survey, Open-file report, 323 p.

Berner, R. A., 1971, Principles of chemical sedimentology: McGraw Hill, New York, 239 p.

Bolt, G. H., 1967, Cation-exchange equations used in soil science—a review: Netherlands Journal Agricultural Science, v. 15, p. 81-103.

Brown, R. H., Konaplyantsev, A. A., Ineson, J., and Kovalevsky, J., 1972, Groundwater studies: An international guide for research and practice: UNESCO, Studies and reports in hydrology, no. 7, chapter 10.

Camp, T. R., 1963, Water and its impurities: Reinhold Publishing Corp., New York, 355 p.

Carlson, C. G., 1973, Geology of Mercer and Oliver Counties, North Dakota: North Dakota Geological Survey, Bull. 56, pt. I, 72 p.; North Dakota State Water Commission, County Groundwater Studies 15, pt. I, 72 p.

Carlson, C. G., and Anderson, S. B., 1970, Sedimentary and tectonic history of North Dakota part of Williston basin: North Dakota Geological Survey, Miscellaneous Series no. 28, p. 1833-1846.

Carlson, C. G., and Anderson, S. B., 1973, Stratigraphy: *in* Mineral and Water Resources of North Dakota: North Dakota Geological Survey, Bulletin 63, p. 31-41.

Cherry, J. A., 1968, Chemical equilibrium between gypsum and brackish and slightly saline waters at low temperatures and pressures: Chemical Geology, v. 3, p. 239-247.

Chervin, V. B., 1973, High- and low-sinuosity stream deposits of the Sentinel Butte Formation (Paleocene) McKenzie County, North Dakota: University of North Dakota, Unpublished MSc Thesis, 73 p.

Christiansen, E. A., 1967, Collapse structures near Saskatoon, Saskatchewan, Canada: Canadian Journal of Earth Sciences, v. 4, p. 757-767.

Christiansen, E. A., 1971, Geology of the Crater Lake collapse structure in southeastern Saskatchewan: Canadian Journal of Earth Sciences, v. 8, no. 12, p. 1505-1513.

Clayton, Lee, 1970, Preliminary geologic map of Dunn County: North Dakota Geological Survey, Miscellaneous Map 11.

Clayton, Lee, Moran, S. R., and Bickley, W. B., 1976, Stratigraphy, origin, and climatic implications of Late Quaternary upland silt in North Dakota: North Dakota Geological Survey, Miscellaneous Series no. 54, 15 p.

Clayton, Lee, Carlson, C. G., Moore, W. L., Groenewold, G. H., Holland, F. D., Jr., and Moran, S. R., 1977, The Slope (Paleocene) and Bullion Creek (Paleocene) Formations of North Dakota: North Dakota Geological Survey, Report of Investigation No. 59, 14 p.

Croft, M. G., 1973, Groundwater resources of Mercer and Oliver Counties, North Dakota: North Dakota Geological Survey, Bulletin 56, pt. III, 81 p., North Dakota State Water Commission, County Groundwater Studies 15, pt. III, 81 p.

Croft, M. G., and Wesolowski, E. A., 1970, Transmissivity and storage coefficient of aquifers in the Fox Hills Sandstone and Hell Creek Formation, Mercer and Oliver Counties, North Dakota: United States Geological Survey, Prof. Paper 700-B, p. B190-B195.

Cvancara, A. V., 1976, Geology of the Cannonball Formation (Paleocene) in the Williston basin, with reference to uranium potential: North Dakota Geological Survey, Report of Investigation No. 57, 22 p.

Dames & Moore, 1974, Phase I of environmental assessment of a coal gasification complex in Dunn County, North Dakota: Natural Gas Pipeline Co. of America, Chicago, IL.

Degens, E. T., 1969, Biogeochemistry of stable carbon isotopes: *in* Eglington, G. and Murphy, M. J. J. (ed), Organic geochemistry, methods and results: Springer, Berlin, 304 p.

Domenico, P. A., 1972, Concepts and models in groundwater hydrology: McGraw-Hill, New York, 405 p.

Fletcher, A. G., 1974, A preliminary engineering, geological, and hydrological environmental assessment of a proposed 250 MMSCFD coal gasification facility: University of North Dakota, Engineering Experiment Station, 175 p.

Fossum, G. O., 1976, Environmental assessment report of 250 MMSCFD dry ash Lurgi gasification facility: II water quality: University of North Dakota, Engineering Experiment Station, Report 76-09-EES-01, v. III.

Freeze, R. A., 1969, Regional groundwater flow—Old Wives Lake drainage basin, Saskatchewan: Canadian Department of Energy, Mines, and Resources, Scientific Series No. 5.

Garrels, R. M., and Christ, C. L., 1965, Solutions, minerals, and equilibria: Harper and Row, New York, 450 p.

Glover, R. E., 1966, Groundwater movement: United States Bureau of Reclamation, Engineering Monograph No. 31, 76 p.

Hamilton, T. M, 1967, Late-Recent alluvium in western North Dakota: *in* Clayton, Lee, and Freers, T. F., (ed), Glacial geology of the Missouri Coteau and adjacent areas: North Dakota Geological Survey, Miscellaneous Series No. 30, p. 151-158.

Hamilton, T. M, 1970, Groundwater flow in part of the Little Missouri River basin, North Dakota: University of North Dakota, Unpublished PhD dissertation, 179 p.

Hares, C. J., 1928, Geology and lignite resources of the Marmarth lignite field, southwestern North Dakota: United States Geological Survey, Bulletin 775, 110 p.

Hemish, L. A., 1975, Stratigraphy of the upper part of the Fort Union Group in southwestern McLean County, North Dakota: University of North Dakota, Unpublished MSc thesis, 160 p.

Hough, B. K., 1969, Basic soils engineering: Ronald Press, New York, 634 p.

Hvorslev, M. J., 1951, Time lag and soil permeability in groundwater observations: United States Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, Bulletin 36, 50 p.

International Atomic Energy Agency, 1975, Environmental isotope concentration in precipitation: Technical Report Series.

Jacob, A. F., 1973, Depositional environments of Paleocene Tongue River Formation, western North Dakota: American Association of Petroleum Geologists Bull., v. 57, no. 6, p. 1038-1052.

Jacob, A. F., 1976, Geology of the upper part of the Fort Union Group (Paleocene), Williston basin, with reference to uranium: North Dakota Geological Survey, Report of Investigation No. 58, 49 p.

Jacob, C. E., 1940, On the flow of water in an elastic artesian aquifer: American Geophysical Union Transaction, v. 21, p. 574-586.

Jenne, E. A., 1968, Controls on Mn, Fe, Co, Ni, Cu, and Zn concentrations in soils and water: The significant role of hydrous Mn and Fe oxides: *in* Gould, R. F., (ed), American Chemical Society, Advances in Chemistry Series, v. 73, p. 337-387.

Jensen, H. E., and Babcock, K. L., 1973, Cation-exchange equilibria on a Yolo Loam: Hilgardia, v. 41, no. 16, p. 475-488.

Johnson, R. P., 1975, Depositional environments of the upper part of the Sentinel Butte Formation, southeastern McKenzie County, North Dakota: University of North Dakota, Unpublished MSc thesis, 63 p.

Kemper, W. D., Olsen, John, and DeMoody, C. J., 1975, Dissolution rate of gypsum in flowing water: Soil Science Society of America Proc., v. 39, p. 458-463.

Klausing, R. L., 1974, Groundwater resources of McLean County, North Dakota: North Dakota Geological Survey, Bull. 60, pt. III, 73 p.; North Dakota State Water Commission, County Groundwater Studies 19, pt. III, 73 p.

Mason, E. S., 1976, Environmental assessment report of 250 MMSCFD dry ash Lurgi gasification facility: III surface hydrology: University of North Dakota, Engineering Experiment Station, Report 76-09-EES-01, v. III.

Moran, S. R., Cherry, J. A., Ulmer, J. H., Peterson, W. M., Somerville, M. H., Schaefer, J. K., Lechner, D. O., Triplett, C. L., Loken, G. R., and Fritz, P., 1976, An environmental assessment of a 250 MMSCFD dry ash Lurgi coal gasification facility in Dunn County, North Dakota: volume V Geology, Groundwater, and Hydrogeochemistry: University of North Dakota, Engineering Experiment Station, Bull. 76-12-EES-01, 450 p.

Payne, B. R., 1972, Isotope hydrology: *in* Advances in hydrosciences. Academic Press, v. 8, p. 95-137.

Price, J. R., and Vossen, R. L., 1975, North Dakota crop and livestock statistics: annual summary for 1974: North Dakota Agricultural Experiment Station, Agricultural Statistics No. 35, 76 p.

Rahn, P. H., 1976, Potential of coal strip-mine spoils as aquifers in the Powder River basins: Old West Regional Commission, Project 10470025 Completion Report, 108 p.

Rocky Mountain Association of Geologists, 1972, Geologic atlas of the Rocky Mountain Region, United States of America: Denver, Colorado, 331 p.

Royse, C. F., Jr., 1967, Tongue River-Sentinel Butte contact in western North Dakota: North Dakota Geological Survey, Report of Investigation No. 45, 53 p.

Royse, C. F., Jr., 1970, A sedimentological analysis of the Tongue River-Sentinel Butte interval (Paleocene) of the Williston basin, western North Dakota: Sedimentary Geology, v. 4, p. 19-80.

Stallman, R. W., 1962, *in*, Ferris, J. G., Knowles, D. B., Brown, R. H., Stallman, R. W., Theory of aquifer tests: United States Geological Survey Water Supply Paper 1536-E, p. 69-174.

Stumm, W., and Morgan, J. J., 1970, Aquatic chemistry: Wiley-Interscience, New York, 583 p.

Todd, D. K., 1959, Groundwater hydrology: John Wiley & Sons, Inc., New York, 336 p.

Truesdell, A. H., and Jones, B. F., 1974, WATEQ, A computer program for calculating chemical equilibria of natural waters: United States Geological Survey Journal Research, v. 2, no. 2, p. 233-248.

United States Public Health Service, 1962, Drinking water standards, 1962: United States Public Health Service

Pub. 956, 61 p.

United States Salinity Laboratory Staff, 1954, Diagnosis and improvement of saline and alkali soils: U.S. Department of Agriculture Handbook, No. 60, 160 p.

Vanselow, A. P., 1932, Equilibria of the base exchange reactions of bentonites permutites, colloids, and zeolites: Soil Science, v. 33, p. 95-113.

VanVoast, W. A., 1974, Hydrologic effects of strip coal mining in southeastern Montana--emphasis: one year of mining near Decker: Montana Bureau of Mines and Geology, Bull. 93, 24 p.

VanVoast, W. A., and Hedges, R. B., 1975, Hydrogeologic aspects of existing and proposed strip coal mines near Decker, southeastern Montana, Montana Bureau of Mines and Geology, Bull. 97, 31 p.

Wigley, T. M. L., 1975, Carbon 14 dating of groundwater from closed and open systems: Water Resources Research, v. 11, no. 2, p. 324-328.

Winograd, I. J., and Farlekas, G. M., 1974, Problems in ^{14}C dating of water from aquifers of deltaic origin: An example from the New Jersey coastal plain: Proc. Symp. on Isotopes in Hydrology, International Atomic Energy Agency, Vienna, p. 69-93.

Woodward-Clyde Consultants, 1975, Environmental impact report: North Dakota gasification project for ANG Coal Gasification Company: Woodward-Clyde.

APPENDIX I
DEPTH TO TOP OF STRATIGRAPHIC MARKER BEDS

Well	UND-1	UND-2	UND-3	UND-4	UND-5	UND-6	UND-7	UND-8	UND-9	UND-10	UND-11	UND-12	UND-13	UND-14-0	UND-14-3	UND-15
Location	143-93- 07 CCC	144-94- 35 DAA	144-94- 13 DAD	144-93- 06 BAB	145-93- 33 BAA	145-93- 16 CBB	145-93- 04 BBC	146-93- 23 CBB	146-93- 27ADD	146-93- 33ADD	145-93- 09 DAA	145-93- 06 CDC	145-93- 21 DAA	145-93- 33 BCC	145-93- 33 CBC	145-93- 36 BCC
Elevation (ft)	2172.4	2247.3	2254	2223	2203.2	2264.9	2280.95	2309.9	2243.65	2233.85	2235.9	2234.0	2189.6	2244	2271.3	2170.4
Coleharbor Group	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Golden Valley Fm.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Sentinel Butte Fm.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.
C-Lignite	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
B-Interval	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
B-Lignite	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
A-Interval	—	—	G.L.	—	—	G.L.	G.L.	G.L.	—	G.L.	G.L.	—	—	G.L.	G.L.	—
A-Lignite	—	—	65	—	—	49	73	121	—	47	52	—	—	44	63	—
DC-Interval	—	G.L.	64	G.L.	G.L.	56	82	130	—	55	59	G.L.	G.L.	53	70	—
DC-Lignite	—	42	87	80	92	166	148	155	—	101	125	88	63	108	122	—
E-Interval	G.L.	57	107	45	111	181	158	168	G.L.	110	136	100	77	126	140	G.L.
E-Lignite	34	114	136.5		123	220	208	207.5	116	143	186	131	117.5	149.5	167	81
F-Interval	37.5	118	139.5		128.5	228.5	209	212	120.5	148	194.5	139	124	154.5	172	86
White Bed Top	37.5	119	147		135	237	215	?	173	192	197	160	129	171	182	—
White Bed Base	49	139.5	161		195	274.5	234	?	215	216	222.5	171	163.5	193	198	—
F-Lignite	112.5	194.5	236		206	288	282	303	214	216.5	250	223	177.5	218	238	162
G-Interval	—	—	—		—	—	284	306	216	219	—	233	—	—	—	—
G-Lignite	—	—	—		—	—	285	323	241.5	231	—	245	—	—	—	—
H-Interval	114	196.5	240		216	299	293	330	248	235.5	258	247.5	186.5	227	245	167
H-Lignite	125.5	199.5	250.5		226	320	319	331	250	239.5	264	252	202.5	243	263	190
I-Interval	131	203	257		231	337	325.5	334	253.5	244.5	269.5	257	208	250	270	198.5
I-Lignite	274.5	350			307.5	424	419	406.5	334	345	398.5	357	322.5	396.5		279
J-Interval	276	352			308.5	427	426	413	340	352	397	360.5	324.5	399.5		282
J-Lignite	346					474	469	478.5	401	399		399	379.5	453.5		340
Bullion Creek*	356					484	480	491	406	408		409	387	462		347.5
M-Lignite																567
N-Interval																588
N-Lignite																743.5
N-Lignite (base)																764
Cannonball Fm.																
Ludlow Fm.																
Hell Creek Fm.																
Fox Hills Fm.																
Pierre Fm																
Fall River Fm.																
Lakota Fm. (base)																
Opeche Fm.																
Minnelusa Fm.																
Minnelusa Fm. (base)																
TD	220	379	332	58	321	494	490	506	494	514	403	495	500	514	514	820

*Arbitrary contact

APPENDIX I—Continued
DEPTH TO TOP OF STRATIGRAPHIC MARKER BEDS

Well	UND-16	UND-17	UND-18	UND-19	UND-20	UND-21	UND-22	UND-23	UND-24	UND-25	UND-26	UND-27	UND-28	UND-29	UND-30	UND-31
Location	144-93-08 BCB	144-93-09 DDD	144-94-23 ADD	144-94-16 AAA	144-94-21 CDC	144-94-25 CAA	143-94-01 ABB	144-93-07 CDD	144-93-07 DCD	144-94-14 DCC	144-94-16 BAB	144-94-16 BBA	144-94-01 CCC	144-93-20 ADA	144-94-07 DAA	145-92-28 DAA
Elevation (ft)	2220.85	2286.7	2361.0	2290.7	2196.6	2312.5	2255.0	2254.15	2241.2	2329.3	2197.5	2192.9	2187.9	2264.0	2265.0	2110.1
Coleharbor Group	—	—	—	—	G.L.	—	—	—	—	—	G.L.	G.L.	G.L.	—	—	—
Golden Valley Fm.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Sentinel Butte Fm.	G.L.	G.L.	G.L.	G.L.	109.5	G.L.	G.L.	G.L.	G.L.	G.L.	117	118	10	G.L.	G.L.	G.L.
C-Lignite	—	48.5	44	—	—	—	—	—	—	10	—	—	—	—	—	—
B-Interval	—	54	49	G.L.	—	—	—	—	—	13.5	—	—	—	—	—	—
B-Lignite	—	67	69	11.5	—	—	—	—	—	32.5	—	—	—	—	—	—
A-Interval	G.L.	77	77	13	—	G.L.	—	G.L.	G.L.	41.5	—	—	—	G.L.	G.L.	—
A-Lignite	5	125	178	42	—	66	—	39	25	146	—	—	—	76	27	—
DC-Interval	9	132	186	43.5	—	70	G.L.	46.5	31.5	153	—	—	—	84	35	G.L.
DC-Lignite	61	206	191	100	—	140	76	86.5	82	157	—	—	—	123	52	17
E-Interval	79	227	210	114	—	166	94	106	100.5	176	—	118	10	149	68	28
E-Lignite	109	256	237.5	173.5	—	200	147.5			211	—	123	57	176	130	64.5
F-Interval	116	260	241	177	—	203.5	151.5				117	125.5	60.5	179	134	66
White Bed Top	—	277	—	194	—	203.5					117	130.5	61	181	139	66
White Bed Base	—	305	—	216	—	234.5					148	147	72	212	170	135
F-Lignite	212.5	331	311	249	109.5	268.5					161	155	140	264	189	136.5
G-Interval	—	—	—	—	112	—					—	—	—	—	194.5	—
G-Lignite	—	—	—	—	119.5	—					—	—	—	—	215	—
H-Interval	217	335.5	314	252	120.5	271					166	160	143	267	218.5	143
H-Lignite	243	354	326	265.5	169	276					184.5	175.5	168.5	387	233	155
I-Interval	250	362.5	330.5	269	170	281					188.5	179.5	173	394	236	164
I-Lignite	351	463.5		388.5	267.5								282.5	430	316.5	243
J-Interval	364	467		390.5	269.5								284.5	432	318.5	246.5
J-Lignite	407			470.5	304								362	469	402.5	315.5
Bullion Creek*	414.5			478	312.5								368	476.5	412	319.5
M-Lignite					597								—	690	701	
N-Interval					612.5								644.5	706	712.5	
N-Lignite					719									849	815	
N-Lignite (base)					736									861	832.5	
Cannonball Fm.																
Ludlow Fm.																
Hell Creek Fm.																
Fox Hills Fm.																
Pierre Fm.																
Fall River Fm.																
Lakota Fm. (base)																
Opeche Fm.																
Minnelusa Fm.																
Minnelusa Fm. (base)																
TD	498	503	402	500	750	360	160	120	120	213	202	222	656	916	970	420

*Arbitrary contact

APPENDIX I—Continued
DEPTH TO TOP OF STRATIGRAPHIC MARKER BEDS

Well	UND-32	UND-33	UND-34	UND-35	UND-36	UND-37	UND-38	UND-39	UND-40	UND-41	UND-42	UND-43	UND-44	UND-45	UND-46	UND-47
Location	145-93- 27 ACB	145-94- 34 DDA	145-92- 22 CCC	144-94- 13 CCC	144-93- 08 CBB	144-93- 17 ADA	144-94- 15 BDD	143-93- 14 AAD	145-93- 02 CDD	145-93- 04 DDD	145-93- 07 DDD	145-94- 27 CAB	145-94- 34 CCC	144-94- 06 CBB	145-94- 34 CBB	145-94- 28 DCD
Elevation (ft)	2110.7	2223.5	2074.3	2300	2197.3	2224.9	2352.9	2156.4	2188.25	2117.15	2200.3	2176.1	2191.9	2302.2	2271.3	2194.6
Coleharbor Group	G.L.	—	G.L.	—	G.L.	G.L.	—	G.L.	—	—	—	G.L.	G.L.	—	—	—
Golden Valley Fm.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Sentinel Butte Fm.	15	G.L.	36	G.L.	177	27	G.L.	192.5	G.L.	G.L.	G.L.	16	105	G.L.	G.L.	G.L.
C-Lignite	—	—	—	—	—	—	—		—	—	—	—	—	—	—	—
B-Interval	—	—	—	G.L.	—	—	G.L.		—	—	—	—	—	—	—	—
B-Lignite	—	—	—	18	—	—	44		—	—	—	—	—	—	—	—
A-Interval	—	G.L.	—	26	—	—	53		—	G.L.	G.L.	—	—	—	—	—
A-Lignite	—	14	—		—	55	101		—	38	41	—	—	—	—	—
DC-Interval	—	21	—		—	58	104		G.L.	40	50	—	—	G.L.	G.L.	—
DC-Lignite	—	54	—		—	83	163		38		89	—	—	54	43	—
E-Interval	15	70	36		—	104	179		42		101	—	—	73	60	—
E-Lignite	31.5	106	55		—	137.5						15	—	90	77	—
F-Interval	36.5	111	57		177	140.5						16	—	95	84	G.L.
White Bed Top	39	135	64		177	143.5							—	—	—	—
White Bed Base	49.5	151	75			154							—	—	—	—
F-Lignite	109	158	76			248.5							—	157	144	57
G-Interval	—	—	—			—							105	163	149	62.5
G-Lignite	—	—	—			—							107	196	182	93.5
H-Interval	119	165.5	79			246							114	200	191	102.5
H-Lignite	145.5	202	102.5			271										134
I-Interval	152.5	206	115			278										143
I-Lignite		307	186													
J-Interval		309	189.5													
J-Lignite		369														
Bullion Creek*		376.5														
M-Lignite		670														
N-Interval		681.5														
N-Lignite		752														
N-Lignite (base)		767														
Cannonball Fm.																
Ludlow Fm.																
Hell Creek Fm																
Fox Hills Fm.																
Pierre Fm.																
Fall River Fm.																
Lakota Fm. (base)																
Opeche Fm.																
Minnelusa Fm.																
Minnelusa Fm (base)																
TD	165	800	212	64	182	289	201	261	43	51	112	17	120	222	201	154

*Arbitrary contact

APPENDIX I—Continued
DEPTH TO TOP OF STRATIGRAPHIC MARKER BEDS

Well	UND-48	UND-49	UND-50	UND-51	UND-52	UND-53	UND-54	UND-55	UND-56	UND-57	UND-58	UND-59	UND-60	UND-61	UND-62	UND-63
Location	144-94- 13 CBB	144-94- 01 CDD	144-94- 01 CCD	144-94- 12 ABA	144-94- 12 ABA	144-94- 01 CBB	144-94- 01 CBC	144-94- 01 BCB	144-93- 32 CDD	144-94- 01 DCB	144-94- 02 DBC	144-94- 12 AAD	144-94- 01 DAA	144-94- 16 ABB	144-94- 16 AAB	144-94- 17 ABB
Elevation (ft)	2258.9	2205.3	2183.4	2204.7	2203.1	2174.05	2172.6	2173.9	2198.0	2179.05	2169.7	2189.6	2222.4	2217.5	2257.9	2322.0
Coleharbor Group	—	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	—	—	—	—
Golden Valley Fm.	- - -	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Sentinel Butte Fm.	G.L.	115	10	53	93+	20	10	161.5	185	110+	67	122+	G.L.	G.L.	G.L.	G.L.
C-Lignite	—	—	—	—	—	—	—	—	—	—	—		—	—	—	—
B-Interval	—	—	—	—	—	—	—	—	—	—	—		—	—	—	—
B-Lignite	—	—	—	—	—	—	—	—	—	—	—		—	—	—	—
A-Interval	G.L.	—	—	—	—	—	—	—	—	—	—		—	—	—	G.L.
A-Lignite	60	—	—	—	—	—	—	—	—	—	—		—	—	—	45
DC-Interval	70	—	—	—	—	—	—	—	—	—	—		G.L.	G.L.	G.L.	47
DC-Lignite		—	—	—	—	—	—	—	—	—	—		Burn	10.5	60	100
E-Interval		—	10	—	—	20	10	—	—	—	—		30	19.5	73	110
E-Lignite		—	29	—	—	56.5		—	—	—	67		86	82.5		
F-Interval		115	32	53	93	61		—	—	110	71.5		91.5	86		
White Bed Top			37	63				—	—	—			97.5			
White Bed Base			45	67				—	—	—			120&			
F-Lignite				143.5				—	238	150						
G-Interval				—				—	—							
G-Lignite				—				—	—							
H-Interval				146				—	242							
H-Lignite				164				161.5	244.5							
I-Interval				170				169	253							
I-Lignite																
J-Interval																
J-Lignite																
Bullion Creek*																
M-Lignite																
N-Interval																
N-Lignite																
N-Lignite (base)																
Cannonball Fm.																
Ludlow Fm.																
Hell Creek Fm.																
Fox Hills Fm.																
Pierre Fm.																
Fall River Fm.																
Lakota Fm. (base)																
Opeche Fm.																
Minnelusa Fm.																
Minnelusa Fm. (base)																
TD	67	122	116	180	93	61	41	181	250	110	82	122	120	96	99	120

*Arbitrary contact

APPENDIX I—Continued
DEPTH TO TOP OF STRATIGRAPHIC MARKER BEDS

Well	UND-64	UND-65	UND-66	UND-67	UND-68	NDGS 32	NDGS 33	NDGS 36	NDGS 37	NDGS 38	NDGS 39	NDGS 40	NDGS 43	NDGS 44	NDGS 45
Location	144-94-17 AAB	145-93-33 BCC	145-93-33 BBC	145-93-33 BBB	145-94-34 AAD	143-92-10 BBB	144-92-10 CCC	146-91-30 CCC	146-92-22 ACC	146-94-02 ADD	146-94-20 DDD	145-95-02 DCC	146-93-10 DBB	145-92-30 DCC	145-91-18 AAD
Elevation (ft)	2264.1	2244.6	2177.1	2178.8	2208.4	2240.0	2160.0	2240.0	2360.0	2375.0	2260.0	2305.0	2430.0	2165	2300
Coleharbor Group	—	—	—	—	—	—	—	—	—	—	—	—	G.L.	—	—
Golden Valley Fm.	—	—	—	—	—	—	—	—	—	—	—	—	10	—	—
Sentinel Butte Fm.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	G.L.	80	G.L.	G.L.
C-Lignite	—	—	—	—	—	—	21	—	—	—	—	—	—	—	—
B-Interval	—	—	—	—	—	G.L.	26	—	—	G.L.	G.L.	—	—	—	—
B-Lignite	—	—	—	—	—	134	45	—	—	74	82	81	—	—	—
A-Interval	—	G.L.	—	—	G.L.	140	50	G.L.	G.L.	89	93	98	80	—	G.L.
A-Lignite	—	43	—	—	3	184	85	110	140	151	122	140	218	—	99
DC-Interval	G.L.	49.5	G.L.	G.L.	5	188	94	113	148	159	125	143	229	G.L.	109
DC-Lignite	52	109.5	54.5	40	40	219	112	126	176	248	154	203	269	54	160
E-Interval	68	127.5	73	58.5	57.5	231	146	156	208	264	165	217	292	65	174
E-Lignite		150.5	87			310	184	247	272	293	204	233	334	115	248
F-Interval		155.5	92			314	188	249	275	296	214	239	339	119	252
White Bed Top						—	—	—	—	—	—	—	—	—	—
White Bed Base						—	—	—	—	—	—	—	—	—	—
F-Lignite						352	278	276	337	314	263	268	382	177	298
G-Interval						362	286	—	—	—	—	—	386	—	301
G-Lignite						378	314	—	—	—	—	—	417	—	319
H-Interval						381	317	279	340	317	266	273	424	182	322
H-Lignite						413	346	308	355	336	318	335	426	200	327
I-Interval						417	349	315	365	343	321	337	426	208	330
I-Lignite						488	423	407	439	500	408	386	511		392
J-Interval						494	426	413	446	505	410	397	519		396
J-Lignite							482			546	434	461	572		506
Bullion Creek*							486			557	447	478	586		516
M-Lignite															
N-Interval															
N-Lignite															
N-Lignite (base)															
Cannonball Fm.															
Ludlow Fm.															
Hell Creek Fm.															
Fox Hills Fm.															
Pierre Fm.															
Fall River Fm.															
Lakota Fm. (base)															
Opeche Fm.															
Minnelusa Fm.															
Minnelusa Fm. (base)															
TD	98	110	90	80	80	590	580	500	530	600	500	600	640	240	710

*Arbitrary contact

APPENDIX I—Continued

DEPTH TO TOP OF STRATIGRAPHIC MARKER BEDS

Well	Dunn Center Municipal Well	Halliday Municipal Well	Oil Test 892	Oil Test 1787	Oil Test 3044	Oil Test 3199	Oil Test 4220	Oil Test 4488	Oil Test 4527	Oil Test 4707	Oil Test 4748	Oil Test 5155	Oil Test 5162	Oil Test 5396
Location	145-94-26 ACD	145-92-25 ABA	144-94-19 CA	143-93-23 AB	143-92-27 AA	144-92-16 AB	145-94-13 AC	145-92-28 AA	143-93-5 CAA	145-93-25 DC	144-94-28 AD	143-94-13 CC	145-93-32 CC	146-93-16 CA
Elevation (ft)	2205	2045	2411 KB	2238 GL	2200 KB	2198 KB	2197 GL	2141 KB	2186 KB	2187 KB	2221 KB	2133 KB	2221 KB	2383 KB
Coleharbor Group	——									——				
Golden Valley Fm.	——									——				
Sentinel Butte Fm.	G.L.									G.L.				
C-Lignite	——									——				
B-Interval	——									——				
B-Lignite	——									——				
A-Interval	——									——				
A-Lignite	——									——				
DC-Interval	G.L.									G.L.				
DC-Lignite	30									72				225
E-Interval	48									92				245
E-Lignite	80.5									105				264
F-Interval	85.5									110				270
White Bed Top														
White Bed Base														
F-Lignite	111									194				377
G-Interval	115									——				381
G-Lignite	127									——				388
H-Interval	136									202				395
H-Lignite	158									212				399
I-Interval	162									220				409
I-Lignite	302									302				483
J-Interval	304									306				490
J-Lignite	358									366				549
Bullion Creek*	366									374				560
M-Lignite	685		824							560	600		668	685
N-Interval	698		837							585	618		678	694
N-Lignite	805		925							765	718		814	1003
N-Lignite (base)	829		950							780	735		830	1015
Cannonball Fm.	1124	798	1225	1005		975	1062	875	920	1026	1065	870	1045	1235
Ludlow Fm.	1371	1068	1485	1210		1220	1297	1165	1130	1236	1274	1095	1305	1470
Hell Creek Fm.	1409	——	——			1385	——	——	——	1415	1455	1295	——	1654
Fox Hills Fm.		1303	1752	1490		1505	——	1420	1445	1510	1580	1460	1613	1728
Pierre Fm.			1976	1775		1730	1807	1717	1705	1785	1815	1650	1835	2025
Fall River Fm.			5370	5008	4995	4945	5077	4850	5040	5040	5120	5025	5185	5342
Lakota Fm. (base)			5760	5333	5245	5270	5387	5175		5420	5488	5345	5555	5725
Opeche Fm.			7060	6566	6456	6360	6770					6685	6782	6975
Minnelusa Fm.			7515	6972	6550	7811	7137					6990	7180	7330
Minnelusa Fm. (base)			7690	7195	6820	7035	7367					7230	7385	7530
TD	1495		9712	8905	12157	9025	13310	5250	5145	5497	5530	7786	8012	9440

*Arbitrary contact

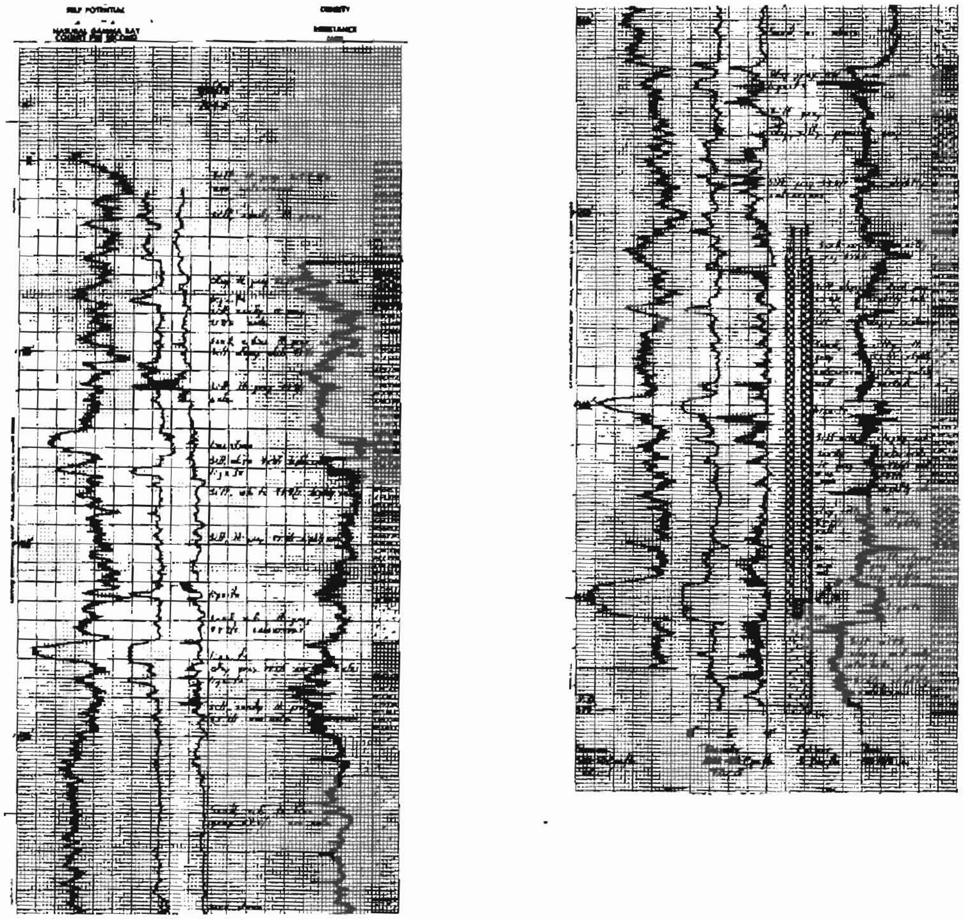
APPENDIX II
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

EXPLANATION

SYMBOLS	LITHOLOGY
▦	Lignite
░	Sand
▤	Silt
▥	Clay
▧	Concretion

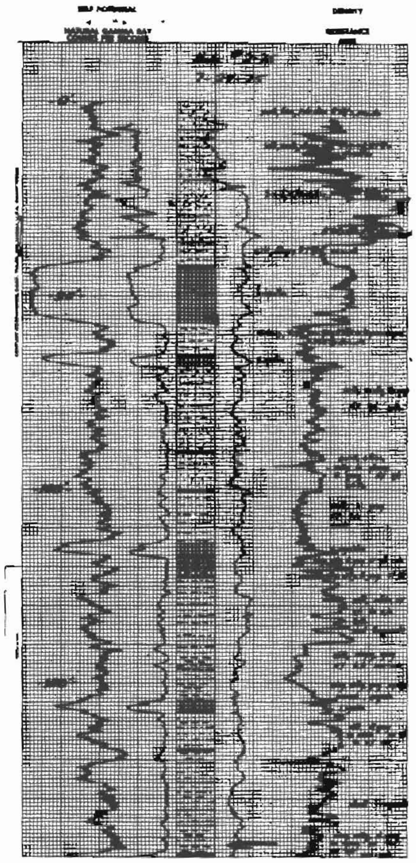
APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

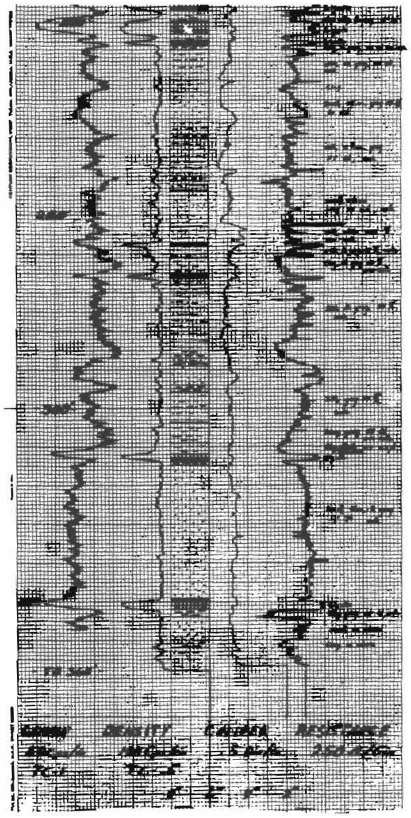
UND EES 75-1-3
SW¼SW¼SW¼
Sec 07, T143N, R93W
Century: 8090 Log



APPENDIX II–Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

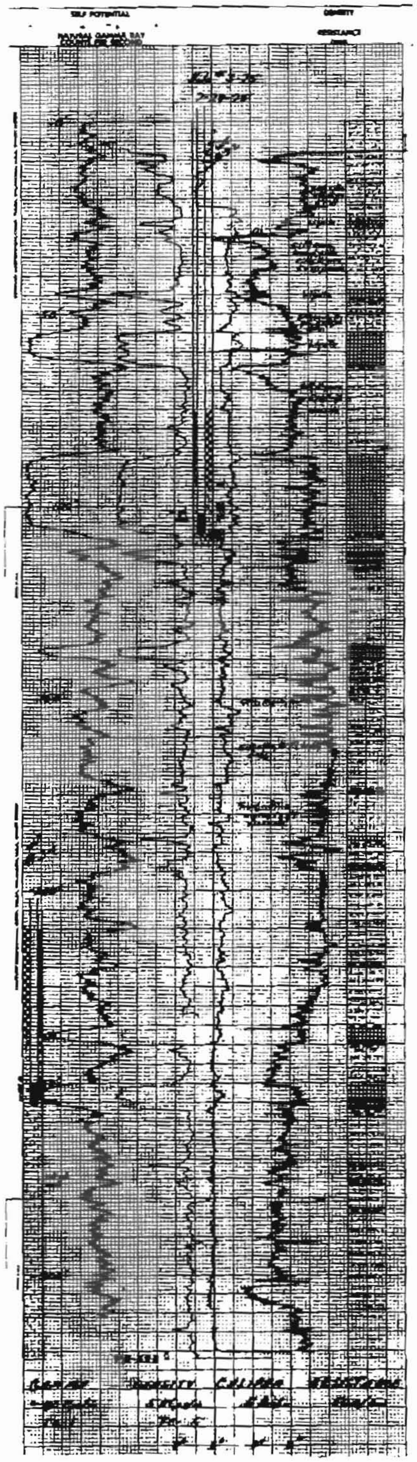
UND EES 75-2-1
NE¼NE¼SE¼
Sec 35, T144N, R94W
Century: 8090 Log



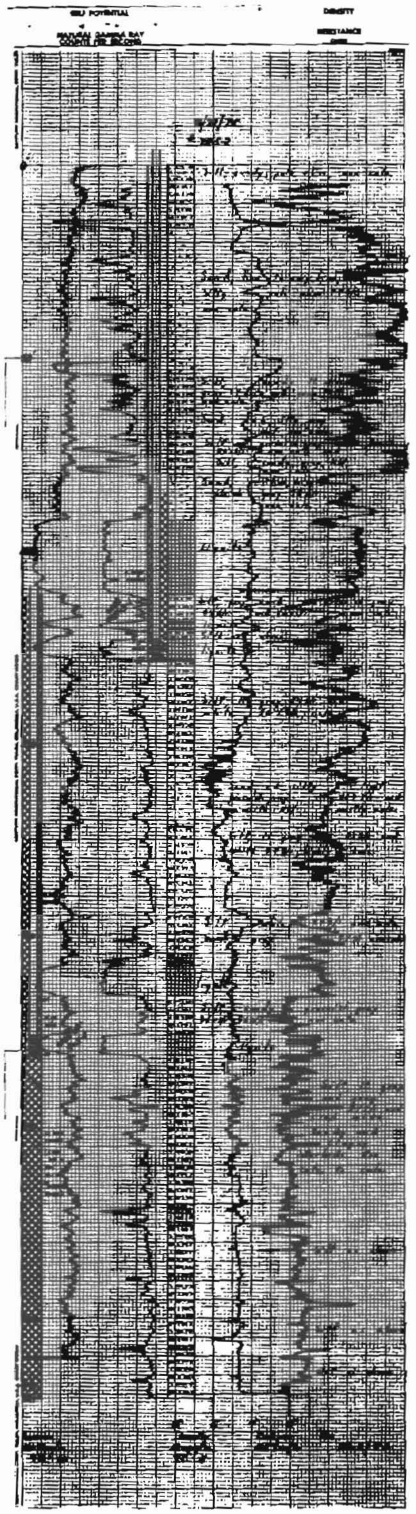


APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

UND EES 75-3-1
SE¼NE¼SE¼
Sec 13, T144N, R94W
Century: 8090 Log

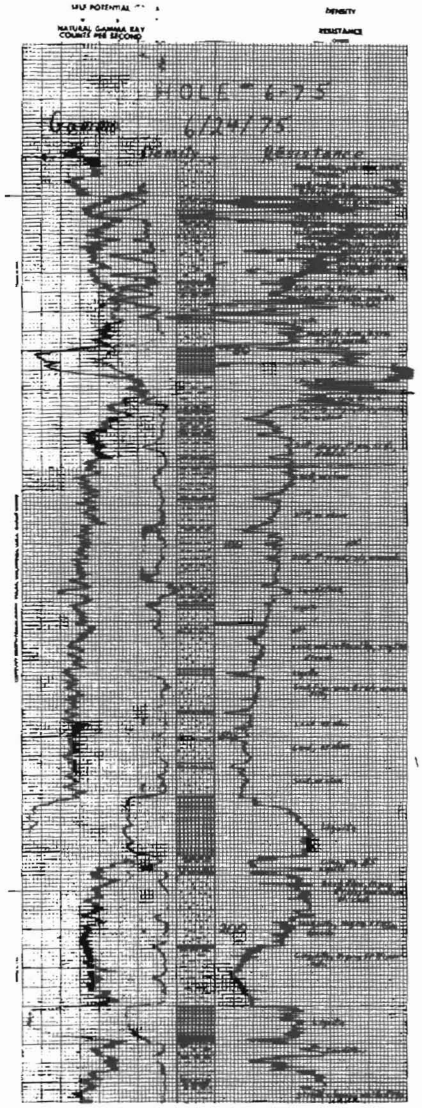


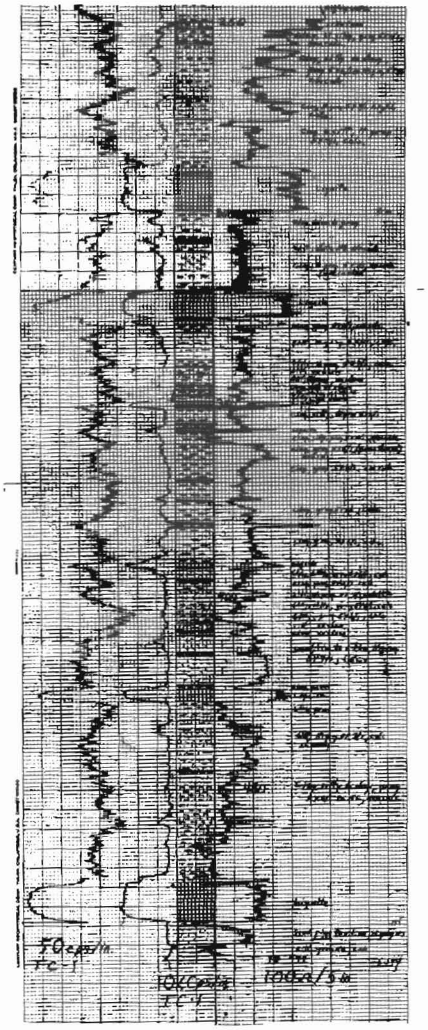
UND EES 75-5-2
NE¼NE¼NW¼
Sec 33, T145N, R93W
Century: 8090 Log



APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

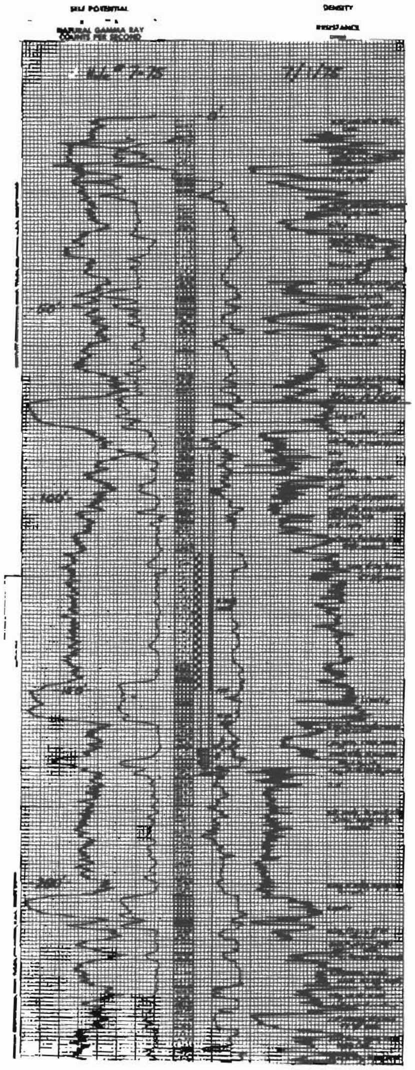
UND EES 75-6-1
NW¼NW¼SW¼
Sec 16, T145N, R93W
Century: 8090 Log
(No Caliper Log)

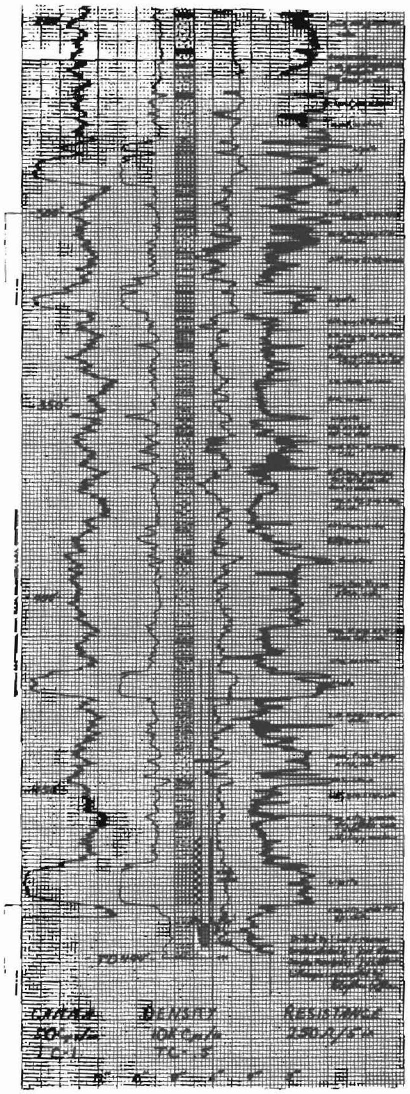




APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

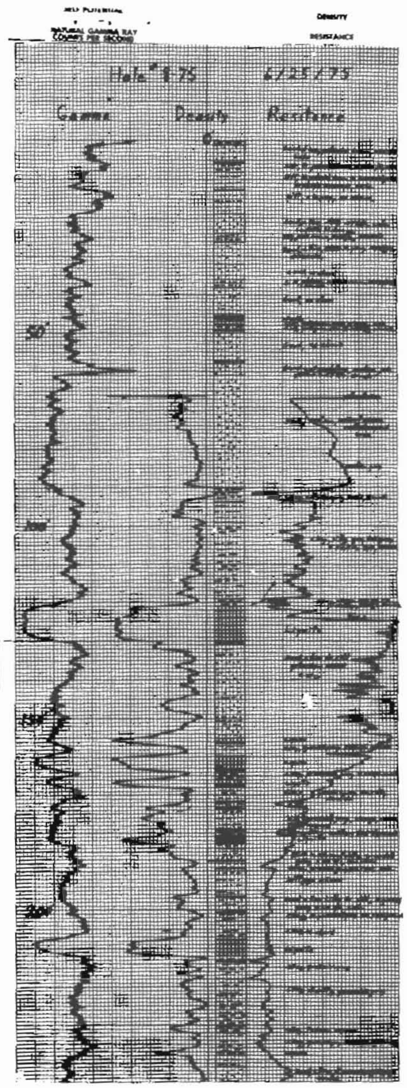
UND EES 75-7-1
SW¼SW¼NW¼
Sec 04, T145N, R93W
Century: 8090 Log

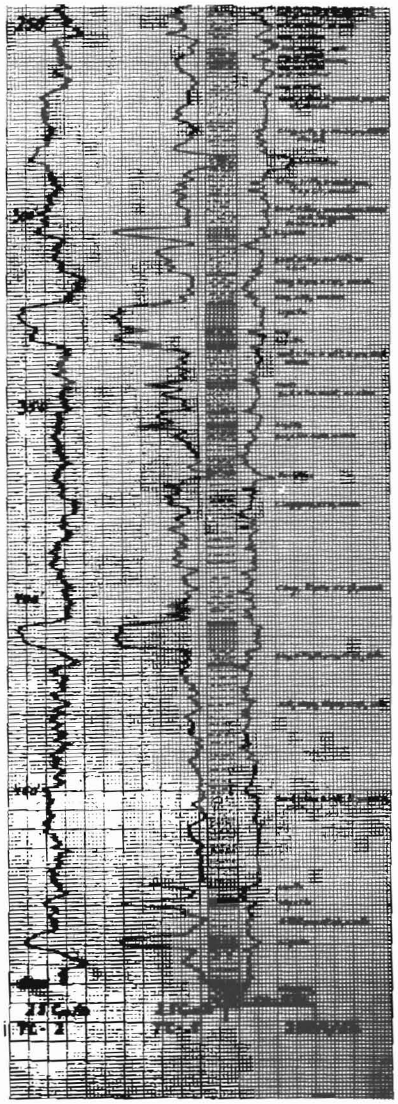




APPENDIX II–Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

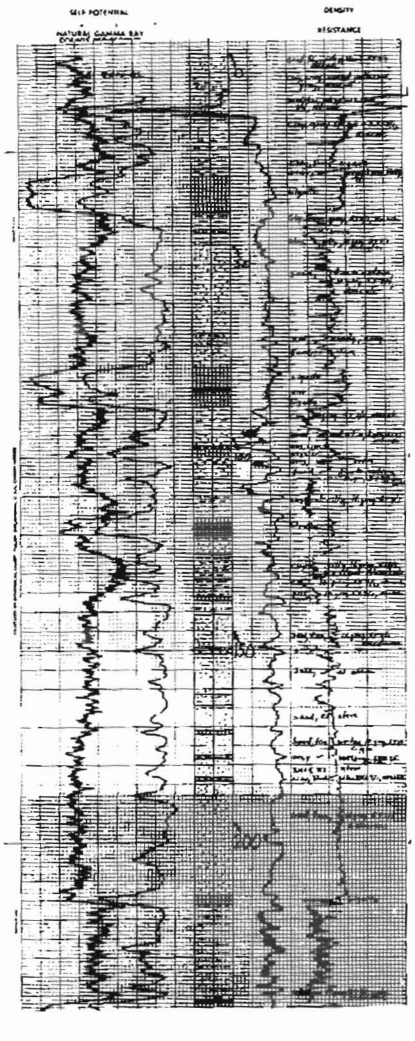
UND EES 75-8-1
NW¼NW¼SW¼
Sec 23, T146N, R93W
Century: 8010-8020 Log

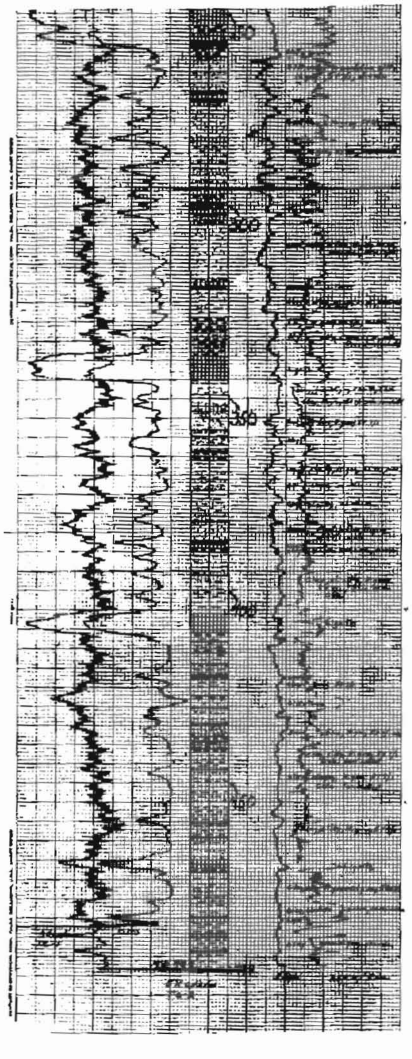




APPENDIX II–Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

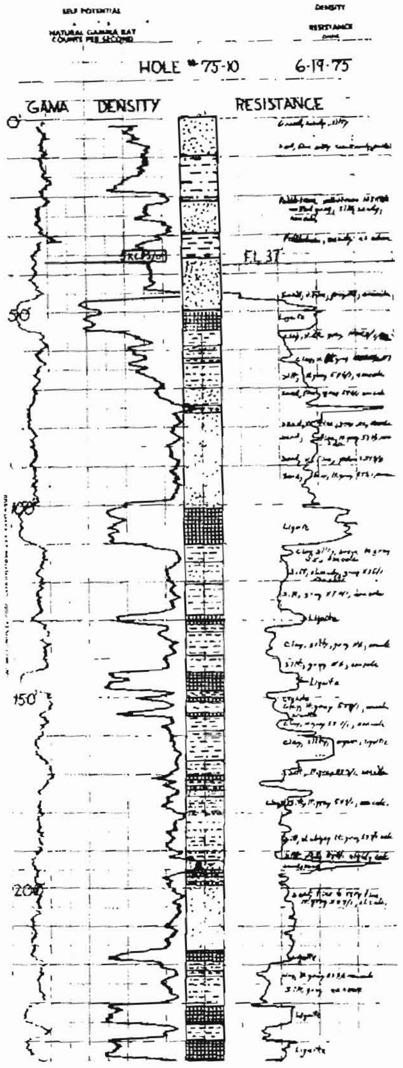
UND EES 75-9-1
NE¼NE¼SE¼
Sec 27, T146N, R93W
Century: 8090 Log

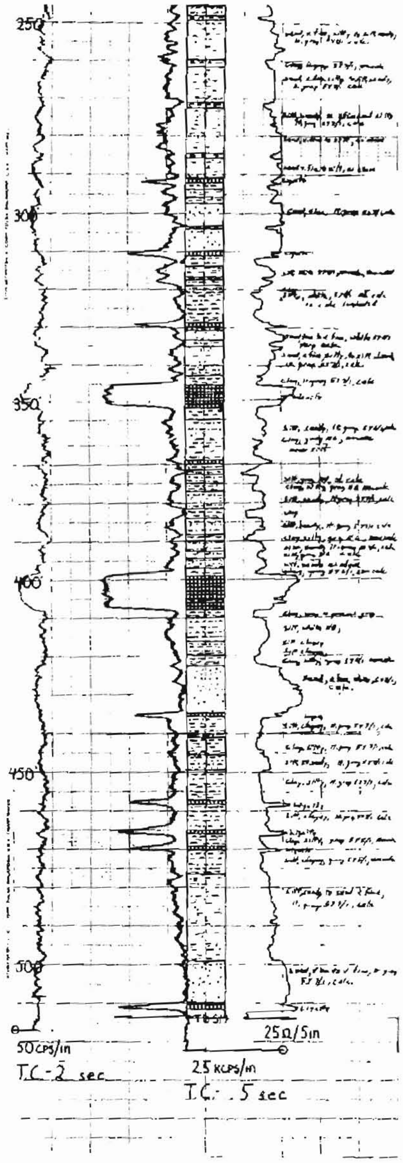




APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

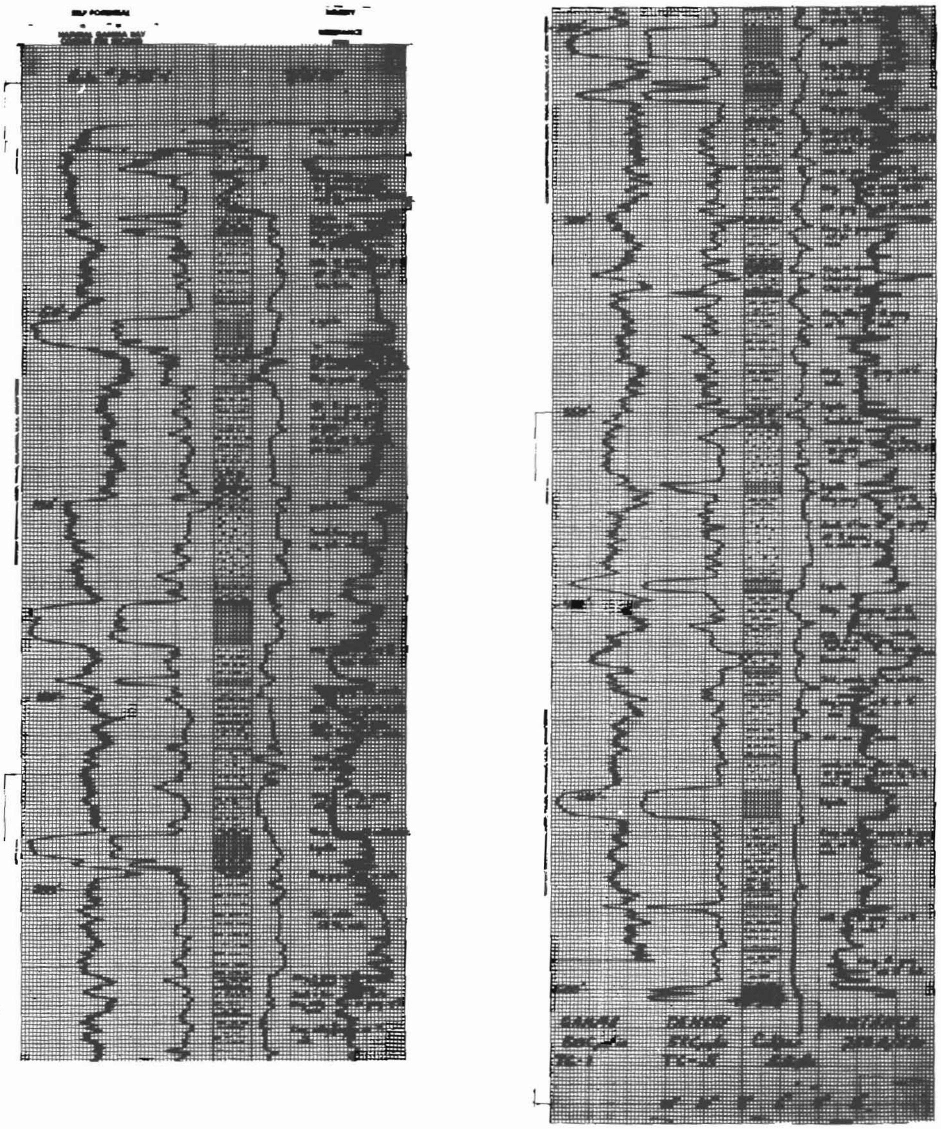
UND EES 75-10-1
SE¼SE¼NE¼
Sec 33, T146N, R93W
Century: 8030 Log





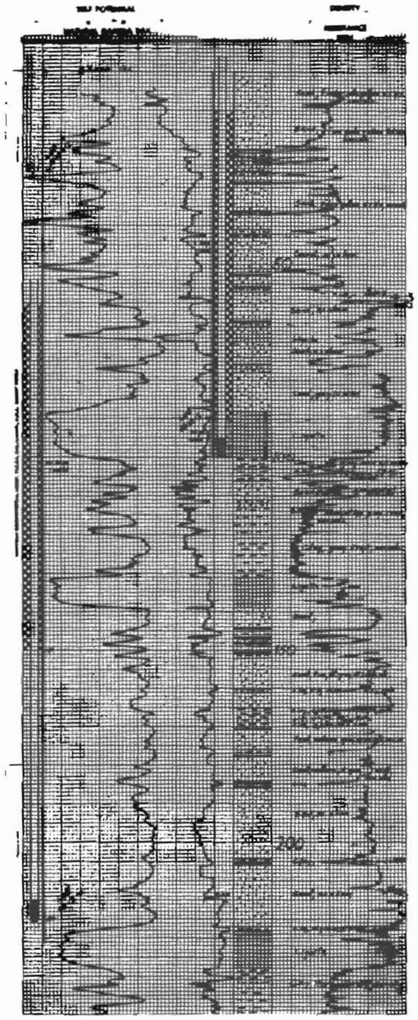
APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

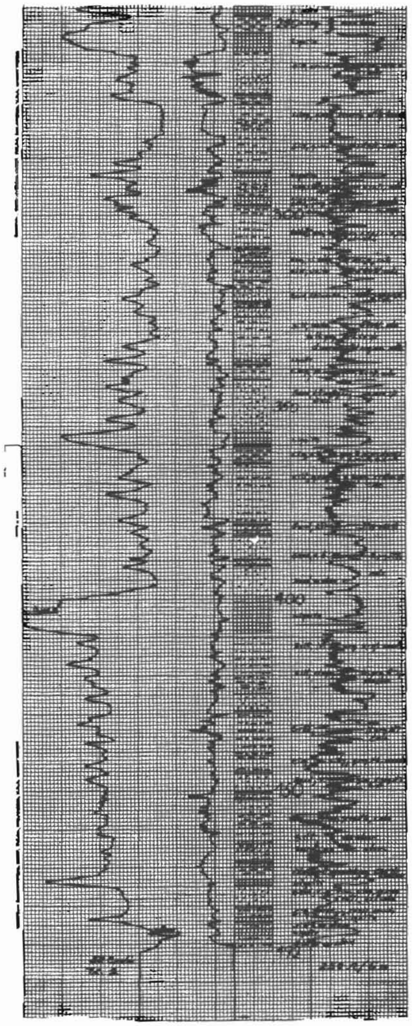
UND EES 75-11-1
NW¼NE¼SE¼
Sec 09, T145N, R93W
Century: 8090 Log



APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

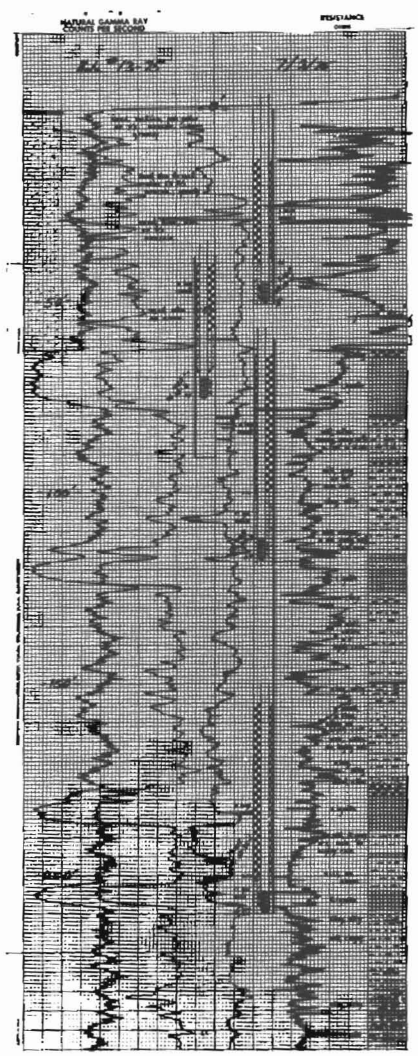
UND EES 75-12-1
SW¼SE¼SW¼
Sec 06, T145N, R93W
Century: 8090 Log

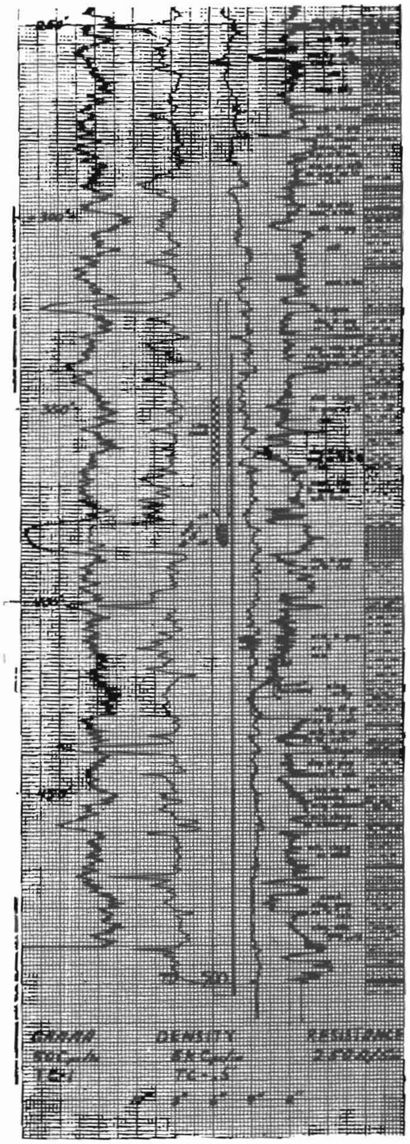




APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

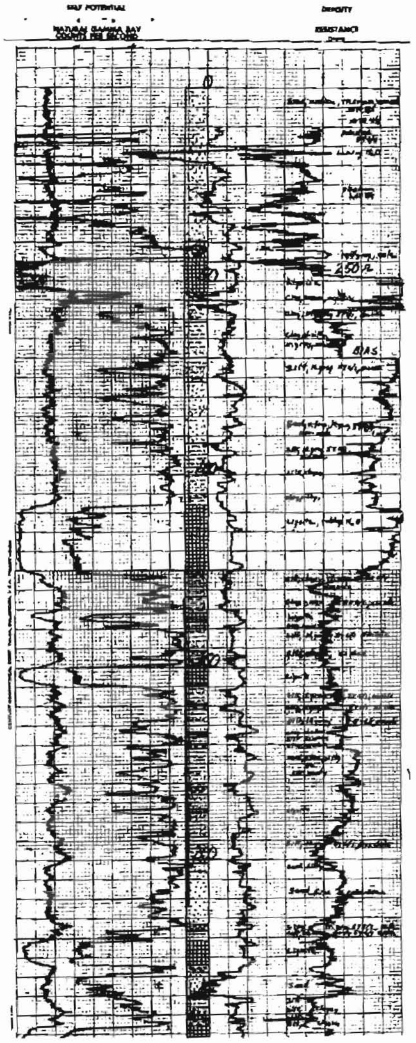
UND EES 75-13-1
NE¼NE¼SE¼
Sec 21, T145N, R93W
Century: 8090 Log

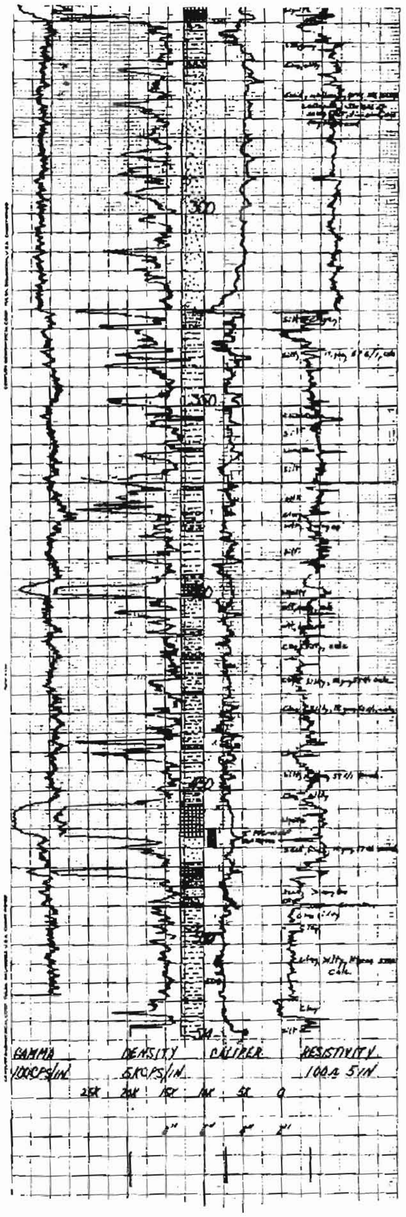




APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

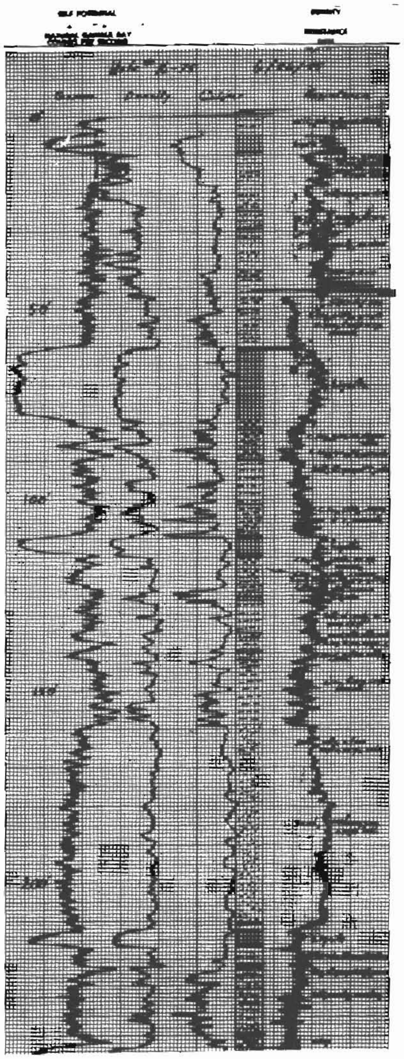
UND EES 75-14-0
SW¼SW¼NW¼
Sec 33, T145N, R93W
Century: 8090 Log

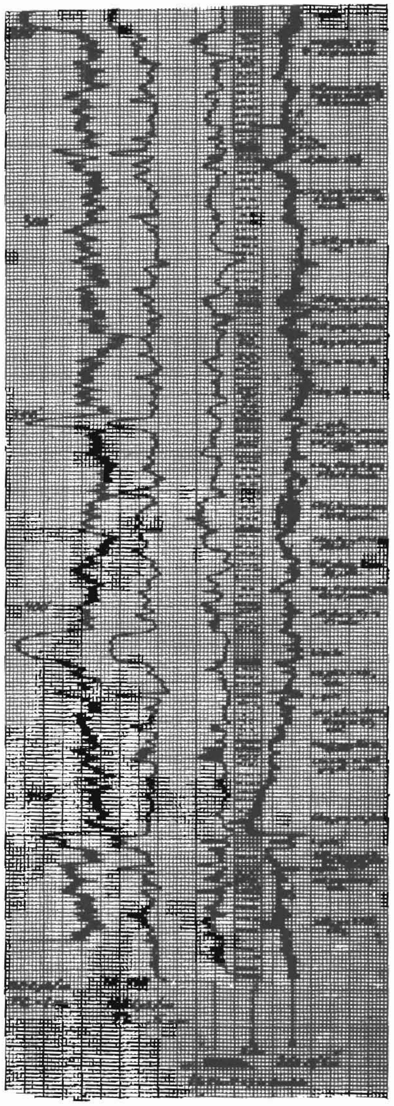




APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

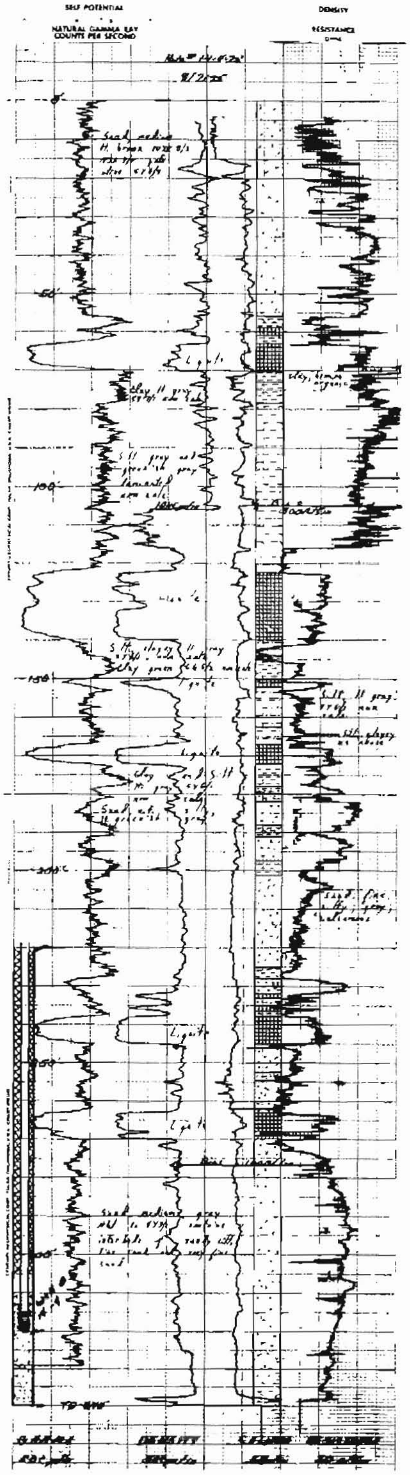
UND EES 75-16-1
NW¼SW¼NW¼
Sec 08, T144N, R93W
Century: 8090 Log



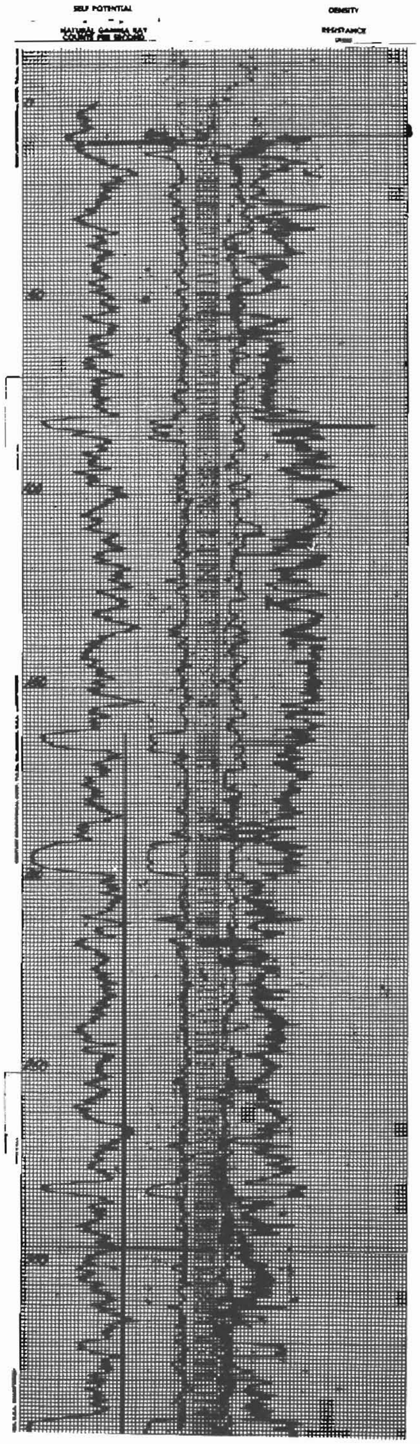


APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

UND EES 75-14-4
SW¼NW¼SW¼
Sec 33, T145N, R93W
Century: 8090 Log

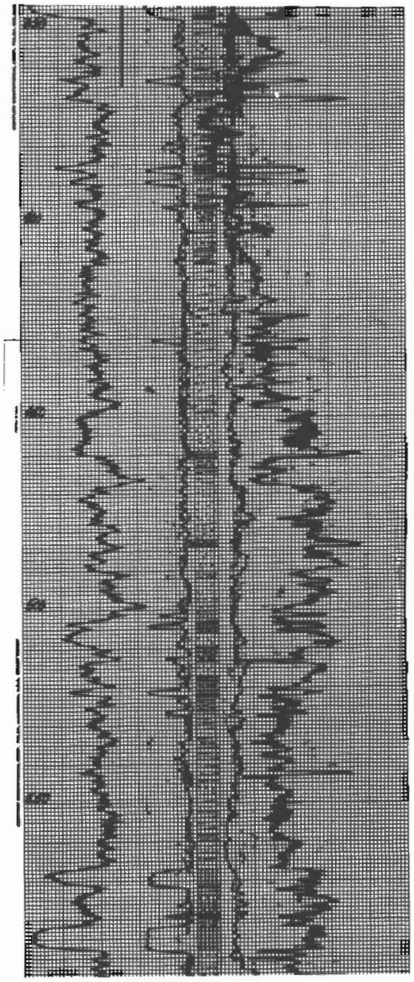


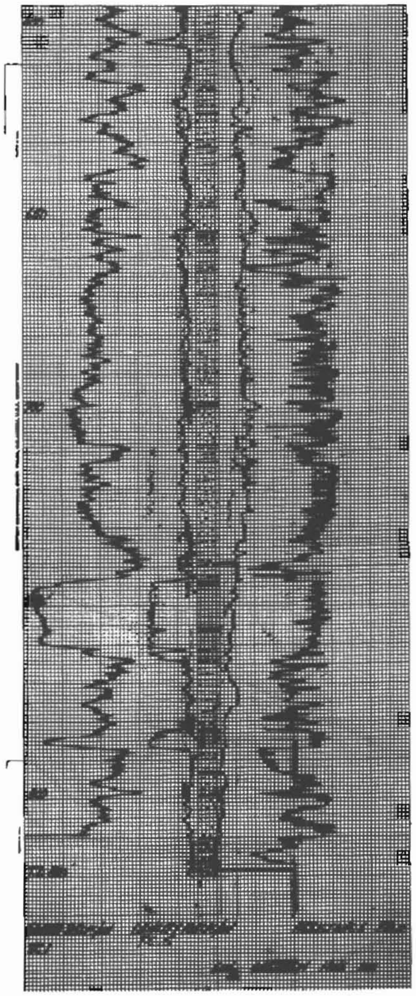
UND EES 75-15-1
SW¼SW¼NW¼
Sec 36, T145N, R93W
Century: 8090 Log



APPENDIX II–Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

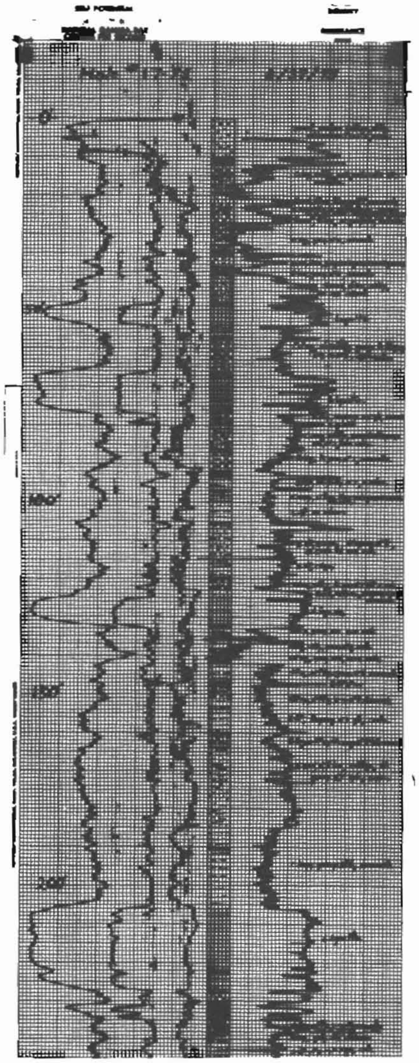
UND EES 75-15-1
SW¼SW¼NW¼
Sec 36, T145N, R93W
Century: 8090 Log
(Continued)

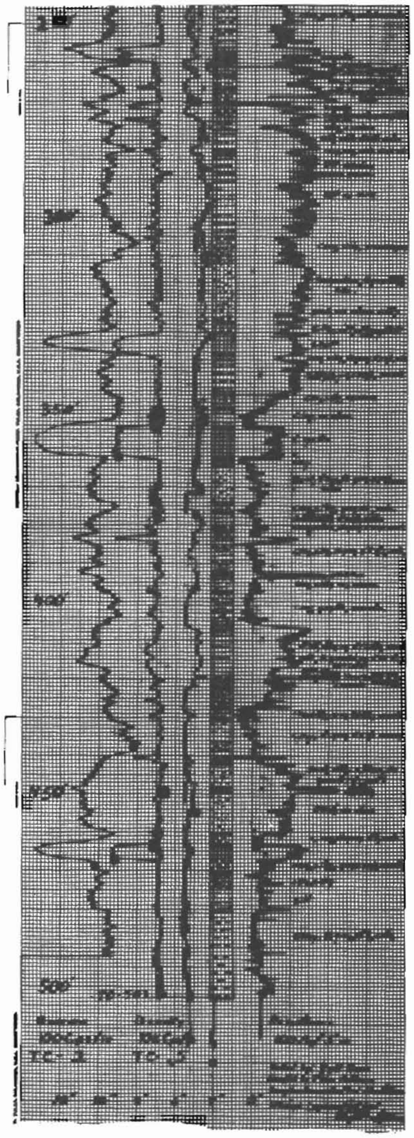




APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

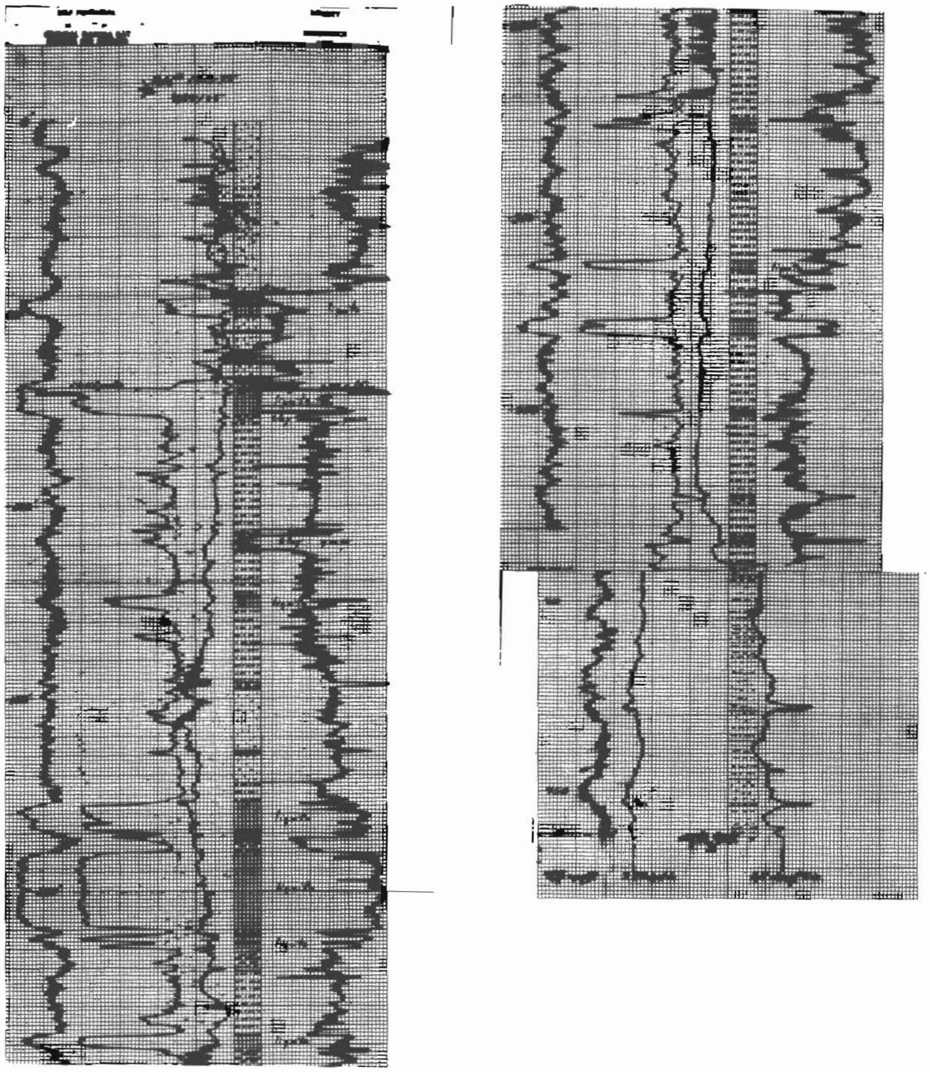
UND EES 75-17-1
SE¼SE¼SE¼
Sec 09, T144N, R93W
Century: 8090 Log





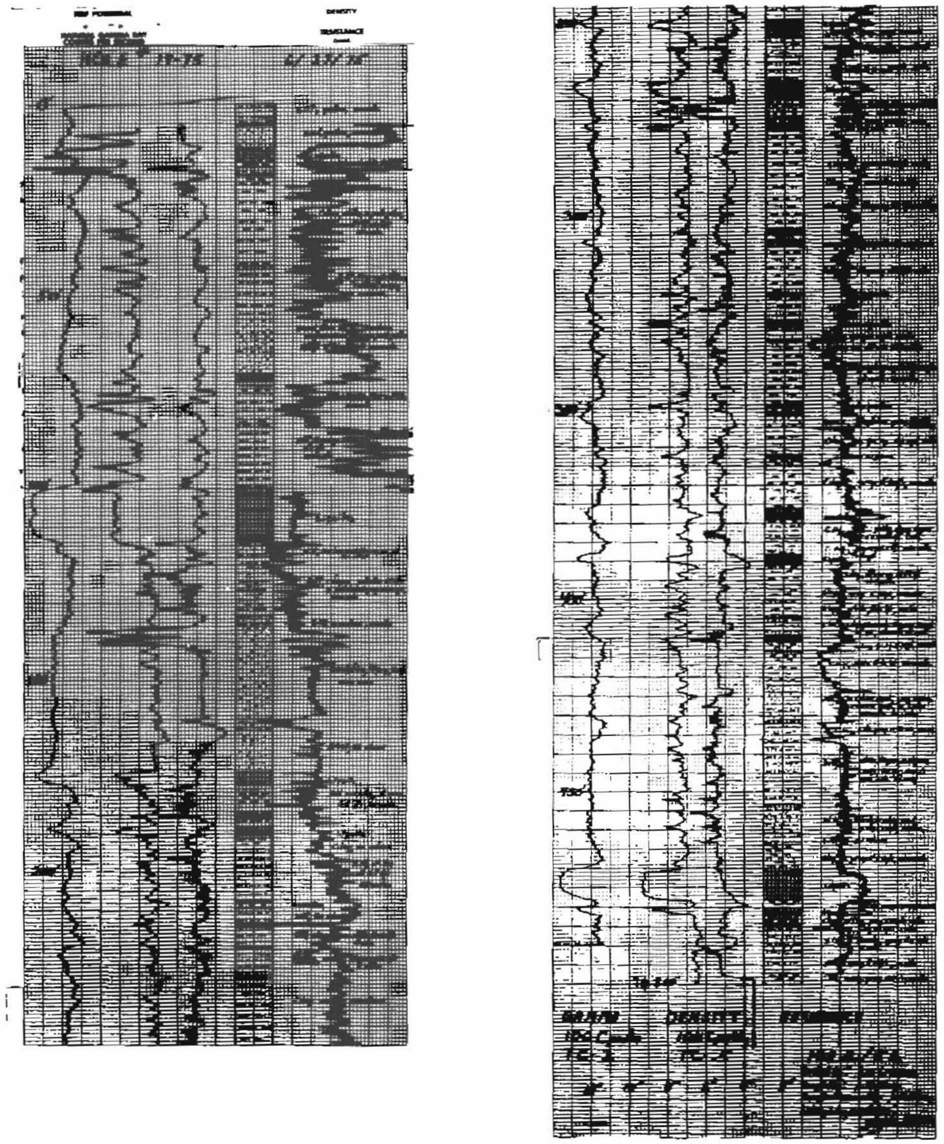
APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

UND EES 75-18-3
SE¼SE¼NE¼
Sec 23, T144N, R94W
Century: 8090 Log



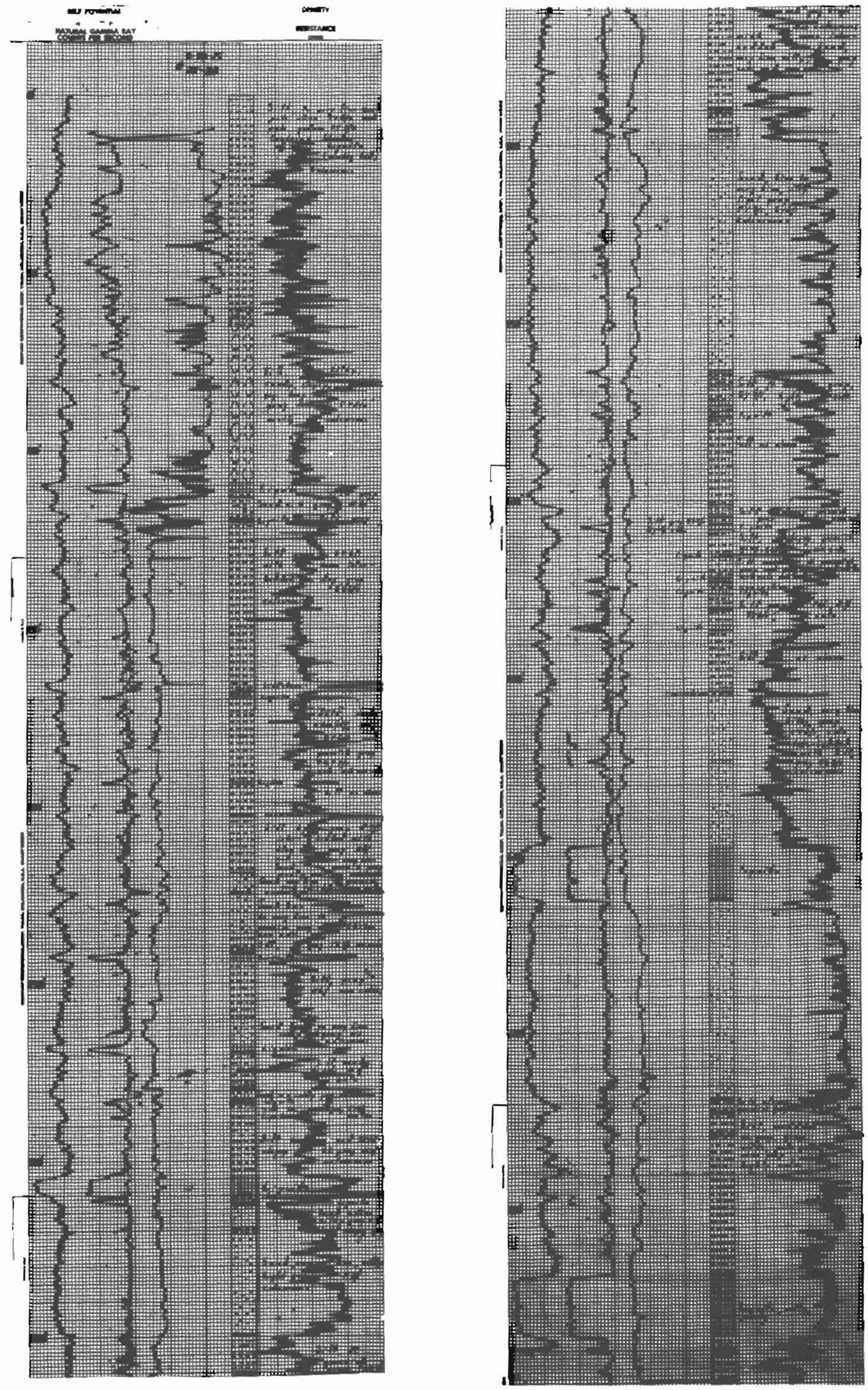
APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

UND EES 75-19-1
NE¼NE¼NE¼
Sec 16, T144N, R94W
Century: 8090 Log



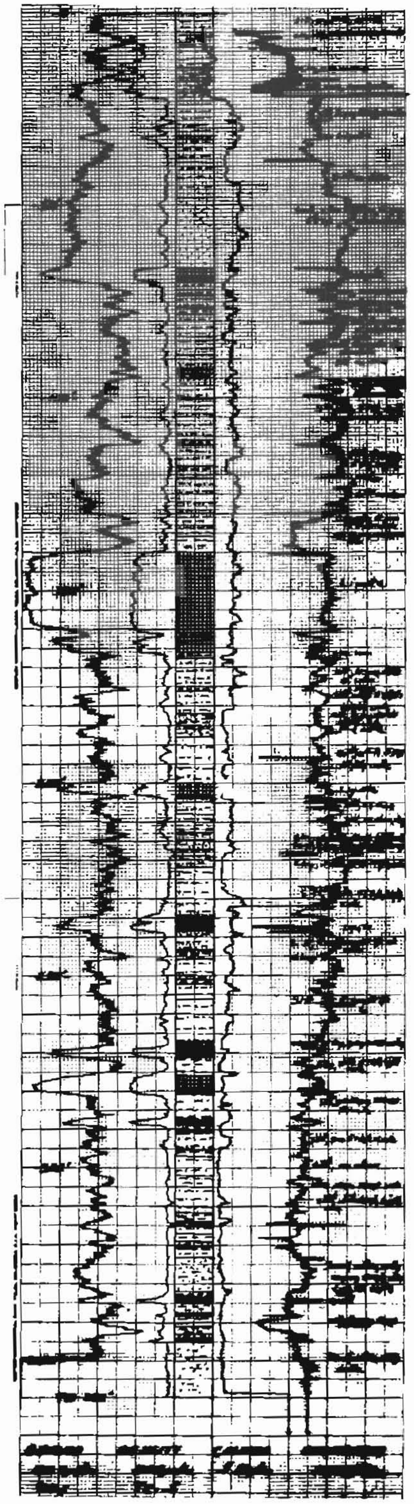
APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

UND EES 75-20-1
SW¼SE¼SW¼
Sec 21, T144N, R94W
Century: 8090 Log

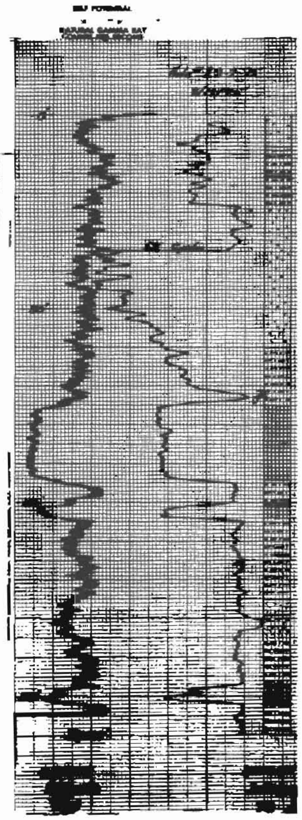


APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

UND EES 75-21-1
NE¼NE¼SW¼
Sec 25, T144N, R94W
Century: 8090 Log

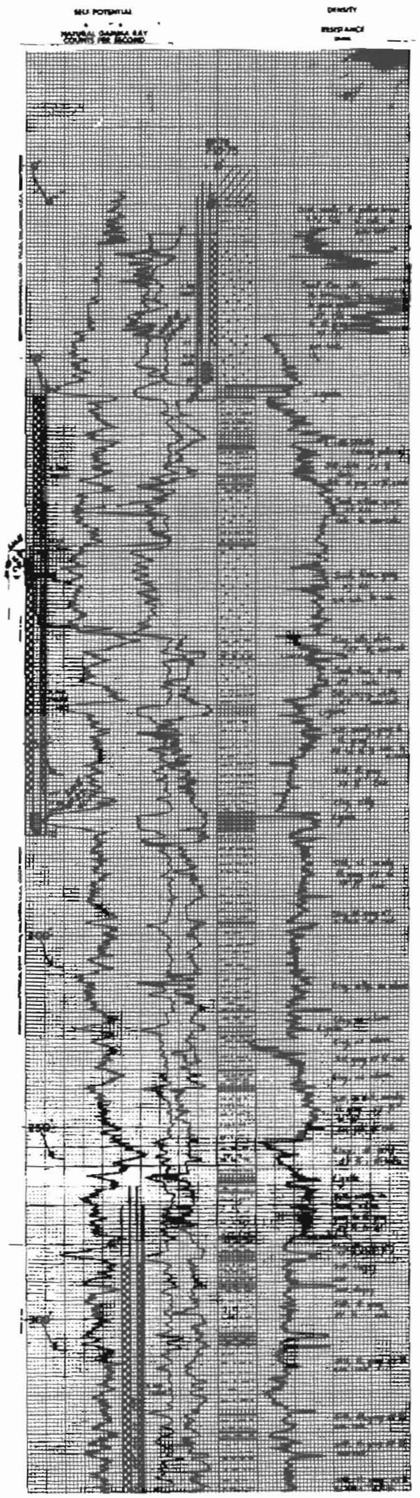


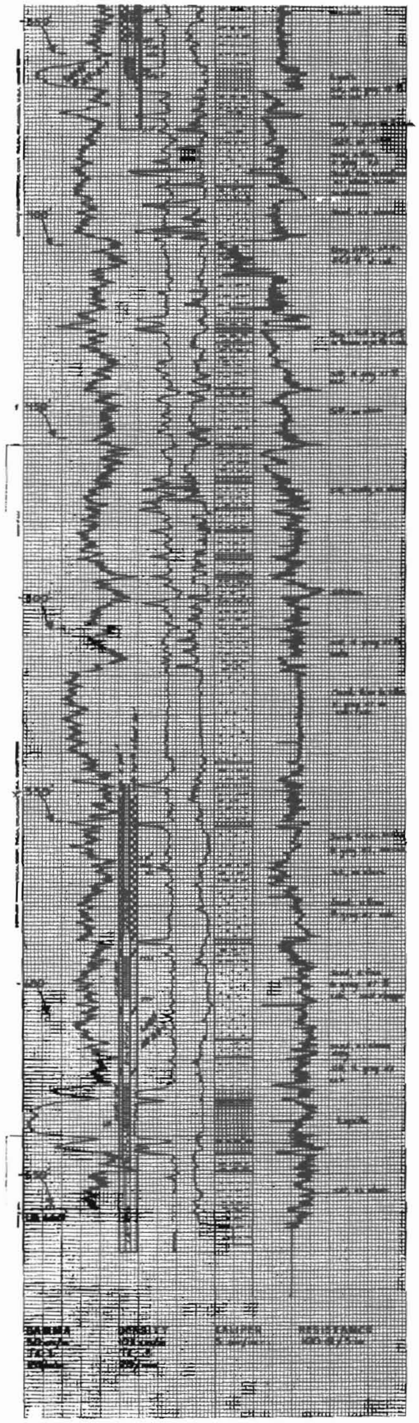
UND EES 75-22-2
NW¼NW¼NE¼
Sec 01, T143N, R94W
Century: 8030 Log
(No Resistance)



APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

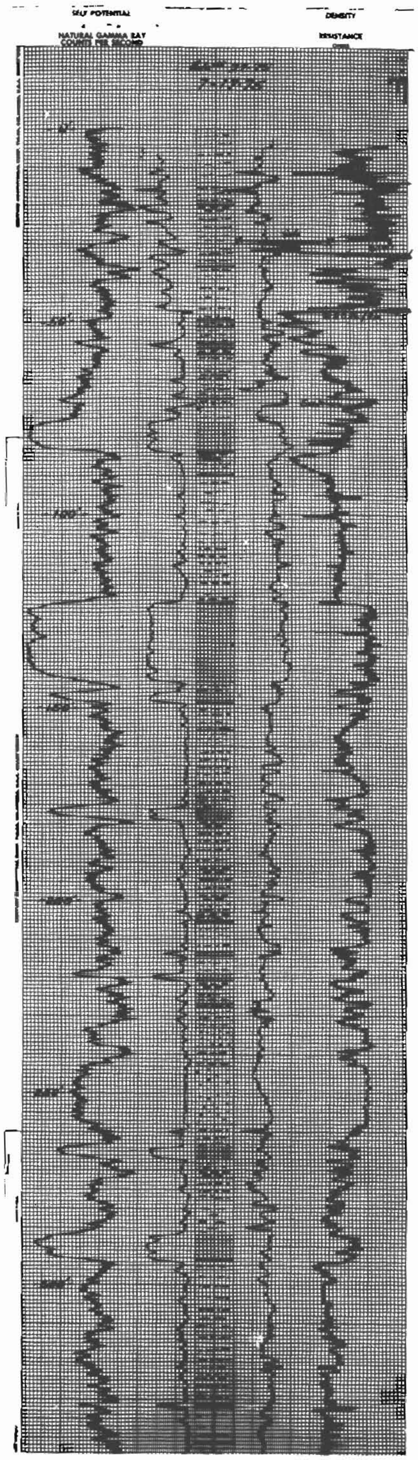
UND EES 75-28-1
SW¼SW¼SW¼
Sec 01, T144N, R94W
Century: 8090 Log

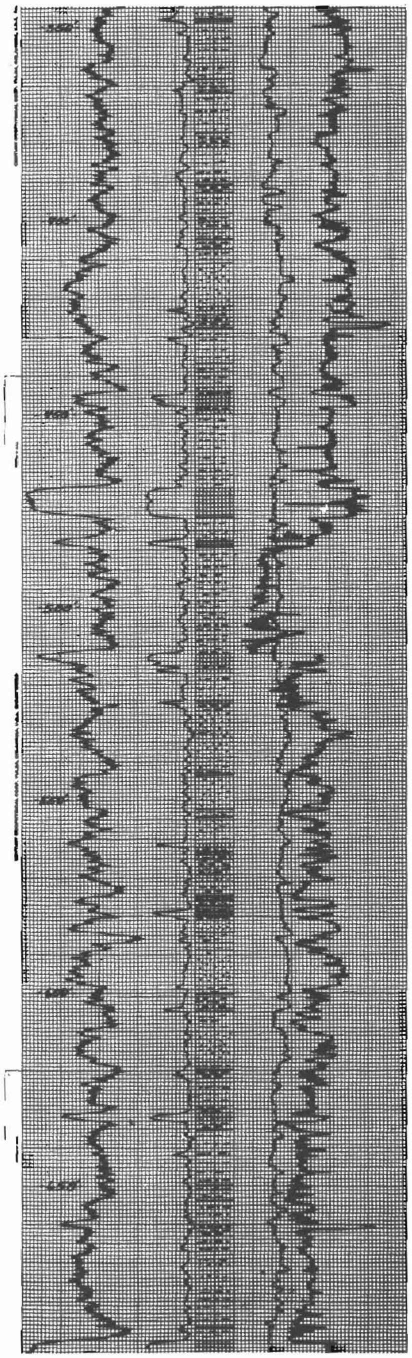




APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

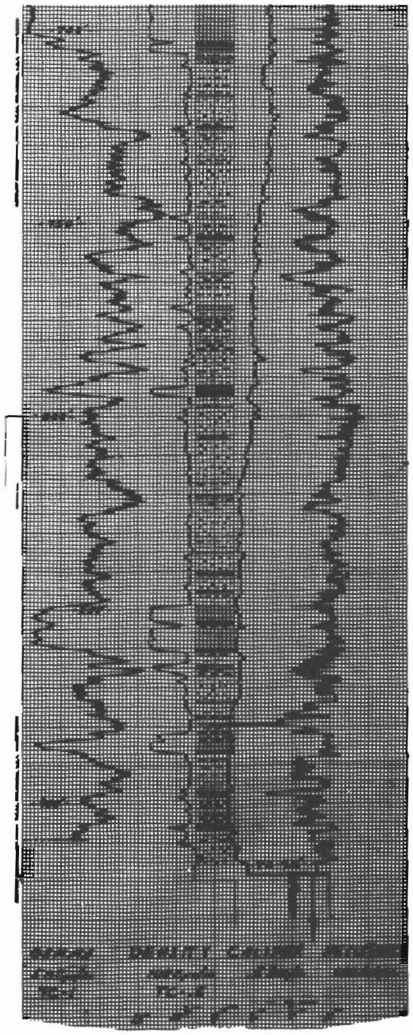
UND EES 75-29-1
NE¼SE¼NE¼
Sec 20, T144N, R93W
Century: 8090 Log



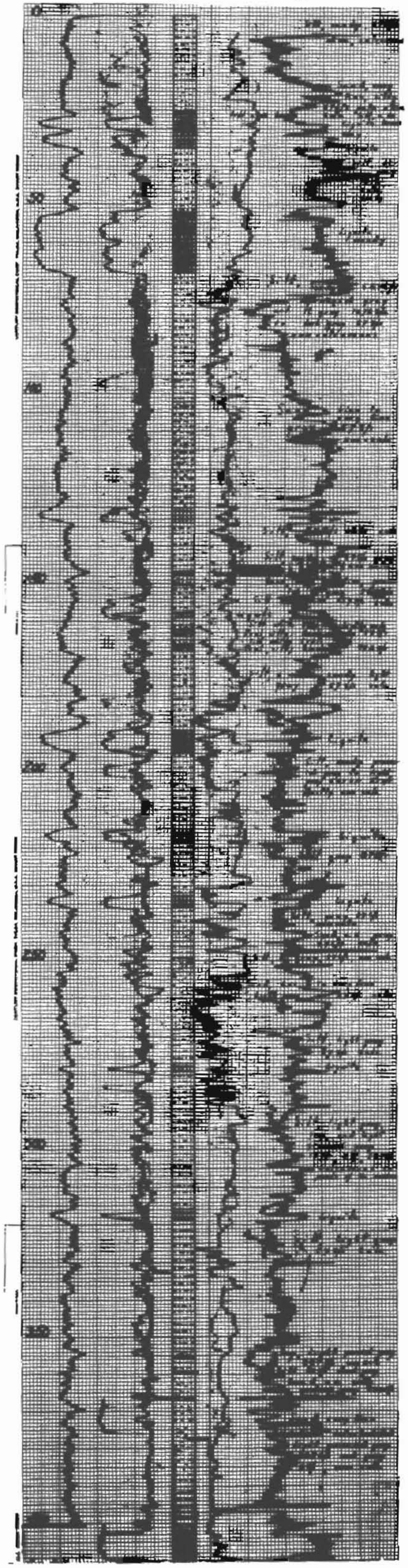


APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

UND EES 75-29-1
NE¼SE¼SE¼
Sec 20, T144N, R93W
Century: 8090 Log
(Continued)

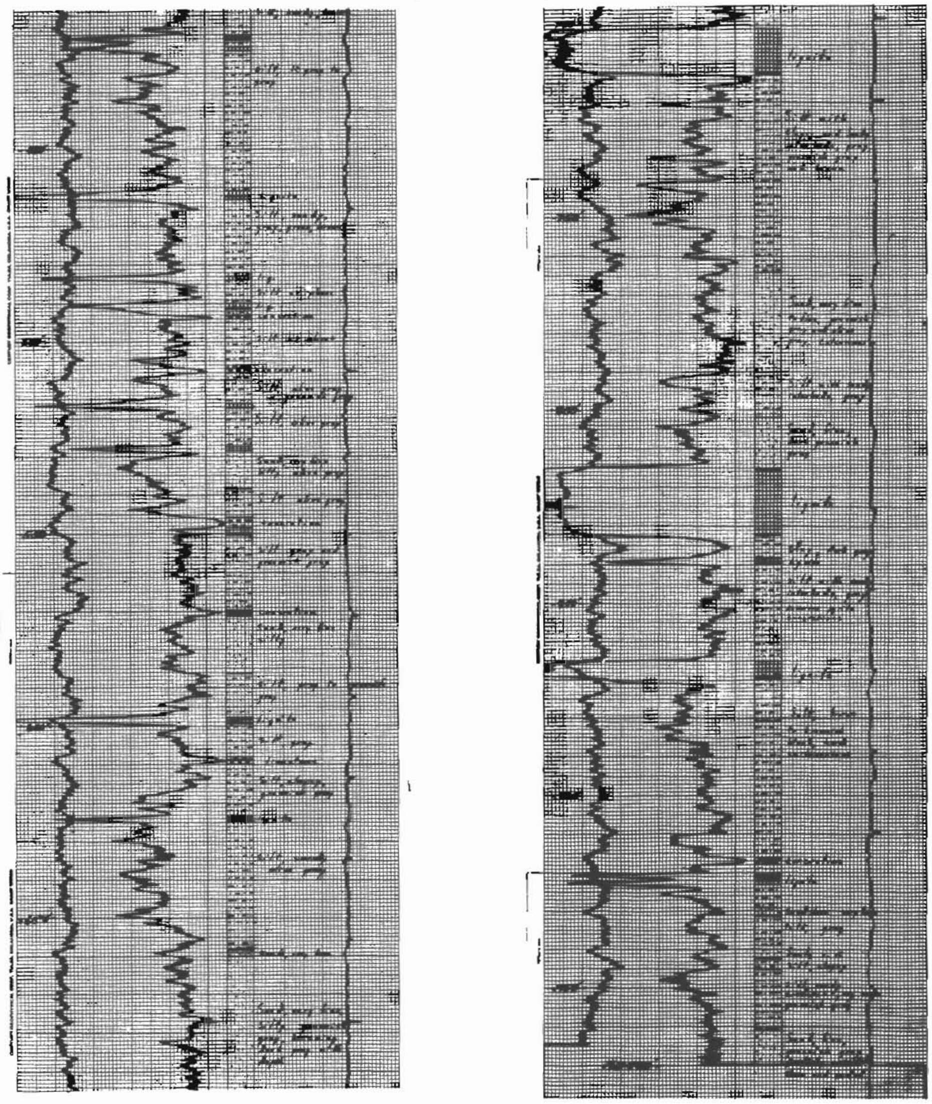


UND EES 75-30-3
SE¼SE¼NE¼
Sec 07, T144N, R94W
Century: 8090 Log



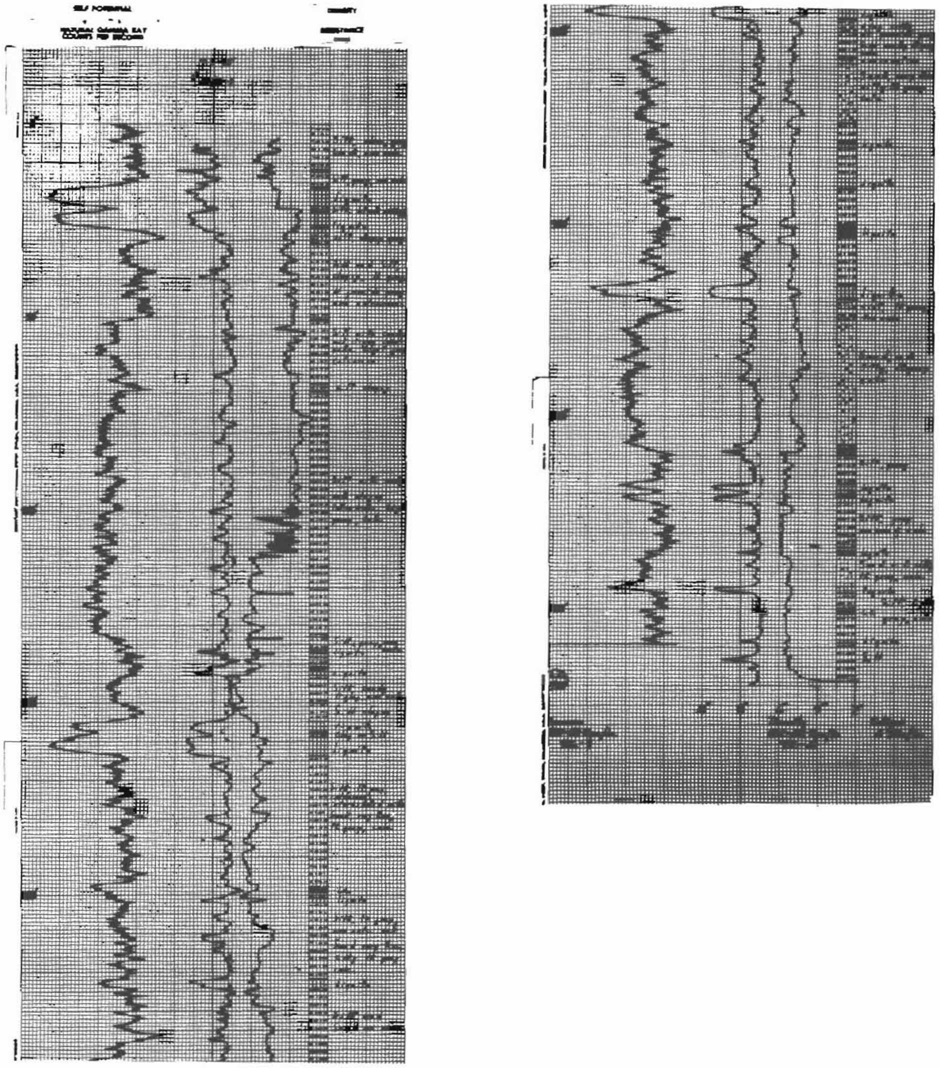
APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

NDSWC 4599
(UND EES 75-30)
SE¼SE¼NE¼
Sec 07, T144N, R94W
Century: 8030 Log



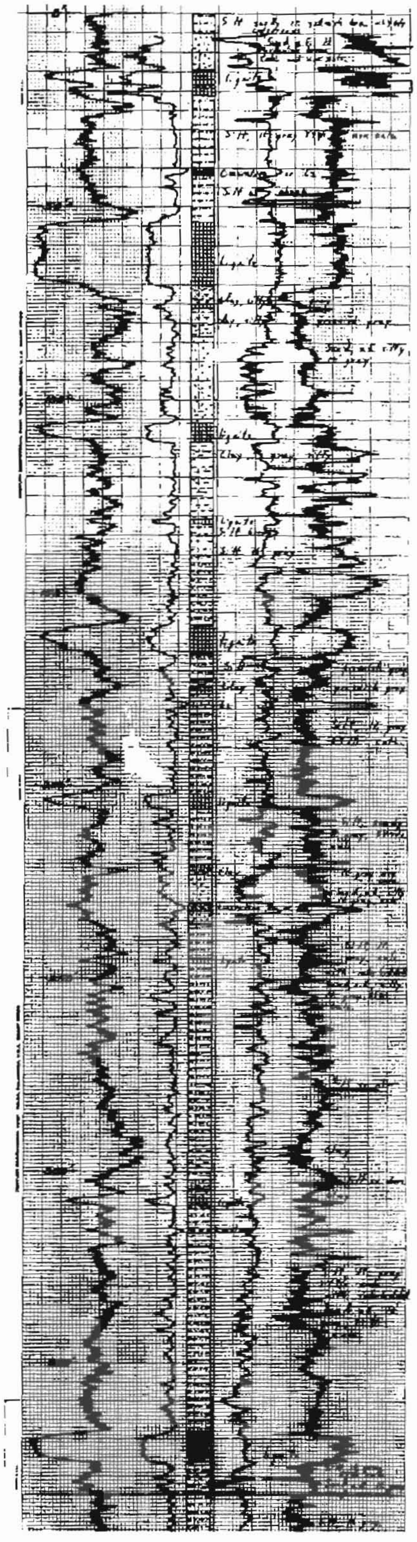
APPENDIX II–Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

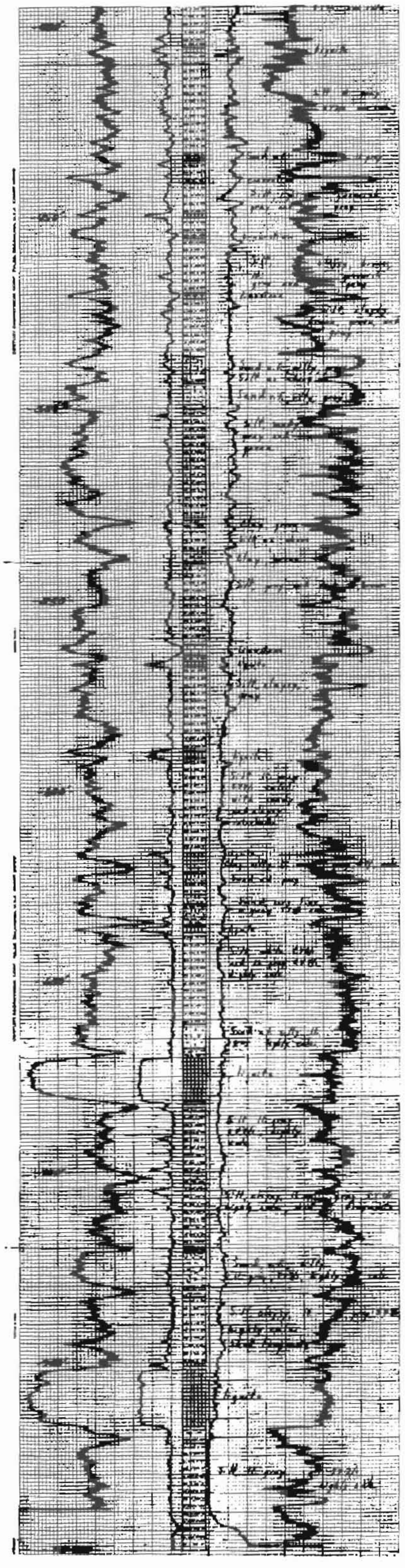
UND EES 75-31-1
NE¼NE¼SE¼
Sec 20, T145N, R92W
Century: 8090 Log
(No Resistance)



APPENDIX II—Continued
GEOPHYSICAL LOGS OF STRATIGRAPHIC TESTHOLES

UND EES 75-33-1
NE¼SE¼SE¼
Sec 34, T145N, R94W
Century: 8090 Log





APPENDIX III
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

UND 75-1-3
143-93-07 CCC
TD: 379 feet

Depth (feet)	Lithologic Description
0 - 29	Silt, sandy, light-gray (2.5Y 7/2), noncalcareous.
29 - 34	Clay, light-gray (5Y 7/1), calcareous.
34 - 35	Lignite.
35 - 36	Clay.
36 - 37.5	Lignite.
37.5- 45	Silt, sandy, light-gray (5Y 7/2), clacareous.
45 - 48.5	Sand, very fine, light-gray, calcareous.
48.5- 53	Silt, clayey, white (5Y 8/1), calcareous.
53 - 71.5	Silt, light-gray (5Y 7/1), calcareous.
71.5- 77	Limestone.
77 - 80	Silt, white (5Y 8/1), highly calcareous.
80 - 82	Lignite.
82 - 91.5	Silt, white (5Y 8/1), highly calcareous.
91.5- 92.5	Lignite.
92.5-112.5	Silt, light-gray (5Y 7/1), highly calcareous.
112.5-114	Lignite.
114 -115	Clay, brown.
115 -126	Sand, very fine, light-gray (5Y 7/1), calcareous.
126 -131	Lignite.
131 -134.5	Clay, gray (5Y 5/1), noncalcareous.
134.5-136	Lignite.
136 -149	Silt, sandy, light-gray (5Y 7/1), noncalcareous.
149 -212	Sand, very fine to fine, gray (5Y 5/1), noncalcareous.
212 -215	Clay, gray (N 6/), noncalcareous.
215 -218	Lignite.
218 -225.5	Silt, gray.
225.5-236	Clay, silty, greenish-gray.
236 -254.5	Silt, gray (5Y 6/1), slightly calcareous.
254.5-255.5	Lignite.
255.5-263.5	Sand, very fine, silty, gray (5Y 6/1).
263.5-274.5	Silt, clayey, dark-gray (5Y 4/1), slightly calcareous.
274.5-276	Lignite.
276 -280	Silt, clayey, dark-gray (5Y 4/1), slightly calcareous.
280 -298	Sand, silty, light-gray (5Y 7/1), slightly calcareous, laminated, well sorted.
298 -302	Lignite.
302 -324	Interbedded sand, silt, and clay; light-gray (5Y 6/1 and 5Y 7/1); slightly calcareous.
324 -336	Clay, silty, light-gray (5Y 7/1), slightly calcareous.
336 -337	Limestone.
337 -346	Silt, clayey, gray (5Y 6/1), very slightly calcareous.
346 -356	Lignite.
356 -379	Silt, interbedded with clay and sand, gray (5Y 6/1), slightly calcareous.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

UND 75-2-1
144-94-35 ADD
TD: 370

Depth (feet)	Lithologic Description
0 - 7	Sand, fine, pale-olive (5Y 6/3), noncalcareous.
7 - 20	Silt, sandy, clayey, light-gray (2.5Y 7/2), noncalcareous.
20 - 36	Sand, very fine to fine, pale-yellow (5Y 7/3), noncalcareous.
36 - 42.5	Silt, dark-gray (5Y 4/1), noncalcareous.
42.5- 57	Lignite, Dunn Center bed.
57 - 65.5	Clay, silty, gray (5Y 5/1) to light-greenish-gray (5GY 7/1), noncalcareous.
65.5- 68	Lignite.
68 - 90.5	Silt, sandy, light-gray (5Y 7/1), calcareous.
90.5-100.5	Sand, very fine, silty, light-gray (5Y 7/1), calcareous.
100.5-114	Silt, light-gray (5Y 7/1), calcareous.
114 -117.5	Lignite.
117.5-119	Clay, silty, light-gray (5Y 7/1), calcareous.
119 -120.5	Silt.
120.5-122.5	Clay, silty, light-gray (5Y 7/1).
122.5-139	Silt, white (5Y 8/1 to 5Y 8/2), calcareous, contains shell fragments.
139 -149	Silt, clayey, gray (5Y 6/1), noncalcareous.
149 -155	Clay, silty, gray (10YR 6/1), noncalcareous, organic rich.
155 -157.5	Lignite.
157.5-167.5	Silt, light-gray to white (5Y 7/1) to (5Y 8/1).
167.5-171	Clay.
171 -194.5	Clay and silt, light-gray (N 7/) to gray (5Y 5/1), noncalcareous.
194.5-196.5	Lignite.
196.5-199.5	Clay, silty, light-gray (5Y 7/1).
199.5-203	Lignite.
203 -204.5	Clay.
204.5-205.5	Lignite.
205.5-207	Clay, light-gray (5Y 7/1), noncalcareous.
207 -215	Silt, light-gray (5Y 7/1), calcareous.
215 -218	Clay.
218 -229	Sand, very fine, gray (5Y 6/1 to 5Y 5/1).
229 -243.5	Silt and clay, gray (5Y 6/1), calcareous.
243.5-253	Sand, very fine, gray (5Y 6/1), calcareous.
253 -257	Silt, white (5GY 8/1), noncalcareous.
257 -258	Lignite.
258 -261	Silt, light-gray (5Y 7/1), calcareous.
261 -265.5	Clay, dark-gray (5Y 4/1), noncalcareous.
265.5-266.5	Lignite.
266.5-283	Silt, light-gray (5Y 7/1), calcareous.
283 -287	Clay.
287 -294	Sand.
294 -296	Clay.
296 -303.5	Silt, gray (5Y 5/1), calcareous.
303.5-309	Clay, gray (5Y 6/1), noncalcareous.
309 -312	Clay, black (5Y 2.5/1), noncalcareous.
312 -313.5	Lignite.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

313.5-315	Clay.
315 -350	Sand, fine, light-gray (5Y 7/1), calcareous.
350 -352	Lignite.
352 -354	Clay, gray (5Y 6/1), calcareous.
354 -360	Sand, fine, light-gray (5Y 7/1), calcareous.
360 -370	Clay and silt, gray (5Y 6/1), calcareous.

UND 75-3-1
144-94-13 DAD
TD: 320 feet

Depth (feet)	Lithologic Description
0 - 26	Sand, very fine, silty, light-gray (5Y 7/1).
26 - 27	Lignite.
27 - 44	Silt and sand, very fine, light-gray (5Y 7/1), noncalcareous.
44 - 46	Lignite.
46 - 55	Silt, sandy, light-gray (5Y 7/1), slightly calcareous.
55 - 63.5	Lignite, A-bed.
63.5- 65	Clay.
65 - 87	Silt, light-gray (5Y 6/1 to 5Y 7/1), noncalcareous.
87 -107	Lignite, Dunn Center bed.
107 -111	Clay, light-gray (5Y 7/1), noncalcareous.
111 -112.5	Lignite.
112.5-113.5	Clay, gray (5Y 6/1), noncalcareous.
113.5-114.5	Lignite.
114.5-119	Clay, gray (5Y 6/1), noncalcareous.
119 -136.5	Silt and clay.
136.5-139.5	Lignite.
139.5-160	Silt and clay.
160 -171	Silt, white (5Y 8/1), highly calcareous.
171 -174	Clay.
174 -175	Lignite.
175 -186	Sand, very fine, light-gray (5Y 7/1), noncalcareous.
186 -187	Lignite.
187 -190	Silt, light-gray (5Y 7/1), calcareous.
190 -195	Silt, light-gray (5Y 7/1), noncalcareous.
195 -208	Silt, light-gray (5Y 7/1), highly calcareous.
208 -211	Clay, light-gray, laminated.
211 -216	Silt, gray.
216 -220.5	Clay, light-gray.
220.5-228.5	Silt, clayey, light-gray.
228.5-236	Clay, silty, light-gray.
236 -239.5	Lignite.
239.5-246	Clay, olive-gray.
246 -250.5	Silt, sandy, light-gray.
250.5-254.5	Lignite.
254.5-255.5	Clay.
255.5-256.5	Lignite.
256.5-271	Silt and clay, light-gray to gray.
271 -272	Lignite.
272 -275	Silt, light-gray.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

275 -276.5	Clay, silty, organic rich.
276.5-280	Silt.
280 -281	Siltstone.
281 -305	Silt, sandy, clayey, light-gray to olive-gray.
305 -309	Clay, olive-gray.
309 -320	Silt, clayey, light-greenish-gray.

UND 75-5-2
145-93-33 BAA
TD: 321 feet

Depth (feet)	Lithologic Description
0 - 16	Silt, sandy, pale-olive, noncalcareous.
16 - 53	Sand, very fine to fine, pale-olive (5Y 6/3), noncalcareous, poorly sorted.
53 - 80	Silt, sandy, light-olive-gray (5Y 6/2), gray (5Y 5/1 and N 6/), greenish-gray (5GY 5/1), noncalcareous.
80 - 92	Sand, very fine to fine, silty, bluish-gray (5B 6/1), noncalcareous.
92 -111	Lignite, woody.
111 -118.5	Silt, greenish-gray (5GY 5/1) and gray (5Y 6/1), noncalcareous.
118.5-120.5	Lignite.
120.5-123	Silt, gray (5Y 6/1), noncalcareous.
123 -128.5	Lignite.
128.5-144	Sand, very fine, silty, and silt, white (5Y 8/1 and 5GY 7/1), noncalcareous.
144 -157	Silt, white (5GY 8/1), calcareous.
157 -171.5	Sand, very fine, silty, light-greenish-gray (5GY 7/1) and white (N 8/1), calcareous.
171.5-194	Silt, white (5Y 8/1), highly calcareous.
194 -206.5	Silt, white (5Y 8/1), noncalcareous and sand, very fine, silty, light-gray (5Y 7/1), noncalcareous.
206.5-207.5	Lignite.
207.5-208	Silt.
208 -216	Lignite.
216 -226	Silt, sandy, greenish-gray (5GY 7/1 and 5GY 6/1), noncalcareous, laminated.
226 -231	Lignite.
231 -271.5	Silt, light-gray (5Y 7/1) and gray (5Y 6/1), laminated, noncalcareous, interbedded with very fine sand and clay, gray (5Y 6/1).
271.5-272.5	Lignite.
272.5-275	Silt, light-gray (5Y 6/1), calcareous.
275 -276	Lignite.
276 -289	Silt and very fine sand, light-gray (5Y 7/1), calcareous, laminated.
289 -290	Lignite.
290 -307.5	Silt, light-gray (5Y 7/1), calcareous, laminated.
307.5-308.5	Lignite.
308.5-321	Silt, sandy, light-gray (5Y 7/1) and gray (5Y 6/1 and N 6/), calcareous to noncalcareous, laminated.

APPENDIX III–Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

UND 75-6-1
145-93-16 CBB
TD: 500 feet

Depth (feet)	Lithologic Description
0 - 14	Sand, medium, silty, pale-brown (10YR 6/3), noncalcareous, iron oxide concretions.
14 - 16	Lignite.
16 - 18	Clay, white (5Y 8/2), noncalcareous.
18 - 21	Sand, fine to medium, strong-brown (7.5YR 5/8), noncalcareous.
21 - 33	Sand, very fine, silty, pebbly, brownish-yellow (10YR 6/6) to white (5Y 8/1), noncalcareous, pebbles of Knife River flint.
33 - 41	Clay, silty, lignitic, gray (N 6/0), noncalcareous.
41 - 43	Lignite.
43 - 49.5	Sand, fine, silty, light-gray (5Y 7/1), noncalcareous.
49.5- 56	Lignite.
56 - 78	Clay, silty, light-gray (5Y 7/1), noncalcareous.
78 -110	Silt, clayey, light-gray (5Y 7/1), noncalcareous.
110 -113	Sandstone.
113 -115.5	Clay, silty, white (5Y 8/1), noncalcareous.
115.5-117	Lignite.
117 -132.5	Sand, fine to medium, gray (5Y 6/1), noncalcareous.
132.5-133.5	Lignite.
133.5-165.5	Sand, fine, gray (5Y 6/1), noncalcareous.
165.5-181	Lignite.
181 -184	Clay, gray (N 5/0), noncalcareous.
184 -185	Lignite.
185 -204.5	Sand, fine, silty, light-gray (5Y 7/1), noncalcareous.
204.5-220	Clay, silty, light-gray (5Y 7/1), noncalcareous.
220 -228	Lignite.
228 -229.5	Clay, gray.
229.5-232.5	Sandstone.
232.5-237	Clay, gray (5Y 5/1), noncalcareous.
237 -250	Clay, silty, white (5Y 8/1), highly calcareous.
250 -251	Sandstone.
251 -271	Clay, slightly silty, gray (5Y 6/1), noncalcareous.
271 -275.5	Clay, light-gray (5Y 7/1), highly calcareous.
275.5-287.5	Clay, silty, light-gray (5Y 7/1), calcareous.
287.5-299	Lignite.
299 -306.5	Clay, light-gray (5Y 7/1), laminated, noncalcareous.
306.5-307.5	Lignite.
307.5-320.5	Clay, light-gray (5Y 7/1), laminated, noncalcareous.
320.5-329	Lignite.
329 -349	Silt and clay, interbedded, light-gray (5Y 7/1), calcareous.
349 -350.5	Lignite.
350.5-380.5	Clay, gray (5Y 6/1), noncalcareous.
380.5-381.5	Limestone.
381.5-410	Clay and silt, interbedded, light-gray (5Y 7/1 to 5Y 6/1), calcareous.
410 -422.5	Sand, fine to very fine, light-gray (5Y 7/1).
422.5-426.5	Lignite.

426.5-433	Clay, silty, gray (N 6/0), calcareous.
433 -445	Sand, very fine, light-gray (5Y 7/1), calcareous.
445 -472	Clay, gray (N 5/0), noncalcareous.
472 -483.5	Lignite, black (10YR 2/1).
483.5-495	Sand, very fine, light-gray (N 7/0), calcareous.
495 -500	Silt, gray (N 6/0), calcareous.

UND 75-7-1
145-93-04 BBC
TD: 494 feet

Depth (feet)	Lithologic Description
0 - 7	Silt, pale-olive (5Y 6/3), calcareous.
7 - 13	Sand, medium, mottled brown and yellow.
13 - 16.5	Silt, pale-olive (5Y 6/3), calcareous.
16.5- 17.5	Lignite.
17.5- 20.5	Silt, pale-olive.
20.5- 21	Lignite.
21 - 30	Silt, mottled pale-olive (5Y 6/3), calcareous.
30 - 42	Sand, very fine to fine, pale-olive (5Y 6/3), calcareous.
42 - 46	Clay, light-olive-gray (5Y 6/2), noncalcareous.
46 - 47	Lignite.
47 - 49	Clay, light-olive-gray (5Y 6/2), noncalcareous.
49 - 50	Lignite.
50 - 57	Clay, light-gray (5Y 6/1), calcareous.
57 - 67	Sand, very fine, silty, gray (5Y 6/1), noncalcareous.
67 - 73	Clay, light-gray (5Y 6/1).
73 - 82	Lignite, peaty.
82 -109	Clay and silt, light-gray (5Y 6/1), noncalcareous.
109 -148	Sand, fine, light-gray (5Y 7/1), noncalcareous.
148 -158	Lignite.
158 -168	Silt, sandy, light-gray (5Y 7/1), noncalcareous.
168 -170	Lignite, peaty.
170 -199	Sand, fine, light-gray (5Y 7/1), noncalcareous.
199 -203	Clay, silty, light-gray (5Y 7/1), noncalcareous.
203 -209.5	Lignite.
209.5-210.5	Clay.
210.5-212	Lignite.
212 -238	Silt, sandy, and silt, clayey, light-gray (5Y 7/1), calcareous.
238 -280	Sand, fine, light-gray (5Y 7/1), calcareous.
280 -282	Silt, gray (5Y 6/1), slightly calcareous, laminated.
282 -284	Lignite.
284 -285	Silt.
285 -293	Lignite.
293 -296	Silt, white (5GY 8/1), noncalcareous, laminated.
296 -310	Sand, fine, light-gray (5Y 7/1), noncalcareous.
310 -318.5	Silt, gray (5Y 6/1), noncalcareous.
318.5-325.5	Lignite.
325.5-333.5	Silt, gray (5Y 6/1), calcareous, laminated.
333.5-334.5	Lignite.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

334.5-352.5	Silt, gray (5Y 6/1), calcareous.
352.5-353.5	Lignite.
353.5-358	Silt, gray (5Y 6/1), calcareous.
358 -373	Sand, fine, gray (5Y 6/1), calcareous.
373 -383	Silt, gray (5Y 6/1) and silt, white (5GY 8/1).
383 -407	Sand, fine, light-gray (5Y 7/1), calcareous.
407 -419.5	Clay, light-gray (5Y 7/1), calcareous.
419.5-426	Lignite.
426 -437	Silt, light-gray (5Y 7/1), noncalcareous.
437 -449	Sand, fine, light-gray (5Y 7/1), calcareous.
449 -469	Silt, clayey, white (5GY 8/1), calcareous.
469 -480	Lignite.
480 -494	Clay, silty, white (5GY 8/1), calcareous.

UND 75-8-1
146-93-23 BCC
TD: 506 feet

Depth (feet)	Lithologic Description
0 - 5	Sand, fine, yellowish-brown (10YR 5/4), calcareous.
5 - 19	Silt, light-yellowish-brown (10YR 6/4), calcareous.
19 - 58	Sand, very fine, light-gray (10YR 7/2) to white (2.5Y 8/0).
58 - 61	Claystone, pale-brown (10YR 6/3), noncalcareous.
61 - 91	Sand, medium, pale-yellow (2.5Y 7/4), mottled, noncalcareous.
91 -121	Clay, light-gray (5Y 7/1), noncalcareous.
121 -130	Lignite.
130 -155	Silt, sandy, gray (N 6/0), calcareous.
155 -156.5	Lignite.
156.5-159.5	Clay, gray (N 6/0), noncalcareous.
159.5-163.5	Lignite.
163.5-166	Clay, gray (N 6/0), noncalcareous.
166 -168	Lignite.
168 -172	Clay, gray (N 6/0), noncalcareous.
172 -181	Silt, light-gray (N 7/0), noncalcareous.
181 -183	Lignite.
183 -187	Sand, very fine, light-greenish-gray (5G 7/1), noncalcareous.
187 -200	Clay, silty, gray (N 6/0), calcareous.
200 -208	Clay, light-gray (N 7/0), noncalcareous.
208 -212	Lignite.
212 -254	Clay, silty, gray (N 6/0), noncalcareous.
254 -303	Sand, very fine to fine, gray (5GY 6/1 to 5Y 6/1), noncalcareous, sandstone from 284-287.
303 -306	Lignite.
306 -309	Clay, slightly silty, light-gray (5Y 7/1), noncalcareous.
309 -315	Sand, fine, silty, gray (5Y 6/1), noncalcareous.
315 -323	Clay, light-gray (5Y 7/1), noncalcareous.
323 -335	Lignite with clay partings.
335 -374	Sand, fine, silty, light-gray (N 7/0), noncalcareous.
374 -385	Clay, light-gray (5Y 7/1), noncalcareous.
385 -392	Sand, fine to silt, gray (5Y 6/1), noncalcareous.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

392 -406.5	Clay, light-gray (5Y 7/1), noncalcareous.
406.5-413	Lignite.
413 -417.5	Clay, silty, light-gray (5Y 7/1), calcareous, laminated.
417.5-474	Silt to very fine sand, light-gray (5Y 7/1), calcareous.
474 -475.5	Lignite.
475.5-478.5	Clay, light-gray (5Y 7/1), noncalcareous.
478.5-480.5	Lignite.
480.5-488	Silt, light-gray (5Y 7/1), calcareous.
488 -491	Lignite.
491 -506	Sand, fine, to silt, light-gray (5Y 7/1), calcareous.

UND 75-9-1
146-93-27 ADD
TD: 494 feet

Depth (feet)	Lithologic Description
0 - 11	Sand, fine, pale-yellow (2.5Y 7/4), noncalcareous.
11 - 27	Clay, gray (5Y 6/1), noncalcareous.
27 - 36.5	Lignite.
36.5- 45	Clay, gray (5Y 5/1) to light-gray (5Y 7/1), noncalcareous.
45 - 77	Sand, medium to fine, light-gray (5Y 7/1), noncalcareous.
77 - 87	Lignite with 1-foot thick parting.
87 - 93	Clay, light-gray (5Y 7/1), noncalcareous.
93 - 97.5	Sand, medium to fine, light-gray (5Y 7/1), noncalcareous.
97.5-101	Lignite.
101 -106.5	Sand, medium to fine, light-gray (5Y 7/1), laminated with white clay, noncalcareous.
106.5-116	Clay, slightly silty, light-gray (5Y 7/1), noncalcareous.
116 -120.5	Lignite.
120.5-138	Clay, silty to silt, light-gray (5Y 7/1), noncalcareous.
138 -219	Sand, fine, light-gray (5Y 7/1), noncalcareous to calcareous.
219 -221	Lignite.
221 -241.5	Sand, fine to medium, light-gray (5Y 7/1), calcareous, shell fragments.
241.5-253.5	Lignite.
253.5-256	Clay, dark-gray (5Y 4/1), noncalcareous.
256 -278	Sand, fine, silty, light-gray (5Y 7/1), calcareous, with lignite stringers.
278 -298	Clay, light-gray (5Y 7/1), calcareous.
298 -314	Sand, medium to fine, light-gray (5Y 7/1), noncalcareous.
314 -323	Clay, light-gray (5Y 7/1), calcareous to noncalcareous, laminated.
323 -324	Siltstone, concretion.
324 -334	Clay, slightly silty, light-gray (5Y 7/1), calcareous.
334 -340.5	Lignite.
340.5-377.5	Clay, silty, light-gray (5Y 7/1), calcareous.
377.5-382	Sand, medium to fine, light-gray (5Y 7/1), calcareous, laminated.
382 -383	Lignite.
383 -401	Clay, slightly silty, light-gray (5Y 7/1), calcareous.
401 -406	Lignite.
406 -433	Sand, very fine, light-gray (5Y 7/1), calcareous, cemented from 423-425.
433 -465	Clay, silty, light-gray (5Y 7/1), calcareous.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

465 -467	Lignite.
467 -494	Clay, light-greenish-gray (5BG 7/1), noncalcareous, and lignite stringers.

UND 75-10-1
146-93-33 DAA
TD: 514 feet

Depth (feet)	Lithologic Description
0 - 5	Gravel, sandy, silty, mottled, yellow and gray, calcareous.
5 - 16	Sand, pebbles, silt, yellow, gray, and white, calcareous.
16 - 18	Silt, sandy.
18 - 19	Lignite.
19 - 22	Silt, sandy.
22 - 31	Sand, silty, gray (N 6/0), noncalcareous.
31 - 44	Sand, very fine, gray (N 6/0), noncalcareous.
44 - 47	Clay, light-gray (N 7/0), noncalcareous.
47 - 55	Lignite.
55 - 70	Clay, very dark-gray (10YR 3/1), noncalcareous to clay, gray (5Y 6/1), noncalcareous.
70 - 74.5	Sand, very fine, crossbedded, gray (N 6/0), noncalcareous.
74.5- 76	Sandstone, white (N 8/0) to light-gray (N 7/0), calcareous.
76 -101	Sand, fine, light-gray (5Y 7/1), noncalcareous.
101 -110	Lignite.
110 -115	Clay, silty, gray (N 5/0), noncalcareous.
115 -120	Silt, slightly sandy, gray (5Y 6/1), noncalcareous.
120 -128.5	Silt, gray (5Y 6/1), noncalcareous.
128.5-131	Lignite.
131 -139	Clay, silty, gray (N 6/0), noncalcareous.
139 -143	Silt, gray (N 6/0), noncalcareous.
143 -148	Lignite, black (10YR 2/1).
148 -150	Clay, light-gray (5Y 7/1), noncalcareous.
150 -151	Lignite.
151 -153.5	Clay, light-gray (5Y 7/1), noncalcareous.
153.5-155	Lignite.
155 -159	Clay, light-gray (5Y 7/1), noncalcareous.
159 -166	Silt, clayey.
166 -174	Clay, light-gray (5Y 7/1), noncalcareous.
174 -182	Silt, light-gray (5Y 7/1), noncalcareous.
182 -185	Sandstone, fine, white (5Y 8/1), slightly calcareous.
185 -216.5	Sand, fine, light-gray (5Y 7/1), slightly calcareous.
216.5-219	Lignite.
219 -230	Silt, sandy, light-gray (5Y 7/1), noncalcareous.
230 -235.5	Lignite.
235.5-239	Clay, light-gray (5Y 7/1), noncalcareous.
239 -244	Lignite.
244 -249	Silt, gray (N 6/0), noncalcareous.
249 -259	Sand, very fine, light-gray (N 7/0 and 5Y 6/1).
259 -262	Silt, light-gray (5Y 7/1), calcareous.
262 -310	Sand, very fine to fine, light-gray (5Y 7/1), calcareous, with lignite stringers and clay partings.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

310 -311	Lignite.
311 -329	Clay, silty, white (5Y 8/1), noncalcareous to calcareous, laminated.
329 -330	Lignite.
330 -342	Sand, very fine, to silt, white (5Y 8/1), noncalcareous to highly calcareous.
342 -345	Clay, slightly silty, light-gray (5Y 8/1), calcareous.
345 -351	Lignite.
351 -398	Silt, clayey, and silt, sandy, light-gray (5Y 7/1, N 7/0, and N 6/0), noncalcareous to calcareous.
398 -407.5	Lignite.
407.5-422	Silt, clayey, light-gray (5Y 6/1 to 5Y 7/1), noncalcareous to calcareous.
422 -435	Sand, very fine, white (5Y 8/1), calcareous.
435 -436	Lignite.
436 -444	Clay, silty, light-gray (5Y 7/1).
444 -450	Sand, very fine, to silt, light-gray (5Y 7/1), calcareous.
450 -457	Clay, silty, light-gray (5Y 7/1), calcareous.
457 -458	Lignite.
458 -465	Clay, dark-gray (5Y 5/1), noncalcareous.
465 -466	Lignite.
466 -469	Clay, silty, light-gray (5Y 7/1), noncalcareous.
469 -470	Lignite.
470 -476	Clay, light-gray (5Y 7/1), calcareous.
476 -510.5	Sand, very fine, silty, light-gray (5Y 7/1), calcareous.
510.5-511.5	Lignite.
511.5-514	Sand, very fine, light-gray (5Y 7/1).

UND 75-11-1
145-93-9 DAA
TD: 503 feet

Depth (feet)	Lithologic Description
0 - 8	Silt, white (10YR 8/2), calcareous.
8 - 25	Sand, medium, light-yellowish-brown (10YR 6/4), noncalcareous.
25 - 26	Lignite.
26 - 28	Clay, gray (N 6/0), noncalcareous.
28 - 30	Lignite.
30 - 52	Silt, gray (5Y 6/1), noncalcareous.
52 - 59	Lignite.
59 - 69	Clay, gray (N 6/0 to N 4/0), noncalcareous.
69 - 95	Silt, clayey, light-gray (5Y 7/1 and N 7/0), noncalcareous.
95 - 99	Clay, gray (5Y 6/1), noncalcareous.
99 -102	Sandstone, fine, gray (N 6/0), calcareous.
102 -120	Sand, fine, gray (N 6/0), calcareous.
120 -125.5	Clay.
125.5-136	Lignite.
136 -145	Silt, gray (5Y 6/1), noncalcareous.
145 -147	Lignite.
147 -151	Clay, gray (N 6/1), noncalcareous.
151 -163	Silt, light-gray (N 7/0), noncalcareous.
163 -174	Sand, very fine, silty, light-gray (N 7/0), calcareous.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

174 -186	Clay, silty, light-gray (N 7/0), noncalcareous.
186 -194.5	Lignite with clay partings.
194.5-197	Clay, gray (N 5/0), noncalcareous.
197 -223	Silt, white (5Y 8/1), calcareous.
223 -245	Clay, silty, light-gray (5Y 7/1), calcareous.
245 -250	Sand, fine, silty, light-gray (N 7/0), calcareous.
250 -258	Lignite.
258 -264	Silt, gray (5Y 6/1), noncalcareous.
264 -265.5	Lignite.
265.5-266.5	Silt, gray (5Y 6/1), noncalcareous.
266.5-269.5	Lignite.
269.5-290	Clay, silty, light-gray (5Y 7/1), noncalcareous.
290 -299	Clay, light-gray (5Y 7/1), noncalcareous.
299 -300.5	Limestone.
300.5-313.5	Clay, light-gray (5Y 6/1), calcareous.
313.5-316	Limestone, gray (N 6/0).
316 -318.5	Clay, gray (5Y 6/1), calcareous.
318.5-319.5	Lignite.
319.5-338	Clay, silty, light-gray (5Y 7/1), calcareous.
338 -348	Clay, gray (5Y 6/1), calcareous.
348 -349	Lignite.
349 -351	Clay, gray (5Y 6/1), calcareous.
351 -353.5	Sandstone, fine, light-gray (5Y 7/1), calcareous.
353.5-368	Sand, fine, light-gray (5Y 7/1), calcareous.
368 -371	Lignite.
371 -376	Clay, silty, gray (5Y 6/1), calcareous.
376 -393.5	Sand, very fine (5Y 7/1), calcareous.
393.5-396.5	Lignite.
396.5-407	Clay, gray (5Y 6/1), noncalcareous.
407 -412.5	Silt, sandy, light-gray (5Y 7/1), calcareous.
412.5-416	Limestone, gray (N 6/0).
416 -423	Silt, sandy, light-gray (5Y 7/1), calcareous.
423 -431	Clay, gray (5Y 5/1 to 5Y 6/1), noncalcareous.
431 -448	Sand, very fine, silty, light-gray (5Y 7/1 to 5Y 6/1), calcareous to noncalcareous.
448 -455.5	Lignite.
455.5-478	Clay, silty, light-gray (N 6/0, 5Y 6/1, and 5Y 7/1), calcareous.
478 -479	Lignite.
479 -489	Silt, light-gray (5Y 7/1), calcareous.
489 -499.5	Clay, light-gray (5Y 7/1), calcareous.
499.5-500.5	Lignite.
500.5-501.5	Clay.
501.5-503	Lignite.

UND 75-12-1
145-93-6 CDC
TD: 492 feet

Depth (feet)	Lithologic Description
0 - 88	Sand, fine, pale-yellow (5Y 7/3), white (2.5Y 8/2), very pale-brown (10YR 8/4), gray (10YR 6/1), noncalcareous.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

88 -100	Lignite.
100 -106	Clay, light-bluish-gray (5B 7/1), noncalcareous.
106 -113	Sand, fine, silty, gray (10YR 6/1), noncalcareous.
113 -131	Clay, gray (10YR 6/1), noncalcareous.
131 -139	Lignite.
139 -144	Silt, light-gray (2.5Y 7/0 and N 7/0), noncalcareous.
144 -152	Silt, clayey, light-gray (2.5Y 7/0 and N 7/0), noncalcareous.
152 -165	Sand, fine, light-gray (2.5Y 7/0), noncalcareous.
165 -171	Clay, silty, white (N 8/0), calcareous.
171 -223	Sand, medium, light-gray (5Y 7/1), noncalcareous.
223 -232	Lignite.
232 -245.5	Clay, light-gray (N 7/0), noncalcareous.
245.5-247.5	Lignite.
247.5-252	Clay, light-gray (N 7/0), noncalcareous.
252 -257	Lignite.
257 -270	Sand, very fine to fine, light-gray (5Y 7/1), calcareous.
270 -280	Clay, gray (5Y 6/1), noncalcareous.
280 -289	Sand, medium, gray (10YR 6/1), silty, noncalcareous.
289 -290	Lignite.
290 -302	Sand, medium, silty, gray (10YR 6/1), noncalcareous.
302 -312	Silt, clayey, light-gray (5Y 7/1 and 5Y 6/1), noncalcareous.
312 -326	Silt, sandy, white (5BG 8/1), calcareous.
326 -343	Silt, clayey, light-gray (2.5Y 7/1 to 5Y 7/1), calcareous.
343 -357	Silt, to very fine sand, light-gray (5Y 7/1), calcareous.
357 -360	Lignite.
360 -380.5	Clay, silty, light-gray (5Y 7/1 and 5Y 6/1), calcareous.
380.5-399	Sand, very fine, light-gray (5Y 7/1), calcareous.
399 -409	Lignite.
409 -425	Silt, light-gray (N 7/0), calcareous.
425 -429.5	Sand, very fine, silty, light-gray (N 7/0), calcareous.
429.5-446	Silt to clay, silty, light-gray (N 7/0 and N 6/0), noncalcareous to calcareous.
446 -456	Sand, very fine, light-gray (N 7/0), calcareous.
456 -473	Silt and clay, light-gray (5Y 7/1), calcareous to noncalcareous.
473 -474.5	Lignite.
474.5-492	Sand, very fine, and silt, gray (5Y 6/1), noncalcareous.

UND 75-13-1
145-93-21 DAD
TD: 500 feet

Depth (feet)	Lithologic Description
0 - 63	Sand, fine to medium, gravelly, pale-yellow (5Y 7/3) to olive (5Y 5/3 and 5Y 4/3), noncalcareous.
63 - 78.5	Lignite.
78.5- 85	Silt, clayey, dark-gray (5Y 4/1), noncalcareous.
85 - 93	Sand, very fine, gray (5Y 5/1), highly calcareous to noncalcareous.
93 -114	Silt, sandy to silt, clayey, gray (5Y 5/1) to very dark-gray (5Y 3/1), noncalcareous.
114 -116	Lignite.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

116 -117.5	Clay.
117.5-124	Lignite.
124 -153	Silt, white (N 8/1), highly calcareous.
153 -159	Sand, very fine, white (N 8/1), highly calcareous.
159 -172	Silt, white (N 8/1), highly calcareous.
172 -173	Limestone, light-gray (N 7/1).
173 -177.5	Sand, very fine, silty, white (N 8/1), highly calcareous.
177.5-178	Lignite.
178 -179	Silt.
179 -180	Lignite.
180 -180.5	Silt.
180.5-186.5	Lignite.
186.5-202.5	Silt, clayey, light-gray (N 7/1), highly calcareous.
202.5-207.5	Lignite.
207.5-240	Silt, clayey, light-gray (N 7/1), calcareous, carbonaceous partings.
240 -241	Limestone, light-gray (N 7/1).
241 -248	Silt, clayey, light-gray (5Y 7/1), calcareous.
248 -250	Clay, light-gray (5Y 7/1), noncalcareous.
250 -251	Lignite.
251 -258	Silt, clayey, light-gray (5Y 7/1), calcareous.
258 -271	Clay, silty, light-gray (5Y 7/1), calcareous.
271 -299	Sand, very fine, and silt, light-gray (5Y 7/1), calcareous.
299 -304	Clay, light-gray (5Y 7/1), calcareous.
304 -320	Sand, very fine, light-gray (5Y 7/1), calcareous.
320 -322.5	Clay, light-gray (5Y 7/1), calcareous.
322.5-324.5	Lignite.
324.5-331	Clay, light-gray (5Y 7/1), calcareous.
331 -332	Limestone, light-gray.
332 -338	Clay, light-gray (5Y 7/1), calcareous.
338 -340.5	Limestone, light-gray.
340.5-349	Silt, clayey, light-gray (5Y 7/1), calcareous.
349 -361	Clay, light-gray (5Y 6/1 and 5Y 7/1), calcareous.
361 -376	Sand, fine, light-gray (N 7/0), noncalcareous.
376 -379.5	Clay, light-gray (5Y 7/1), calcareous.
379.5-387	Lignite.
387 -390	Silt, light-gray (5Y 7/1), calcareous.
390 -398	Sand, very fine, light-gray (N7/0 and 5Y 7/1), calcareous.
398 -401	Clay, light-gray (5Y 7/1), calcareous.
401 -402	Lignite.
402 -422	Silt, and clay, light-gray (5Y 7/1), calcareous.
422 -431	Clay, light-gray (5Y 7/1), calcareous.
431 -437.5	Silt, light-gray (5Y 7/1), calcareous.
437.5-439.5	Lignite.
439.5-445	Clay, light-gray (5Y 7/1), calcareous.
445 -446	Lignite.
446 -457	Clay, becoming increasingly silty downward, light-gray (5Y 7/1), calcareous.
457 -460	Limestone, light-gray (N 7/0).
460 -500	Clay, light-gray (5Y 7/1 and 5Y 6/1), calcareous with lignite stringers.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

UND 75-14-0
145-93-33 BCC
TD: 514 feet

Depth (feet)	Lithologic Description
0 - 44	Sand, medium, light-brown (10YR 8/3) to pale-olive (5Y 6/4), to olive-brown (2.5Y 4/4), noncalcareous.
44 - 53	Lignite.
53 - 61	Clay, slightly silty, light-gray (5Y 7/1), noncalcareous.
61 - 99	Silt, slightly sandy, light-gray (5Y 7/1).
99 -108	Silt, clayey, gray (5Y 6/1 to 5Y 5/1), noncalcareous.
108 -126	Lignite.
126 -136	Silt, clayey, gray (5Y 6/1), noncalcareous.
136 -138	Lignite.
138 -149.5	Silt, clayey, gray (5Y 6/1), noncalcareous.
149.5-155	Lignite.
155 -201	Silt and clay, gray (5Y 6/1), noncalcareous.
201 -216.5	Sand, silty, gray (5Y 6/1), calcareous.
216.5-221	Clay, light-gray (5Y 6/1 and 10YR 6/1), calcareous.
221 -227	Lignite.
227 -236	Sand, light-gray (2.5Y 7/1), mottled, noncalcareous.
236 -243.5	Silt, light-gray (5Y 7/1), noncalcareous.
243.5-250	Lignite with a ½ foot thick clay parting.
250 -252	Silt, light-gray (5Y 7/1), noncalcareous.
252 -325	Sand, very fine to medium, light-gray (N 7/0 and 5Y 7/1), noncalcareous.
325 -353	Silt, clayey, light-gray (5Y 7/1), noncalcareous.
353 -354	Siltstone.
354 -361	Silt, gray (5Y 6/1), calcareous.
361 -362	Limestone, light-gray (N 7/0).
362 -378	Silt, gray (5Y 6/1), calcareous.
378 -380	Clay, light-gray (5Y 6/1), calcareous.
380 -397	Silt, sandy, light-gray (5Y 6/1), noncalcareous.
397 -399.5	Lignite.
399.5-454	Silt and clay, light-gray (5Y 6/1), calcareous to noncalcareous.
454 -462	Lignite.
462 -470.5	Sand, fine, light-gray (5Y 6/1), noncalcareous.
470.5-472	Lignite.
472 -514	Clay, silty, light-gray (5Y 6/1), calcareous.

UND 75-14-3
145-93-33 CBC
TD: 340 feet

Depth (feet)	Lithologic Description
0 - 56	Sand, medium, light-brown (10YR 8/3), dark-yellowish-brown (10YR 4/4), and pale-olive (5Y 6/3).
56 - 59	Silt, clayey, laminated, dark-brown.
59 - 61	Lignite.
61 - 63	Silt, clayey, laminated, dark-brown.
63 - 70	Lignite.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

70 - 79	Clay, light-gray (5Y 7/1), noncalcareous.
79 -122	Silt, gray and greenish-gray, laminated, noncalcareous.
122 -140	Lignite.
140 -145	Silt, clayey, light-gray (5Y 6/1), noncalcareous.
145 -150.5	Clay, greenish-gray (5Y 5/2), noncalcareous.
150.5-152	Lignite.
152 -168	Silt, light-gray (5Y 6/1), noncalcareous.
168 -172	Lignite.
172 -178	Clay, light-gray (5Y 6/1), noncalcareous.
178 -182	Silt, light-gray (5Y 6/1), noncalcareous.
182 -232	Sand, very fine, silty, to silt, greenish-gray to gray, calcareous.
232 -233	Lignite.
233 -235	Clay.
235 -236	Lignite.
236 -238	Clay.
238 -245	Lignite.
245 -263	Silt to very fine sand, light-gray and silt, light-greenish-gray, carbonaceous.
263 -270	Lignite.
270 -338	Sand, very fine to fine, light-gray (salt and pepper).
338 -339	Lignite.
339 -340	Sand, as above.

UND 75-15-1
145-93-36 BCC
TD: 820 feet

Depth (feet)	Lithologic Description
0 - 7	Sand, fine, clayey, gray.
7 - 16	Gravel, yellow.
16 - 20	Clay, gray to black.
20 - 25	Silt, sandy, gray.
25 - 48	Sand, fine, silty, brownish-gray.
48 - 54	Silt, gray.
54 - 81	Sand, very fine to silt, gray.
81 - 86	Lignite.
86 -134	Silt and sandy silt, gray.
134 -137	Clay, gray.
137 -153	Sand, silty, gray.
153 -155	Clay, gray.
155 -162	Sand, medium.
162 -167	Lignite.
167 -190	Silt, gray.
190 -198.5	Lignite.
198.5-209.5	Silt, sandy, gray.
209.5-210.5	Lignite.
210.5-215	Clay, gray.
215 -218	Silt, gray.
218 -235	Silt, clayey, gray.
235 -263	Silt, sandy, gray.
263 -268	Clay, gray.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

268 -279	Silt, sandy, to silt, clayey, gray.
279 -282	Lignite.
282 -292	Silt, sandy, gray.
292 -299	Clay, brownish-gray.
299 -307	Silt, sandy, gray.
307 -320	Clay, silty, gray.
320 -323	Siltstone, yellow.
323 -340.5	Silt, sandy, gray.
340.5-347.5	Lignite.
347.5-363	Silt, sandy, gray.
363 -364	Lignite.
364 -367.5	Silt, gray.
367.5-369	Limestone, gray.
369 -385.5	Clay, gray.
385.5-387	Lignite.
387 -389	Clay, gray.
389 -390	Lignite.
390 -449	Silt, gray.
449 -459	Sand, fine, gray.
459 -460.5	Limestone.
460.5-468	Clay, greenish-gray.
468 -482	Sand.
482 -483	Limestone.
483 -490	Sand, silty, gray.
490 -498	Silt, gray.
498 -501	Clay, gray.
501 -502	Lignite.
502 -503.5	Clay, gray.
503.5-505	Lignite.
505 -510	Sand, fine, gray.
510 -520.5	Silt, gray.
520.5-522	Lignite.
522 -567	Silt, clayey, gray.
567 -571.5	Lignite.
571.5-582	Sand.
582 -588	Lignite.
588 -631	Silt, clayey, gray.
631 -638	Clay, gray.
638 -645	Sand, very fine to fine, gray.
645 -647	Clay, gray.
647 -654	Sand, very fine to fine, gray.
654 -664	Sand, very fine, and clay, gray.
664 -708	Sand, fine, gray.
708 -713	Clay, gray.
713 -732	Sand, fine, gray.
732 -744	Clay, gray.
744 -764	Lignite.
764 -782.5	Silt, gray.
782.5-787	Lignite.
787 -800	Silt, clayey, gray.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATGRAPHIC TESTHOLES

800 -803	Sand, silty, gray.
803 -807	Silt, gray.
807 -810	Sand, silty, gray.
810 -820	Silt, clayey, gray.

UND 75-16-1
144-93-08 BCB
TD: 502 feet

Depth (feet)	Lithologic Description
0 - 5	Silt, pale-yellow (2.5Y 7/4), calcareous.
5 - 9.5	Lignite.
9.5- 18	Clay, brown (7.5YR 4/2), light-gray (5Y 7/1 and N 6/0), noncalcareous.
18 - 25	Silt, gray (N 6/0), calcareous.
25 - 47	Sand, very fine, silty, calcareous.
47 - 60.5	Clay, silty, light-gray (5Y 6/1 and 5Y 7/1), noncalcareous.
60.5- 79.5	Lignite.
79.5- 90	Clay, gray (N 5/0), noncalcareous and lignite stringers.
90 -110	Silt, light-gray (N 7/0), calcareous.
110 -115	Lignite.
115 -142	Sand, very fine, silty, light-gray (5Y 7/1), calcareous, and clay, white (5Y 8/1), noncalcareous.
142 -159	Clay, light-gray (5Y 7/1), noncalcareous and silt, clayey, white (5Y 8/1), calcareous.
159 -212.5	Sand, medium, gray (5Y 6/1), calcareous.
212.5-217	Lignite.
217 -222	Sand, very fine, light-gray (5Y 7/1), calcareous.
222 -224	Clay, light-gray (5Y 7/1), noncalcareous.
224 -240	Sand, fine, light-gray (N 7/0), calcareous.
240 -243	Clay, gray.
243 -251	Lignite.
251 -351.5	Clay and silt, light-gray (5Y 7/1), calcareous.
351.5-354	Lignite.
354 -407	Clay, gray (N 4/0) to light-gray (5Y 7/1), noncalcareous.
407 -415	Lignite, black (10YR 2/1).
415 -423	Silt, sandy, gray (5Y 6/1), calcareous.
423 -424	Lignite.
424 -440	Silt to very fine sand, light-gray (5Y 7/1), calcareous.
440 -460	Clay, silty, gray (N 6/0), calcareous.
460 -463	Lignite, black (10YR 2/1), clay parting.
463 -468	Silt, light-gray (N 7/0 and N 6/0).
468 -469	Lignite.
469 -502	Silt, sandy, gray (5Y 6/1), calcareous.

UND 75-17-1
144-93-9 DDD
TD: 503 feet

Depth (feet)	Lithologic Description
0 - 12	Sand, fine to medium, pale-olive (5Y 6/3), calcareous.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

12 - 21	Clay, silty, pale-yellow (5Y 7/3), light-gray (N 6/0), noncalcareous.
21 - 27	Sand, fine, light-gray (N 7/0), noncalcareous.
27 - 41	Clay, gray (N 6/0), noncalcareous.
41 - 49	Sand, fine, silty, light-gray (N 7/0 and N 6/0), noncalcareous.
49 - 54	Lignite, black (10YR 2/1).
54 - 67	Clay, silty, light-gray (N 7/0), noncalcareous.
67 - 77	Lignite.
77 - 78.5	Clay, light-gray (5Y 7/1), noncalcareous.
78.5- 79.5	Lignite.
79.5- 92.5	Clay, light-gray (N 7/0), noncalcareous.
92.5- 93.5	Limestone, light-gray (N 7/0).
93.5-105.5	Silt and clay, light-gray (N 7/0 and N 6/0), calcareous.
105.5-107	Sandstone, fine grained, light-gray (N 7/0), calcareous.
107 -125	Silt, sandy, light-gray (N 7/0), slightly calcareous to noncalcareous.
125 -132.5	Lignite.
132.5-163	Clay, gray (N 6/0), noncalcareous.
163 -185	Sand, very fine, silty, light-gray (5Y 7/1), noncalcareous to calcareous.
185 -206	Clay, gray (N 6/0), noncalcareous.
206 -227	Lignite.
227 -231.5	Clay, silty, gray (N 6/0), noncalcareous.
231.5-233	Lignite.
233 -233.5	Clay.
233.5-234.5	Lignite.
234.5-256	Clay, gray (N 6/0), noncalcareous.
256 -260	Lignite.
260 -270.5	Silt and clay, light-gray (N 6/0 to 5Y 7/1), noncalcareous to calcareous.
270.5-272	Lignite.
272 -274	Silt, light-gray (5Y 7/1), calcareous.
274 -275	Lignite.
275 -305	Silt, white (5Y 8/1), calcareous.
305 -312	Clay, silty, greenish-gray.
312 -331	Sand, medium, light-gray (5Y 7/1), calcareous.
331 -336	Lignite.
336 -346	Silt, light-gray (5Y 7/1), noncalcareous.
346 -354	Clay, silty, light-gray (5Y 7/1), noncalcareous.
354 -362	Lignite, black (10YR 2/1).
362 -383	Clay, silty, gray (N 6/0), calcareous.
383 -384	Lignite.
384 -406	Clay, silty, gray (N 6/0), calcareous.
406 -440	Clay, silty to clay, gray (N 6/0) to light-greenish-gray (5GY 7/1), noncalcareous.
440 -441	Lignite.
441 -460	Silt, sandy, light-gray (N 7/0 and 5Y 7/1), noncalcareous.
460 -463.5	Clay, light-gray (N 7/0), calcareous.
463.5-467	Lignite.
467 -503	Clay, silty to clay, light-gray (N 7/0), calcareous.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

UND 75-18-1
144-94-23 ADD
TD: 462 feet

Depth (feet)	Lithologic Description
0 - 18	Silt, clayey, pale-yellow (2.5Y 8/4), mottled, noncalcareous.
18 - 20	Lignite.
20 - 44	Sand, fine, silty, gray (5Y 6/1), noncalcareous.
44 - 49	Lignite.
49 - 65	Sand, fine, gray (5Y 6/1), noncalcareous.
65 - 73	Lignite.
73 - 86	Sand, fine, gray (5Y 6/1), noncalcareous.
86 -113.5	Silt, clayey, and clay, gray (5Y 6/1), noncalcareous.
113.5-114.5	Lignite.
114.5-121.5	Silt, gray (5Y 6/1), noncalcareous.
121.5-123.5	Lignite.
123.5-131	Clay, silty, gray (5Y 6/1), noncalcareous.
131 -132	Lignite.
132 -136	Silt, gray (5Y 6/1), calcareous.
136 -138	Lignite.
138 -174.5	Sand, fine to medium, gray (5Y 6/1), calcareous to noncalcareous.
174.5-182	Lignite.
182 -189	Clay, light-greenish-gray (5GY 7/1), noncalcareous.
189 -210	Lignite.
210 -213	Clay, gray (5Y 6/1), noncalcareous.
213 -215	Lignite.
215 -220	Clay, gray (5Y 6/1), noncalcareous.
220 -233	Silt, clayey, gray (5Y 6/1), noncalcareous.
233 -249	Clay, slightly silty, light-gray (10YR 6/1), noncalcareous.
249 -263	Silt and clay, gray (10YR 6/1 and 5Y 6/1), calcareous to noncalcareous.
263 -268	Silt, gray (10YR 6/1), calcareous.
268 -291	Clay and silt, gray (5Y 6/1 and 10YR 6/1), and light-greenish-gray (5GY 7/1), noncalcareous.
291 -292	Siltstone.
292 -313	Sand, very fine, silty, light-gray (5Y 7/1), calcareous.
313 -315	Lignite.
315 -327	Sand, very fine, silty, light-gray (5Y 7/1), calcareous.
327 -331	Lignite.
331 -382.5	Sand, very fine, silty, light-gray (5Y 7/1), calcareous.
382.5-384	Sandstone, very fine, light-gray, calcareous.
384 -462	Sand, very fine, silty, and silt, light-gray (5Y 7/1), calcareous.

UND 75-19-1
144-94-16 AAA
TD: 500 feet

Depth (feet)	Lithologic Description
0 - 12	Silt and fine sand, mottled, yellow, noncalcareous.
12 - 14	Lignite.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

14 - 42	Clay, white (5Y 8/1) to pale-yellow (5Y 8/4), noncalcareous.
42 - 56	Silt, light-gray (10YR 7/1) to dark-brown (10YR 4/3), noncalcareous.
56 - 72	Sand, fine to very fine, pale-yellow (2.5Y 7/4) to light-yellowish-brown (2.5Y 6/4), noncalcareous.
72 -100	Silt, light-gray (5Y 7/1), noncalcareous.
100 -114	Lignite.
114 -138	Silt, light-gray (5Y 7/1), noncalcareous.
138 -174	Sand, fine, light-gray (5Y 7/1), noncalcareous.
174 -177.5	Lignite.
177.5-188	Silt and clay, light-gray (5Y 7/1), noncalcareous.
188 -190	Lignite.
190 -249.5	Silt and clay, white (5Y 8/1) to light-gray (5Y 7/1), noncalcareous becoming calcareous below 220 feet.
249.5-251.5	Lignite.
251.5-265.5	Silt and sand, very fine, gray (5Y 6/1), noncalcareous.
265.5-269	Lignite.
269 -276.5	Sand, very fine, to silt, light-gray (5Y 7/1 and 5Y 6/1), noncalcareous to calcareous.
276.5-277.5	Lignite.
277.5-307	Clay, light-gray (5Y 7/1 and 5Y 6/1), calcareous.
307 -308	Claystone concretion, light-gray (5Y 7/1), highly calcareous.
308 -327.5	Clay, light-gray (5Y 7/1), calcareous.
327.5-328.5	Lignite.
328.5-349	Clay, light-gray (5Y 7/1), noncalcareous to calcareous.
349 -350	Lignite.
350 -388.5	Clay, gray (5Y 6/1), noncalcareous to calcareous.
388.5-390.5	Lignite.
390.5-405	Clay, dark-gray (10YR 4/1), gray (5Y 5/1 and 5Y 6/1), and white (5G 8/1), noncalcareous to calcareous.
405 -410	Sand, very fine, light-gray (5Y 7/1), highly calcareous.
410 -432	Silt, to very fine sand, gray (5Y 5/1), white (5Y 8/1), noncalcareous.
432 -446.5	Clay, very dark-gray (10YR 3/1), noncalcareous.
446.5-464	Sand, very fine, silty, gray (5Y 6/1), calcareous.
464 -470.5	Clay, gray (5Y 6/1), noncalcareous.
470.5-478	Lignite.
478 -480	Clay, gray (5Y 6/1), noncalcareous.
480 -482	Lignite.
482 -500	Clay, gray (5Y 6/1), calcareous.

UND 75-20-1
144-94-21 CDC
TD: 750 feet

Depth (feet)	Lithologic Description
0 - 28	Silt and sand, very poorly sorted, calcareous, pale-olive (5Y 6/3).
28 - 60	Sand, silty, much detrital lignite, pale-yellow (5Y 7/4), calcareous.
60 -109.5	Till, gray (5Y 6/1), calcareous.
109.5-112	Lignite.
112 -165	Silt, gray (5Y 6/1), with interbedded clay, gray (5Y 6/1), calcareous.
165 -168	Limestone or siltstone.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

168 -215	Silt, light-gray (N 7/0, N 6/0, and 5Y 6/1), and light-greenish-gray (5GY 7/1), noncalcareous to calcareous with interbedded clay, gray (N 6/0), noncalcareous to calcareous, and lignite stringers.
215 -242	Sand, fine to very fine, silty, light-gray (N 7/0 and 5Y 6/1), noncalcareous.
242 -243.5	Lignite.
243.5-268	Silt, gray (N 6/0), noncalcareous, and sand, very fine to fine, light-greenish-gray (5GY 7/1), calcareous.
268 -269	Lignite.
269 -280	Silt, sandy, light-gray (N 7/0), calcareous.
280 -282	Limestone, light-gray.
282 -304	Silt, sandy, and silt, clayey, light-gray (N 7/0), calcareous.
304 -312	Lignite with clay partings.
312 -321	Silt, gray (5Y 6/1), and silt, clayey (N 6/0), calcareous.
321 -350	Sand, very fine, silty, light-gray (N 7/0 and N 6/0), calcareous.
350 -369	Silt, light-greenish-gray (5GY 7/1) to white (5Y 8/1), noncalcareous.
369 -380	Silt, mottled gray to white, noncalcareous, becomes sand, very fine, light gray (N 7/0), calcareous towards bottom of interval.
380 -400	Silt, gray to white, noncalcareous.
400 -465	Sand, very fine, silty, light-greenish-gray (5GY 7/1), light-gray (N 7/0), noncalcareous to calcareous.
465 -502	Alternating beds of silt, light-gray (5Y 7/1 and 5Y 6/1), highly calcareous, and sand, very fine, light-gray (N 7/0), calcareous.
502 -507	Silt, clayey, light-greenish-gray (5GY 7/1), noncalcareous.
507 -508	Lignite.
508 -519	Silt, mottled—gray to white, noncalcareous to calcareous.
519 -524	Sand, fine, silty, gray (N 6/0), calcareous.
524 -554	Silt, mottled—light-greenish-gray, gray, and white, noncalcareous to calcareous, lignite stringers.
554 -555	Sandstone or siltstone concretion.
555 -597.5	Sand, very fine, silty, gray (5Y 6/1), calcareous.
597.5-612.5	Lignite.
612.5-669	Sand, very fine, silty, light-gray (5Y 7/1), highly calcareous.
669 -719	Silt, mottled, light-gray, gray, and white, highly calcareous.
719 -736	Lignite, peaty, silty.
736 -750	Clay, silty, light gray.

UND 75-21-1
144-93-25 CAA
TD: 360 feet

Depth (feet)	Lithologic Description
0 - 18	Clay, silty, pale-yellow (5Y 8/3), gray (5Y 6/1), noncalcareous.
18 - 48	Silt, pale-olive (5Y 6/3), greenish-gray (5G 5/1), and light-gray (5Y 7/1), noncalcareous to slightly calcareous.
48 - 66.5	Sand, very fine to fine, light-gray (5Y 7/1), calcareous to noncalcareous.
66.5- 69.5	Lignite.
69.5- 95	Silt, white (5GY 8/1), light-gray (5Y 7/1), noncalcareous to slightly calcareous.
95 -106	Sand, very fine, silty, light-gray (5Y 7/1), calcareous.

APPENDIX III–Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

106 -112	Silt, white (5Y 8/1), calcareous.
112 -130	Silt, light-gray (5Y 7/1), highly calcareous.
130 -140	Clay, silty, light-gray (5Y 7/1), noncalcareous.
140 -161	Lignite.
161 -162	Silt, black (5Y 2.5/1).
162 -166.5	Lignite.
166.5-185	Silt, light-gray (5Y 7/1), calcareous.
185 -188	Sand.
188 -200	Silt, white (5Y 8/1), highly calcareous.
200 -203.5	Lignite.
203.5-234.5	Clay, silt, and very fine sand, white (5Y 8/1 and 5GY 8/1), highly calcareous.
234.5-238.5	Lignite with clay parting.
238.5-269	Silt, light-gray (5Y 7/1), calcareous.
269 -271	Lignite.
271 -276	Clay, white (5Y 8/1), highly calcareous.
276 -281	Lignite.
281 -287.5	Silt, greenish-gray (5GY 6/1), noncalcareous.
287.5-289	Lignite.
289 -324	Silt and clay, gray (5Y 6/1), calcareous.
324 -332	Sand, very fine, silty, light-gray (5Y 7/1 and N 7/0), calcareous.
332 -334	Clay.
334 -335	Lignite.
335 -341	Silt, dark-gray (5Y 4/1), noncalcareous.
341 -343	Clay, gray (5Y 6/1), noncalcareous.
343 -360	Silt and very fine sand, light-gray (5Y 7/1), calcareous.

UND 75-28-1
144-94-01 CCC
TD: 660 feet

Depth (feet)	Lithologic Description
0 - 27	Silt, sandy, light-yellowish-brown (2.5Y 6/4), slightly calcareous to noncalcareous.
27 - 49	Sand, fine to very fine, silty, light-brownish-gray (2.5Y 6/2), pale-yellow (5Y 7/3), and light-gray (5Y 7/1), noncalcareous.
49 - 51.5	Lignite.
51.5- 60	Sand, fine to very fine, silty, light-gray (5Y 7/1 and 5Y 7/2), white (5Y 8/1), calcareous to noncalcareous.
60 - 63	Limestone, light-gray (N 7/0).
63 -113	Sand, very fine to fine, gray (5Y 6/1), noncalcareous to calcareous.
113 -118	Clay, silty, white (5Y 8/2), noncalcareous.
118 -119.5	Limestone, light-gray (N 7/0).
119.5-132	Silt, clayey, white (5Y 8/1), noncalcareous.
132 -134.5	Lignite, black (10YR 2/1).
134.5-160.5	Silt and silt, sandy, light-gray (5Y 7/1), noncalcareous to calcareous.
160.5-164.5	Lignite.
164.5-166.5	Silt, gray (5Y 6/1), noncalcareous.
166.5-167.5	Lignite.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

167.5-188.5	Silt, silt, sandy, and very fine, silty sand, light-gray (N 7/0, 5Y 7/1, 5Y 6/1), calcareous.
188.5-189.5	Lignite.
189.5-210.5	Silt and clay, light-gray (N 7/0), calcareous to noncalcareous.
210.5-211.5	Limestone, light-gray (N 7/0).
211.5-215.5	Clay, light-gray (N 7/0), calcareous.
215.5-216.5	Lignite.
216.5-231	Clay, light-gray (N 7/0), white (5Y 8/1), slightly calcareous.
231 -232	Lignite.
232 -254	Clay and silt, light-gray (5Y 7/1 and 5Y 6/1), noncalcareous to calcareous.
254 -255	Lignite.
255 -274	Silt, clayey to sandy, dark-gray (5Y 4/1) to light-gray (5Y 7/1), calcareous to noncalcareous.
274 -276	Lignite.
276 -282	Silt, gray (5Y 5/1).
282 -283.5	Limestone, light-gray (N 7/0).
283.5-295.5	Silt, light-gray (5Y 7/1), noncalcareous to calcareous.
295.5-297	Siltstone, pale-yellow (2.5Y 7/4), noncalcareous.
297 -298.5	Silt, light-gray (5Y 7/1), calcareous.
298.5-299.5	Siltstone, pale-yellow (2.5Y 7/4), noncalcareous.
299.5-327	Silt, light-gray (5Y 7/1), noncalcareous.
327 -328	Limestone, light-gray (N 7/0).
328 -353	Silt, gray (5Y 6/1 to 5Y 5/1), noncalcareous.
353 -359	Lignite.
359 -365	Silt, very dark-gray (5Y 4/1), noncalcareous.
365 -366	Lignite.
366 -374	Clay and silt, light-gray (5Y 7/1), noncalcareous.
374 -385	Sand, very fine to fine, light-gray (5Y 7/1), noncalcareous.
385 -387.5	Sandstone, fine grained, light-gray (5Y 7/1), slightly calcareous.
387.5-398	Sand, fine, light-gray (5Y 7/1), noncalcareous.
398 -418	Clay, silty, white (5GY 8/1), silt, sandy, light-gray (5Y 7/1), calcareous, silt, light-gray (5Y 7/1), calcareous.
418 -419	Lignite.
419 -421	Clay, brown (10YR 5/3), noncalcareous.
421 -422	Lignite.
422 -510	Clay and silt, light-gray (5Y 7/1 and 5Y 6/1), white (5GY 8/1), calcareous, some lignite stringers.
510 -536	Sand, fine to very fine, light-gray (N 7/0), noncalcareous.
536 -538.5	Lignite.
538.5-549.5	Silt and clay, light-gray (5Y 7/1), calcareous.
549.5-550.5	Lignite.
550.5-553	Silt, clayey, light-gray (5Y 7/1), calcareous.
553 -558	Sand, very fine to fine, light-gray (N 7/0), noncalcareous.
558 -589	Silt and clay, light-gray (N 7/0), calcareous.
589 -607	Sand, very fine, salt and pepper colored, calcareous.
607 -619	Silt and clay, light-gray (N 7/0), calcareous.
619 -621.5	Lignite.
621.5-623	Clay.
623 -632	Lignite.
632 -633	Clay.
633 -635.5	Lignite.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

635.5-660	Sand, very fine, gray, salt and pepper colored, calcareous.

UND 75-22-2
143-94-01 ABB
TD: 160 feet

Depth (feet)	Lithologic Description
0 - 8	Sand, fine to medium, light-olive-gray (5Y 6/2), noncalcareous.
8 - 15	Silt, light-brownish-gray (10YR 6/2), noncalcareous.
15 - 23	Silt, light-gray (5Y 7/2), noncalcareous, laminated.
23 - 60	Sand, fine to very fine, light-olive-gray (5Y 6/2), noncalcareous, laminated, iron oxide stained.
60 - 75	Silt, sandy, light-olive-gray (5Y 6/2), noncalcareous, no sample return below 65 feet.
75 - 94	Lignite.
94 -101	Silt.
101 -104	Lignite.
104 -130	Silt.
130 -133	Siltstone or sandstone.
133 -148	Silt and clay.
148 -151.5	Lignite.
151.5-160	Silt.

UND 75-29-1
144-93-20 ADA
TD: 916 feet

Depth (feet)	Lithologic Description
0 - 10	Silt, sandy, pale-olive (5Y 6/3), noncalcareous to calcareous.
10 - 12	Lignite, very dark-grayish-brown (10YR 3/2).
12 - 55.5	Silt, sandy, and clay, silty, light-gray (N 7/0), noncalcareous.
55.5- 56.5	Lignite.
56.5- 70	Clay, light-gray (N 7/0), noncalcareous.
70 - 72	Sandstone, fine, light-gray (N 7/0), calcareous.
72 - 76	Silt, light-gray (N 7/0), noncalcareous.
76 - 84	Lignite.
84 - 89	Clay, gray (N 6/0), noncalcareous.
89 -122.5	Clay, light-gray (5Y 7/1), noncalcareous.
122.5-143	Lignite.
143 -146	Clay, light-gray (5Y 7/1), noncalcareous.
146 -148.5	Lignite.
148.5-176	Clay and silt, gray (5Y 5/1) to white (5Y 8/1), noncalcareous to calcareous.
176 -179	Lignite.
179 -213	Silt, light-gray (5Y 7/1), noncalcareous.
213 -214	Lignite.
214 -219	Silt, clayey, light-gray (5Y 7/1), calcareous.
219 -220.5	Lignite—poor samples below 220 feet.
220.5-233	Clay, gray.
233 -238	Sand, gray.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

238-243	Clay, silty, light-gray (5Y 7/1).
243-258	Sand.
258-264	Silt.
264-267	Lignite.
267-287	Clay, silty, light-gray (5Y 7/1), calcareous.
287-294	Lignite.
294-411	Silt and clay, gray (5Y 5/1) to light-gray (5Y 7/1) and light-greenish-gray (5GY 7/1).
411-427	Sand, very fine, light-gray (5Y 7/1), slightly calcareous.
427-445	Silt, dark-gray (5Y 4/1) to light-gray (5Y 7/1).
445-448	Lignite.
448-469	Silt and clay, light-gray (5Y 7/1), calcareous.
469-476.5	Lignite.
476.5-482.5	Silt.
482.5-484	Lignite.
484-512	Clay.
512-515	Lignite.
515-516	Clay.
516-517	Lignite.
517-529	Silt, light-gray (5Y 7/1).
529-540	Sand, very fine, light-gray (5Y 7/1), calcareous.
540-546	Silt.
546-555	Sand.
555-557	Silt.
557-573	Silt and very fine sand, interbedded.
573-577.5	Clay, silty.
577.5-579	Sand, fine, white.
579-580	Lignite.
580-581	Clay.
581-584	Sand, very fine, light-gray.
584-589	Clay, light-gray.
589-598	Sand, very fine, light-gray.
598-604	Silt, light-gray.
604-605	Lignite.
605-610	Clay, light-gray.
610-617	Sand, very fine, light-gray.
617-631	Silt and clay, light-gray.
631-633	Lignite.
633-660	Silt, light-gray.
660-661	Siltstone, pale-olive.
661-690	Sand, very fine to silt, light-gray.
690-706	Lignite.
706-718	Silt, light-gray.
718-724	Sand, very fine, light-gray.
724-729	Clay, light-gray.
729-743	Sand, very fine, light-gray.
743-793	Clay, silt, and very fine sand, light-gray.
793-795	Lignite.
795-798	Silt, light-gray.
798-816	Sand, very fine, light-gray.
816-825	Clay, light-gray.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

825 -849	Sand, very fine, silty, light-gray.
849 -861	Lignite.
861 -864.5	Clay, light-gray.
864.5-866	Lignite.
866 -874	Sand, very fine, light-gray.
874 -884	Clay, silty, light-gray.
884 -886.5	Lignite.
886.5-910	Clay and silt, light-gray.
910 -916	Sand, very fine, light-gray.

UND 75-30-3
144-94-07 DAA
TD: 1200 feet

Depth (feet)	Lithologic Description
0 - 17	Silt, sandy, olive (5Y 5/3), calcareous.
17 - 25	Sand, very fine, silty, pale-olive (5Y 6/3), calcareous.
25 - 27.5	Silt, very dark-brown (5Y 3/1), noncalcareous.
27.5- 30.5	Lignite.
30.5- 32	Clay.
32 - 35	Lignite.
35 - 52	Silt, light-gray (5Y 7/1), calcareous.
52 - 68	Lignite.
68 - 102	Silt, sandy, greenish-gray (5GY 6/1), light-gray (10YR 7/2) to dark-gray (5Y 4/1), noncalcareous.
102 - 130	Sand, fine to very fine, gray (5Y 5/1), noncalcareous.
130 - 134	Lignite.
134 - 146	Silt, white (5Y 8/1), calcareous, and silt, sandy, gray (5Y 5/1), noncalcareous.
146 - 148	Clay.
148 - 150	Sand, very fine, greenish-gray (5GY 6/1).
150 - 158	Silt, white (5Y 8/1), calcareous.
158 - 159	Lignite.
159 - 162	Silt, white (5Y 8/1), highly calcareous.
162 - 164	Peat, silty, dark-gray (5Y 4/1).
164 - 166	Silt, white (5Y 8/1), highly calcareous.
166 - 168	Peat, silty, black (5Y 2.5/1).
168 - 189	Silt, sandy, light-gray (5Y 7/1), calcareous.
189 - 204.5	Lignite.
204.5- 215.5	Silt, sandy, greenish-gray (5GY 6/1) to light-gray (5Y 7/1), noncalcareous.
215.5- 218.5	Lignite.
218.5- 233	Silt, gray (5Y 5/1).
233 - 236	Lignite.
236 - 242	Silt, gray (5Y 6/1), noncalcareous.
242 - 245	Sand, very fine, gray (5Y 6/1), calcareous.
245 - 253	Silt, gray (5Y 6/1), noncalcareous.
253 - 268	Sand, fine to very fine, light-gray (5Y 7/1), calcareous.
268 - 278	Silt, light-gray (5Y 7/1), calcareous.
278 - 279	Lignite.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

279 -317	Silt, light-gray (5Y 7/1 and N 7/0) and light-greenish-gray (5GY 7/1), calcareous to noncalcareous.
317 -318.5	Lignite.
318.5-353	Silt, light-gray (5Y 7/1), calcareous.
353 -356	Clay, light-greenish-gray (5GY 7/1), noncalcareous.
356 -359	Silt, dark-gray (5Y 4/1).
359 -366	Sand, very fine, silty, greenish-gray (5GY 5/1), noncalcareous.
366 -367	Sandstone.
367 -403	Sand, very fine, light-greenish-gray (5GY 7/1), and gray (N 7/0), noncalcareous, becomes silty downward.
403 -409	Lignite.

The lithologic descriptions from 409 to 1200 feet are from North Dakota State Water Commission testhole 4599.

409 -421	Siltstone, sandy, carbonaceous, brownish-gray.
421 -510	Shale, silty, dark-gray to greenish-gray; becomes very sandy with depth.
510 -592	Siltstone, carbonaceous, light-olive-gray; sandstone and carbonaceous shale interbeds.
592 -628	Shale, silty, sandy, carbonaceous, medium- to dark-gray.
628 -661	Siltstone, sandy, clayey, carbonaceous, light-olive-gray to brownish-gray.
661 -696	Sandstone, very fine grained, greenish-gray; becomes very carbonaceous with depth.
696 -712	Lignite, hard, black.
712 -765	Siltstone, shaly, sandy, variegated gray, green, and brown.
765 -782	Sandstone, fine-grained, carbonaceous, dark-greenish-gray.
782 -803	Siltstone, clayey, sandy, medium-gray.
803 -815	Sandstone, very fine grained, carbonaceous, dark-greenish-gray; shale interbeds.
815 -833	Lignite, hard, black.
833 -912	Shale, silty, medium-gray; thin sandstone interbeds.
912 -957	Siltstone, sandy, carbonaceous, brownish-gray; thin sandstone interbeds.
957 -1004	Sandstone, fine to medium-grained, grayish-green to dark-green.
1004 -1041	Sandstone, very fine grained, dark-greenish-gray; few indurated beds.
1041 -1142	Siltstone, clayey, sandy, variegated gray and green; thin sandstone interbeds.
1142 -1169	Siltstone, clayey, medium-gray to greenish-gray.
1169 -1200	Sandstone, very fine to fine-grained, carbonaceous, greenish-gray.

UND 75-31-1
145-92-28 DAA
TD: 420 feet

Depth (feet)	Lithologic Description
0 - 16	Silt, olive (5Y 5/4), gray (5Y 6/1), black (10YR 2/1), light-greenish-gray (5GY 7/1) and dark-gray (5Y 4/1), noncalcareous, limonite concretions in the first 5 feet.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

16 - 21.5	Lignite.
21.5- 22.5	Silt, black (10YR 2/1), noncalcareous.
22.5- 28	Lignite.
28 - 31	Silt, clayey, gray (N 6/0), noncalcareous.
31 - 51	Silt and silt, clayey, light-gray (5Y 7/1) and light-greenish-gray (5GY 7/1), noncalcareous, lignitized organic matter and pyrite nodules.
51 -112	Silt with sandy and clayey interbeds, light-gray (5Y 7/1) to greenish-gray (5GY 5/1), calcareous.
112 -132	Sand, very fine to fine, light-gray (5Y 7/1), calcareous.
132 -143	Silt, light-gray (5Y 7/1), noncalcareous.
143 -151	Sand, very fine, silty, light-gray (5Y 7/1), noncalcareous, laminated.
151 -155	Clay, light-gray (N 7/0), noncalcareous.
155 -157.5	Lignite.
157.5-159	Clay.
159 -164	Lignite.
164 -198	Silt, light-gray (N 7/0), noncalcareous to calcareous, and sand, very fine, (N 7/0), calcareous.
198 -199	Limestone, light-gray (N 7/0).
199 -201	Silt.
201 -202	Lignite.
202 -222	Silt, light-gray (N 7/0 and N 6/0), noncalcareous, and sand, very fine, silty, light-gray (N 7/0 and N 6/0), noncalcareous.
222 -224	Lignite.
224 -243	Silt to very fine sand, light-gray (N 7/0 and N 6/0), noncalcareous to calcareous.
243 -246.5	Lignite.
246.5-250	Clay, silty, dark-greenish-gray (5GY 4/1), noncalcareous.
250 -255	Silt, sandy, light-gray (N 7/0), calcareous.
255 -273	Sand, very fine, silty, light-gray (N 7/0), highly calcareous.
273 -316	Silt and very fine sand interbedded, dark-gray (5Y 4/1) to light-gray (N 7/0), noncalcareous to calcareous.
316 -319	Lignite.
319 -325	Silt, light-gray (N 7/0), noncalcareous to calcareous.
325 -359	Sand, very fine, silty, light-gray (N 7/0), calcareous.
359 -359.5	Lignite.
359.5-367.5	Silt, light-gray (N 7/0), noncalcareous.
367.5-369	Lignite.
369 -370.5	Silt.
370.5-372	Lignite.
372 -386	Silt, light-gray (5Y 7/1), calcareous.
386 -394	Sand, very fine, silty, light-gray (5Y 7/1), calcareous.
394 -395.5	Lignite.
395.5-420	Silt, light-gray (5Y 7/1), calcareous.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

UND 75-33-1
145-94-34 DDA
TD: 800 feet

Depth (feet)	Lithologic Description
0 - 5	Silt, sandy, light-yellowish-brown (2.5Y 6/4), calcareous.
5 - 15	Sand, very fine, light - yellowish - brown (2.5Y 6/4), calcareous and noncalcareous.
15 - 21	Lignite with clay partings.
21 - 40	Silt, light-gray (5Y 7/1), noncalcareous.
40 - 42	Siltstone or limestone.
42 - 54	Silt, light-gray (5Y 7/1), noncalcareous.
54 - 70	Lignite.
70 - 75	Clay, silty, gray.
75 - 76	Lignite.
76 - 84	Clay, silty, greenish-gray.
84 -106	Sand, very fine, silty, light-gray.
106 -111	Lignite.
111 -131	Clay, silty, gray.
131 -132	Lignite.
132 -135	Silt, brown.
135 -158	Silt, light-gray.
158 -165.5	Lignite.
165.5-172	Silt, greenish-gray.
172 -176	Clay, greenish-gray.
176 -178	Silt, light-gray.
178 -180	Limestone, light-gray (N 7/0).
180 -202	Silt, light-gray (5Y 7/1), calcareous.
202 -206	Lignite.
206 -221	Silt, sandy, light-gray (5Y 7/1), calcareous.
221 -223	Clay, light-gray (5Y 7/1), noncalcareous.
223 -235.5	Sand, very fine, silty, light-gray, calcareous, cemented from 230.5 to 232.5.
235.5-245	Silt, light-gray (5Y 7/1), calcareous.
245 -246	Lignite.
246 -291	Silt, light-gray (5Y 7/1), calcareous, with interbedded sand, very fine, silty, light-gray (5Y 7/1), calcareous.
291 -299	Clay, dark-gray, laminated.
299 -304	Silt, light-gray.
304 -306	Clay, gray.
306 -309	Lignite.
309 -315	Silt, brown, gray, and light-gray.
315 -316	Limestone, light-gray (N 7/0).
316 -319.5	Clay, silty, gray.
319.5-369	Silt, sandy, light-gray (5Y 7/1), calcareous with interbedded sand, very fine, light-gray (5Y 7/1), calcareous.

APPENDIX III—Continued
DESCRIPTIVE LOGS OF STRATIGRAPHIC TESTHOLES

369-376	Lignite.
376-379	Silt, light-gray (5Y 7/1), calcareous.
379-385	Sand, very fine, light-gray (5Y 7/1), noncalcareous.
385-433	Silt, light-gray (5Y 7/1), noncalcareous.
433-435.5	Sand, very fine, light-gray.
435.5-440	Silt, light-gray (5Y 7/1), noncalcareous.
440-441	Siltstone.
441-449	Silt, light-greenish-gray and gray.
449-450	Lignite.
450-454	Silt, gray (5Y 6/1), noncalcareous.
454-456	Siltstone, calcareous.
456-470	Silt, clayey, brown, light-greenish-gray and gray.
470-472	Limestone, light-gray.
472-486	Silt, clayey, brown, green, and gray.
486-490	Sand, very fine, silty, gray.
490-493	Silt, gray.
493-500	Sand, very fine, silty, gray.
500-528.5	Silt, sandy, gray and green.
528.5-531	Clay, green.
531-562	Silt, gray and dark-brown.
562-564.5	Limestone, light-gray.
564.5-566.5	Clay.
566.5-567.5	Lignite.
567.5-589.5	Silt, clayey, gray.
589.5-591.5	Lignite.
591.5-618	Silt, light-gray (5Y 7/1), calcareous, with sandy and clayey interbeds.
618-622	Clay, silty, light-gray (N 7/0), calcareous.
622-624	Sand, very fine, gray.
624-626	Silt, gray.
626-633	Sand, very fine, light-gray (5Y 7/1), calcareous.
633-636	Clay, silty, gray (N 6/0), noncalcareous.
636-637	Lignite.
637-661	Silt, white (5Y 8/1), and light-gray (5Y 7/1), highly calcareous.
661-668	Sand, very fine, silty, light-gray, highly calcareous.
668-670	Clay, silty, light-gray (5Y 7/1), calcareous.
670-682	Lignite.
682-684	Clay, light-gray (N 7/0), highly calcareous.
684-700	Silt, light-gray (5Y 7/1), highly calcareous.
700-703	Clay.
703-721	Silt, light-gray (5Y 7/1), highly calcareous.
721-730	Sand, very fine, silty, light-gray (5Y 7/1), highly calcareous.
730-733	Clay.
733-752	Silt, clayey, light-gray (5Y 7/1), highly calcareous, contains shell fragments.
752-767	Lignite.
767-800	Silt, light-gray (5Y 7/1), highly calcareous.

APPENDIX IV
DESCRIPTIONS OF CORE SAMPLES

UND 75-1-2C
143-93-07 CCC

Cored Interval 18-24	Total recovery 5.6'
18.0-18.9	Silt, slightly clayey, dark-gray (5Y 4/1), calcareous.
18.9-19.9	Silt, clayey, olive-brown (2.5Y 4/4), calcareous, laminated, mottled.
19.9-20.4	Silt, clayey, mottled, olive (5Y 4/4) to dark-yellowish-brown (10YR 3/4) and dark-gray (5Y 5/1), calcareous, contorted bedding.
20.4-21.3	Silt, clayey, gray (5Y 5/1), calcareous, nonlaminated, balls of silt 7 mm, upper and lower contacts are contorted.
21.3-22.3	Silt, olive-brown (2.5Y 4/4), calcareous, laminated, balls of silt slightly darker in color and less than 7 mm diameter.
22.3-22.6	Silt, as above—color change to gray (5Y 5/1).
22.6-23.1	Silt, as above—olive-brown (2.5Y 4/4).
23.1-23.25	Clay, olive (5Y 4/3), calcareous, laminated, organic matter.
23.25-23.4	Clay, dark-yellowish-brown (10YR 4/4), calcareous, laminated.
23.4-23.6	Silt, clay and sand—alternating, olive (5Y 5/4), calcareous, organic matter.

Cored Interval 45-50	Total recovery 5.0'
45.0-45.8	Silt, gray (5Y 6/1), some very fine sand interbedded, pieces of woody lignite (up to .25 feet long), calcareous.
45.8-46.6	Clay, greenish-gray (5GY 8/1), balls of clay darker color, pyrite nodules (marcasite).
46.6-47.1	Silt and clay interbedded, gray (5Y 6/1), laminated, calcareous, plant material.
47.1-47.35	Silt and lignite interbedded laminated, gray (5Y 6/1), contorted lower contact.
47.35-49.15	Clay, gray (N 5/), calcareous, laminated, clay balls, lignitic material becomes siltier downward.
49.15-50.0	Clay and lignite interbedded laminated, very dark-gray (5Y 3/1), calcareous.

Cored Interval 88-93	Total recovery 5.0'
88.0-88.15	Sand, very fine, silty, light-gray (5Y 6/1), calcareous.
88.15-88.3	Siltstone, soft, pale-olive (5Y 6/3), calcareous.
88.3-88.4	Clay, slightly silty, gray (5Y 6/1), calcareous.
88.4-91.5	Missing. Sand, gray (5Y 6/1), laminated, calcareous (only 0.2 feet recovered from this interval).
91.5-92.2	Silt, gray (5Y 6/1), laminated, calcareous.
92.2-92.4	Clay, silty, gray (5Y 6/1), calcareous, lignite fragments, clay balls.
92.4-92.7	Clay, gray (5Y 5/1), laminated, calcareous, clay balls, lignite stringers 2 mm thick.
92.7-93	Lignite and clay.

APPENDIX IV—Continued
DESCRIPTIONS OF CORE SAMPLES

UND 75-2-2
144-94-35 DAA

Cored Interval 58-63	Total recovery 5.3'
58.0-61.3	Silt and clay interbedded, overall dark-greenish-gray (5G 4/1), noncalcareous, organic fragments, pyrite nodules, clay and silt or both, laminated with laminations about 1-2 mm thick, silt is more gray (N 5/1), some very fine detrital lignite on the bedding planes.
61.3-62.2	Silt and clay and lignite interbedded, dark-brown (5Y 3/1), noncalcareous, silt balls, detrital lignite.
62.2-63.1	Silt and clay interbedded, dark-greenish-gray (5G 4/1), noncalcareous, clay and silt beds are laminated (1-mm thick). Organic fragments, fine detrital lignite.

UND 75-6-2C
145-93-16 CBB

Cored Interval 25-30	Total recovery 0'
	No core, gravel and sand washed out of core barrel.
Cored Interval 57-63.1	Total recovery 6.1'
57.0-59.15	Clay, greenish-gray (5GY 6/1), noncalcareous, organic matter, roots, stems, very platey looking clay when broken, chips of lignite.
59.15-59.5	Clay, very silty, greenish-gray (5GY 6/1), noncalcareous, nonlaminated.
59.5-61.8	Clay, dark-greenish-gray (5G 4/1), noncalcareous, nonlaminated, organic fragments throughout, slightly silty.
61.1-63.1	Silt, grading to very fine sand, greenish-gray (5G 5/1), noncalcareous, nonlaminated, chips of lignite, fragments of organic matter.
Cored Interval 72-77	Total recovery 4.8'
72.0-72.2	Clay, greenish-gray (5GY 5/1), noncalcareous, nonlaminated.
72.2-72.4	Clay silty, greenish-gray (5GY 6/1), slightly calcareous, nonlaminated balls of silt.
72.4-72.6	Clay, greenish-gray (5GY 5/1), noncalcareous, nonlaminated.
72.6-74.2	Silt, dark-gray (5Y 5/4), calcareous, laminated, silt balls, pyrite nodules.
74.2-74.4	Clay, greenish-gray (5GY 5/1), slightly calcareous, nonlaminated, silt balls.
74.4-75.2	Silt, clayey, laminated (finely), slightly calcareous, silt balls, dark-gray (5Y 5/4).
75.2-75.8	Silt to very fine sand, dark-gray (5Y 5/4), calcareous, laminated, laminations are lighter-gray.
75.8-76.4	Silt, clayey, dark-gray (5Y 5/4), slightly calcareous, laminated, laminations are light-gray (5Y 7/1).
76.4-76.8	Sand, very fine to silt, dark-gray (5Y 5/4), slightly calcareous, laminated.

APPENDIX IV—Continued
DESCRIPTIONS OF CORE SAMPLES

Cored Interval 100-105	Total recovery 5.0'
100-105	Sand, medium to fine, dark - greenish-gray (5GY 4/1), noncalcareous, laminated, detrital lignite highlighting the laminations. Sand seems to be finer at 100' and gravel to medium sandy at 105', quartz and amphibole, and specks of biotite.
Cored Interval 135-140	Total recovery 5.0'
135-140	Sand, medium and fine very dark - gray (5Y 3/1), quartz, amphibole, mica, noncalcareous, very slightly laminated.
137-138	A few clay balls found.
Cored Interval 153-158	Total recovery 4.3'
153.0-155.0	Sand, medium to fine, greenish-gray (5G 5/1), salt and pepper pyrite nodule, noncalcareous, crossbedded, quartz, amphibole, mica.
155.0-155.1	Lignite.
155.1-156.0	Sand, as above.
156.0-156.3	Silt, clayey, brownish-gray (5Y 4/1), laminated organic matter.
156.3-157.3	Sand, medium to fine, greenish-gray (5G 5/1), noncalcareous, crossbedded, quartz, amphibole, mica, pyrite nodules.
Cored Interval 188-193	Total recovery 5.7'
188.0-190.3	Sand, fine, gray (5Y 5/1), noncalcareous, slightly laminated, pyrite nodules, chips of organic fragments.
190.3-190.5	Clay, silty, gray (5Y 4/1), noncalcareous, laminated, silt balls.
190.5-193.7	Sand, fine to medium, slightly laminated, noncalcareous, pyrite nodules, organic fragments, gray (5Y 5/1).
UND 75-13-3C **145-93-21 DAA**	
Cored Interval 30-40	Total recovery 6.0'
30.0-31.5	Sand, medium, olive (5Y 4/4), quartz, feldspar amphibole (glacial sand).
31.5-32.0	Pebbles and cobbles of granitic rock types, Knife River flint, ironstone concretions and fine grained sandstone.
32.0-33.2	Sand, medium, olive (5Y 4/4), quartz, feldspar, amphibole.
33.2-34.5	Sand, medium, olive-yellow (5Y 5/8), laminated, iron stained, quartz, amphibole, feldspar.
34.5-36.0	Sand, medium, gray and olive-yellow (5Y 4/1 and 5Y 6/8).
Cored Interval 62-66	Total recovery 1.5'
62.0-63.5	Lignite, hard, black, with small thin veins of hematite.

APPENDIX IV—Continued
DESCRIPTIONS OF CORE SAMPLES

Cored Interval 66-74	Total recovery 7.0'
66.0-73.0	Lignite, black to dark-brown, hard blocky.
Cored Interval 74-80	Total recovery 6.0'
74.0-78.1	Lignite, fairly hard, some iron staining.
78.1-78.6	Clay, very dark-gray (5Y 3/1), with organic stringers (laminated), noncalcareous.
78.6-79.6	Lignite (broken chunks).
79.6-80.0	Clay, gray (5Y 5/1), laminated, noncalcareous.
Cored Interval 80-88.5	Total recovery 7.5'
80.0-80.5	Silt, clayey with thin stringers of lignite, laminated gray (5Y 5/1), noncalcareous.
80.5-81.1	Clay, silty, gray (5Y 5/1).
81.1-81.8	Silt, slightly clayey, gray (5Y 5/1), not calcareous, becomes sandy near the bottom, not laminated.
81.8-85.5	Silt and very fine sand, gray (5Y 5/1), noncalcareous.
85.5-85.7	Clay, silty, gray (5Y 5/1), noncalcareous.
85.7-86.7	Silt and very fine sand, gray (5Y 5/1), noncalcareous, laminated.
86.7-86.8	Clay, mottled, gray and light-gray (5Y 5/1 and 5Y 7/1).
86.8-87.5	Silt to very fine sand interbedded with clay, gray (5Y 5/1), clay is white (5Y 8/1).
UND 75-16-3C **144-93-08 BCB**	
Cored Interval 15-20	Total recovery 5.0'
15.0-15.9	Interbedded silt and clay beds .1 thick (approx.) silt, olive (5Y 4/3), clay, olive-gray (5Y 4/2), rootlets filled with limonite or iron. Appears slightly fractured. Both silt and clay laminated with organic impression on fresh broken surfaces, noncalcareous.
15.9-16.3	Clay, laminated, noncalcareous, olive-gray (5Y 4/2), iron deposits on bedding surface, much organic matter, peaty, clay is fractured.
16.3-17.5	Clay, laminated, noncalcareous, dark-brown (10YR 3/3) and olive-gray (5Y 4/2), much organics.
17.5-17.7	Lignite.
17.7-17.9	Clay, very dark-gray (5Y 3/1), laminated, noncalcareous, 1 mm-thick stringers of lignite.
17.9-20.0	Clay, gray (5Y 5/1), laminated, noncalcareous, laminae 3-4 mm thick, clay balls, a few lighter bands of clay, olive (5Y 5/3) at 19.4'.
Cored Interval 30-36	Total recovery 6.0'
30.0-33.0	Silt, gray (5Y 5/1) overall color, laminated, calcareous, laminae being 3 mm thick alternating in color from light-gray (5Y 6/1), more silty to dark-gray (5Y 4/1), more clayey, uniform core (one piece).

APPENDIX IV—Continued
DESCRIPTIONS OF CORE SAMPLES

33.0-33.3	Sand, very fine, laminated, calcareous, dark-greenish-gray (5GY 4/1).
33.3-34.65	Silt, dark-greenish-gray (5GY 4/1), calcareous, laminated, laminae 1 mm thick.
34.65-34.8	Sand, very fine, dark-greenish-gray (5GY 4/1), laminated and calcareous.
34.8-36.0	Silt, dark-greenish-gray (5GY 4/1), laminated, calcareous, laminae 1-2 mm thick.
Cored Interval 50-60	Total recovery 6.0'
	Clay, dark - gray (5Y 4/1), slightly calcareous, laminated, carbonaceous material less than 1 mm thick. Bands of clay, light-gray (5Y 6/1), silty, 1/10 of a foot thick throughout the length of core. The last foot has bands of dark brown organic rich clay (10YR 3/1) about 4 mm thick. Lignite stringer 2 mm thick at 59.2'.
Cored Interval 95-100	Total recovery 4.4'
95.0-96.4	Alternating thin beds of sand, very fine, dark-greenish-gray (5GY 4/1), slightly calcareous, and clay, dark-gray (5Y 4/1), and lignite stringer < 2 mm thick.
96.4-98.4	Clay, dark-gray (5Y 4/1), slightly silty, noncalcareous, laminated, thin lignite stringers.
98.4-99.4	Clay as above; with thin bands of slightly silty clay, pale-yellow (5Y 7/3).
UND 75-17-2C **144-93-09 DDD**	
Cored Interval 12-17	Total recovery 4.1'
12.0-12.3	Silt, clayey, olive (5Y 5/3), slightly calcareous, laminated, leaf impressions, iron stained.
12.3-12.6	Clay, dark-gray (5Y 4/1), noncalcareous, laminated as above.
12.6-12.9	Silt, clayey, olive (5Y 5/3), slightly calcareous, laminated as above.
12.9-15.5	Clay, dark-olive-gray (5Y 3/2), noncalcareous, laminated as above.
15.5-15.8	Clay, dark-gray (5Y 4/1), noncalcareous, nonlaminated.
15.8-16.1	Clay, dark-olive (5Y 3/2), noncalcareous, laminated, leaf and stem impressions replaced by iron.
Cored Interval 27-32	Total recovery 5.0'
27.0-27.7	Absent, sand, no recovery.
27.7-27.75	Sand, fine, gray (5Y 4/1), noncalcareous.
27.75-27.85	Silt, gray (5Y 5/1), noncalcareous.
27.85-28.0	Clay, slightly silty, gray (5Y 5/1), noncalcareous.
28.0-28.33	Silt, coarse to very fine sand, dark-gray (5Y 4/1), organic stringers, noncalcareous, pyrite nodules.
28.33-29.4	Clay, very slightly silty, noncalcareous, no lamination, pyrite nodules.

APPENDIX IV—Continued
DESCRIPTIONS OF CORE SAMPLES

29.4-30.15	Clay, slightly silty, finer than above, pyrite nodules, gray (5Y 5/1), noncalcareous, nonlaminated.
30.15-31.3	Clay, silty, noncalcareous, nonlaminated, dark-gray (5Y 4/1).
31.3-31.63	Clay, silty, as above with lignite interbeds.
31.63-32.0	Silt, gray (5Y 4/1), noncalcareous, nonlaminated.
Cored Interval 55-60	Total recovery 6.0'
55.0-57.2	Clay and silt interbedded, dark-gray (5Y 4/1), noncalcareous, laminated, chunks of peaty lignite throughout, pyrite crystals.
57.2-58.4	Silt, clayey, gray (5Y 5/1), noncalcareous, laminated, pyrite crystals.
58.4-58.9	Clay, dark-greenish-gray (5GY 4/1), noncalcareous.
58.9-59.5	Silt and clay interbedded, gray (5Y 5/1), noncalcareous.
59.5-60.8	Clay, gray (5Y 5/1), noncalcareous, lignite fragments, slightly laminated.
60.8-61.0	Silt and clay interbedded, gray (5Y 5/1), noncalcareous, lignite fragments.
Cored Interval 80-85	Total recovery 3.0'
80.5-82.5	Clay and interbedded clay, silty, dark-gray (5Y 4/1), organic matter, few chips.
82.5-83.5	Siltstone, light-brownish-gray (2.5Y 6/2). Abandoned rest of core because of siltstone.
Cored Interval 115-120	Total recovery 3.3'
115.0-115.5	Sand, very fine to fine, laminated—lignite fragments define the laminations, gray (5Y 6/1), noncalcareous.
115.5-116.3	Silt, gray (5Y 6/1), laminated as above, noncalcareous.
116.3-116.9	Clay, dark-gray (5Y 4/1), laminated, slightly silty, noncalcareous.
116.9-117.35	Clay, alternating bands of color from white (5Y 8/1) to gray (5Y 6/1), laminated, noncalcareous.
117.35-117.55	Siltstone, olive (5Y 6/3), noncalcareous, nonlaminated.
117.55-118.1	Clay, laminated with alternating bands of color as above, noncalcareous.
118.1-118.4	Silt, light-greenish-gray (5GY 7/1), noncalcareous chunks of lignite.
Cored Interval 138-143	Total recovery 5.0'
138.0-138.8	Clay, greenish-gray (5G 5/1), with chunks of coal, noncalcareous.
138.8-139.4	Clay, silty, slightly laminated, greenish-gray (5G 5/1), noncalcareous.
139.4-140.3	Silt, dark-greenish-gray (5G 4/1), noncalcareous, laminated.
140.3-140.8	Clay, dark-greenish-gray (5G 4/1), laminated, noncalcareous.
140.8-142.2	Silt, clayey, laminated, light-greenish-gray (5GY 7/1), some interbedded clay.
142.2-142.6	Lignite, peaty, woody.

APPENDIX IV—Continued
DESCRIPTIONS OF CORE SAMPLES

142.6-143.7	Clay, silty, light - greenish-gray (5GY 7/1), noncalcareous, laminated.
143.7-144.3	Clay, organic rich, black (5Y 2.5/2), laminated-organic matter, noncalcareous.
Cored Interval 175-180	Total recovery 0.0'
	No core.
Cored Interval 200-205	Total recovery 5.15'
200-205	Clay, gray (5Y 4/1), noncalcareous, laminated, 2 mm thick, slightly silty; some laminations are more silty, light-gray (5Y 7/1), and about 4 mm thick.
205-205.15	Lignite.
Cored Interval 235-240	Total recovery 5.4'
235.0-235.8	Silt, gray (5Y 5/1), laminated, noncalcareous, balls of clay inside core.
235.8-237.2	Sand, very fine, noncalcareous, gray (5Y 6/1), laminated, detrital lignite highlighting the laminations, pyrite nodules.
237.2-237.6	Sand, very fine, grading to silt, laminated, gray (5Y 6/1), noncalcareous, grading to clay, gray (5Y 5/1), noncalcareous, slightly laminated.
237.6-239.55	Clay, gray (5Y 5/1, 5Y 6/1, 5Y 7/1), different bands of color throughout.
239.55-239.65	Siltstone, very pale-brown (10YR 7/4), very fine, nonlaminated, noncalcareous.
239.65-240.1	Clay, gray (5Y 5/1), nonlaminated, noncalcareous, chunks of lignite, balls of silt.
240.1-240.3	Silt, light-gray (5Y 7/1), laminated, calcareous.
240.3-240.4	Clay, gray (5Y 5/1), nonlaminated, calcareous.
UND 75-18-2C **144-92-03 ADD**	
Cored Interval 15-20	Total recovery 5.0'
15.0-17.0	Silt, bluish-gray (5B 6/1) (moist), laminated, concretions of organic matter defining laminations, noncalcareous.
17.0-17.7	Broken pieces of core-mixture of silt, bluish-gray and clay, silty, bluish-gray.
17.7-18.8	Clay, bluish-gray (5B 6/1) (moist), no bedding, very plastic, noncalcareous.
18.8-19.2	Lignite, very hard, black.
19.2-20.0	Clay, bluish-gray (5B 6/1) (moist), no bedding, lignite (organic) fragments within clay, clay slightly silty, noncalcareous.

APPENDIX IV–Continued
DESCRIPTIONS OF CORE SAMPLES

Cored Interval 35-40	Total recovery 5.0'
35.0-36.3	Sand, very fine to fine, bluish-gray (5B 5/1) (moist), slight crossbedding with organic matter, noncalcareous, uniform throughout.
36.3-36.6	Clay, pale-olive (5Y 6/3), nonbedded, noncalcareous, nonplastic, slightly silty.
36.6-40.0	Sand, fine to medium, bluish-gray (5B 5/1) (moist), quartz, feldspar, small percent amphibole, nonbedded, uniform throughout, noncalcareous.

Cored Interval 82-92	Total recovery 7.7'
82.0-83.5	Sand, very fine to silt, bluish-gray (5B 5/1) (moist). Laminated, detrital lignite laminae, noncalcareous, uniform.
83.5-83.9	Clay, bluish-gray (5B 5/1) (moist), nonlaminated, noncalcareous, small balls (globs) of silt mixed throughout.
83.9-87.8	Sand, very fine, bluish-gray (5B 5/1) (moist). Laminated with detrital lignite, noncalcareous.
87.8-88.0	Clay, bluish-gray (5B 5/1) as above. Small balls of silt mixed throughout.
88.0-88.7	Sand, very fine to silt, laminated with lignite (organic matter), noncalcareous.
88.7-89.7	Core broken–mixture of silt and very fine sand, bluish-gray (5B 5/1), and clay. Silt mixed with balls of clay, clay mixed with balls of silt, as above.

Cored Interval 105-110	Total recovery 2.0'
105.0-105.4	Clay, very dark-gray (5Y 3/1), noncalcareous, nonlaminated.
105.4-105.8	Silt, clayey, dark-grayish-brown (2.5Y 4/2).
105.8-107.0	Clay, slightly silty, greenish-gray (5G 5/1), nonlaminated, noncalcareous, contains lignite fragments. Core was stuck in core barrel probably because core bit was worn down and cutting too large of a core. Core was almost totally destroyed in getting it out. The remaining few good pieces dried out in the 1½-hour long battle. Only 2 feet of salvagable core.

Cored Interval 125-130	Total recovery 4.5'
125.0-128.0	Clay, light-greenish-gray (5GY 8/1), noncalcareous, organic stems, bank leaves, lignite fragments.
128.0-129.5	Lignite, brown, friable. Core stuck in core barrel and was broken in pieces to remove it.

Cored Interval 165-170	Total recovery 5.0'
165.0-166.0	Sandstone, calcium carbonate cemented, fine grain, broken in chunks, white (2.5Y 8/1).

APPENDIX IV—Continued
DESCRIPTIONS OF CORE SAMPLES

166.0-167.8	Sandstone, calcium carbonate cemented as above, one solid chunk, grading into sand, gray (5Y 6/1), very fine to fine, laminated, detrital lignite.
167.8-168.2	Sand, very fine to fine, gray (5Y 6/1), highly carbonate, laminated with detrital lignite.
168.2-170.0	Clay, Fe concretions pebble size, sand as above laminated, all mixed when being removed from core barrel. Core stuck in barrel, had to drop drill stem down it to remove core.

UND 75-19-2C
144-94-16 AAA

Cored Interval 20-25.8	Total recovery 5.8'
20.0-21.45	Clay, silty, olive-gray (5Y 5/2), slightly mottled in color with yellow nodules (fresh), grade more silty downward, noncalcareous, organic matter-leaves, stems.
21.45-21.7	Silt, pale olive (5Y 6/3) (fresh), slightly clayey, noncalcareous, gypsum crystals.
21.7-23.0	Clay, silty, olive-gray (5Y 7/2) (fresh), NO, bedding grades more silty downward, noncalcareous.
23.0-23.8	Clay, as above, with dark specks, organic or possibly grease from rig? grades to a silt at 23.8, pale olive (5Y 6/3) (fresh), gypsum crystals, noncalcareous.
23.8-24.9	Silt, olive (5Y 5/3), small nodules of iron, noncalcareous, grades to very fine sand.
24.9-25.8	Sand, very fine to silt, olive (5Y 5/3), noncalcareous.
Cored Interval 40-50	Total recovery 10.0'
40.0-41.0	Clay, olive-gray (5Y 5/3) (moist), noncalcareous, bedded with silt, yellowish-brown (10YR 5/4) (moist).
41.0-41.1	Sand, fine to very fine, light olive-brown (2.5Y 5/4) (moist), noncalcareous.
41.1-42.0	Clay and interbedded silt and very fine sand, colors as above, noncalcareous.
42.0-42.2	Sand, very fine, olive-yellow (2.5Y 6/4).
42.2-42.8	Silt, yellowish-brown (10YR 5/4) (moist), and interbedded sand, very fine, colors as above.
42.8-44.6	Interbedded silts and clays, yellowish-brown (10YR 5/4) (moist), olive (5Y 5/3) (moist), iron concretions (nodules) 5 cm diameter, noncalcareous. The core tends to break apart at the sand and silts.
44.6-45.2	Sand, very fine, olive-yellow (2.5Y 6/8) (moist), and interbedded silts as above.
45.2-46.2	Interbedded clay, grayish-brown (2.5Y 5/2) (moist), silt, yellowish-brown (10YR 5/4), sand, very fine, olive-yellow (2.5Y 6/4), sand beds are only a few cm thick.
46.4-50.0	Silt, clayey, very dark grayish-brown (2.5Y 3/2), some small chunks (1-2 cm diameter) of organic material (dark brown), interbedded with sand, very fine, light olive-brown (2.5Y 5/6), 2 cm thick, spaced about 20 cm apart. All noncalcareous.

APPENDIX IV—Continued
DESCRIPTIONS OF CORE SAMPLES

Cored Interval 55-60	Total recovery 5.0'
55.0-57.0	Sand, dark - brown (10YR 3/3) (moist), fine to very fine, interbedded with silt, gray (10YR 5/1), coarse, and organic leaf impressions and lignite, silt, yellowish-brown (10YR 5/4).
57.0-60.0	Sand, fine to very fine, dark-brown (10YR 3/3) (moist), cross bedded, detrital lignite, organic material.
Cored Interval 65-73	Total recovery 8.0'
65.0-67.6	Sand, fine grained, loosely cemented, brown (10YR 3/3), fossiliferous (leaf impressions) cross bedded.
67.6-72.8	Clay, silty, olive (5Y 5/2).
72.8-73.0	Clay, silty, greenish-gray (5GY 5/1).
Cored Interval 80-90	Total recovery 11.0'
80.0-91.0	Silt, gray (N 5/), noncalcareous, pyrite crystals, lignite fragments, uniform interval.
Cored Interval 95-100	Total recovery 4.3'
95.0-98.0	Silt, greenish-gray (5G 5/1), pyrite crystals, slightly laminated, slightly clayey.
98.0-99.3	Lignite.
UND 75-28-4C **144-94-01 CCC**	
Cored Interval 20-25	Total recovery 5.0'
20.0-23.5	Sand, medium, olive-yellow (5Y 6/5), quartz, feldspar, amphibole, no bedding, noncalcareous.
23.5-25	Sand, medium as above, interbedded with peaty lignite, sand is slightly iron stained.
Cored Interval 70-77.5	Total recovery 7.05'
70.0-70.4	Clay, olive (5Y 4/3), noncalcareous.
70.4-71.2	Clay, gray (5Y 6/1), noncalcareous, interbedded with clay, light-brownish-gray (2.5Y 6/2), calcareous, and clay, white (5Y 8/1), calcareous, less than 2 mm thick.
71.2-71.6	Lignite.
71.6-71.75	Silt, very dark-brown (10YR 2/2).
71.75-73.15	Clay, dark-gray (5Y 4/1), slightly calcareous, lignite stringers.
73.15-73.65	Silt, very dark - grayish-brown (2.5Y 3/2), noncalcareous, interbedded clay, grayish-brown (2.5Y 5/2).
73.65-74.15	Sand, fine, very dark-grayish-brown (2.5Y 3/2), noncalcareous, rootlets turned to peat.
74.15-74.45	Sand, fine, olive-gray (5Y 4/2), noncalcareous.
74.45-77.05	Sand, fine, greenish-gray (5GY 5/1), peaty rootlets.

APPENDIX IV—Continued
DESCRIPTIONS OF CORE SAMPLES

Cored Interval 100-105	Total recovery 5.75'
100-105.75	Sand, fine, slightly calcareous, dark-greenish-gray (5GY 4/1).

Cored Interval 142-150.5	Total recovery 8.5'
142.0-144.6	Clay, silty, greenish-gray (5GY 7/1), calcareous, laminated.
144.6-145.5	Silt and clay interbedded, greenish-gray (5GY 7/1), calcareous, laminated.
145.5-146.1	Clay, dark-greenish-gray (5GY 4/1), interbedded with clay, light-gray (5Y 7/1); both clays calcareous and laminated.
146.1-149.0	Silt and clay interbedded, greenish-gray (5GY 7/1), calcareous, laminated, clay balls, a 3 mm siltstone.
149.0-150.5	Silt to very fine sand, greenish-gray (5GY 7/1), calcareous, laminated.

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Cored Interval 10-20	Total recovery 10.0'
10.0-15.3	Clay, silty, calcareous, color bands, gray (5Y 5/1) and brownish-yellow (10YR 6/8).
15.3-20.0	Clay, silty, gray (5Y 5/1), calcareous with alternating thin beds (up to .5 feet) of sand, very fine, calcareous, pale-olive (5Y 6/3), with organic material.

Cored Interval 20-27	Total recovery 7.0'
20.0-24.8	Sand, very fine, silty, calcareous, laminated with lignitized organic matter, color bands of brownish-yellow (10YR 6/8), pale-olive (5Y 6/3), and gray (5Y 5/1).
24.8-27.0	Clay, silty, black (5Y 2.5/1), noncalcareous, organic rich, lignitized organic material.

Cored Interval 42-52	Total recovery 9.7'
42.0-43.35	Thinly interbedded silt, clayey, dark-gray (5Y 4/1), noncalcareous and lignite.
43.35-45.9	Silt, clayey, calcareous, dark-gray (5Y 4/1), lignitized organic matter.
45.9-47.15	Silt, sandy, soft, gray (5Y 5/1), calcareous, lignitized organics.
47.15-48.8	Sand, very fine, silty, calcareous, dark-gray (5Y 4/1).
48.8-51.7	Silt, clayey, gray (5Y 5/1), calcareous, lignitized organic material.

Cored Interval 70-78	Total recovery 8.0'
70.0-70.65	Lignite, black (5Y 2.5/1).
70.65-71.05	Silt, lignitic, dark-reddish-brown (5YR 2.5/2), noncalcareous.
71.05-74.35	Silt, slightly clayey, grayish-brown (2.5Y 5/2), noncalcareous, lignitized organic material.
74.35-78.0	Clay, silty, greenish-gray (5GY 5/1), noncalcareous.

APPENDIX IV–Continued
DESCRIPTIONS OF CORE SAMPLES

Cored Interval 95-102.65 Total recovery 7.65'

95.0-100.55	Silt, sandy, noncalcareous, dark-gray (5Y 4/1), laminated, contains small pale-yellow sand clasts.
100.55-100.8	Sand, very fine, gray (5Y 5/1), noncalcareous.
100.8-100.95	Silt, as above.
100.95-102.65	Sand, as above.

Cored Interval 120-125 Total recovery 5.3'

120.0-125.3	Sand, fine grained, dark-greenish-gray (5GY 4/1), noncalcareous.

Cored Interval 160-169.3 Total recovery 9.3'

160.0-160.9	Clay, black (5Y 2.5/2), noncalcareous, laminated.
160.9-161.4	Silt, dark-olive (5Y 3/2), noncalcareous.
161.4-161.45	Pyrite or marcasite nodule.
161.45-162.5	Lignite.
162.5-163.2	Silt with thin stringers of lignite throughout, noncalcareous, gray (5Y 6/1). Pyrite or marcasite concretion at the bottom of interval .05 feet thick.
163.2-169.3	Silt, gray (5Y 5/1), calcareous, lignitized organic material.

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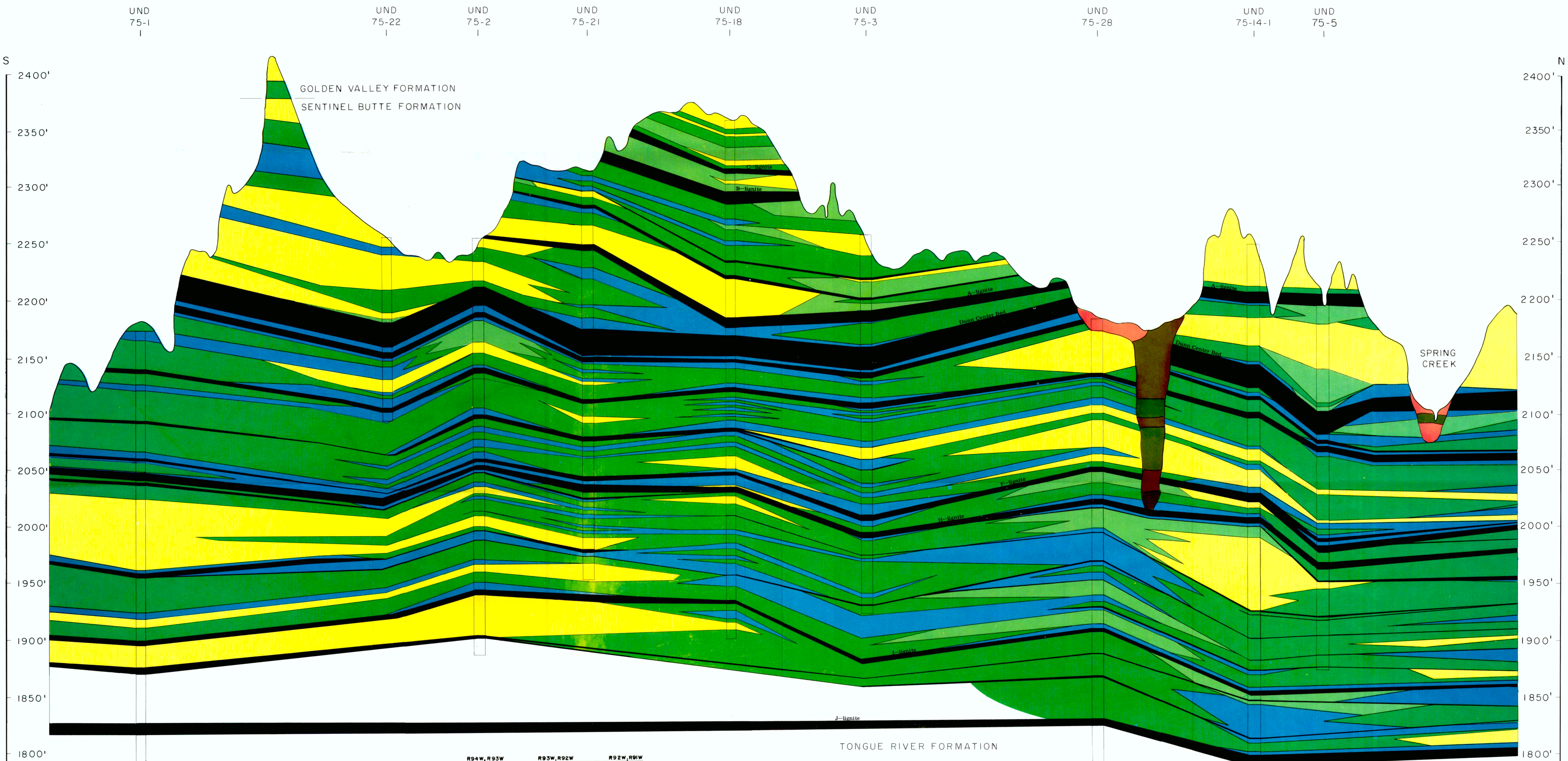
Plate 1

North-South Stratigraphic Cross Section of the Sentinel Butte Formation

Dunn Center Area

South Half



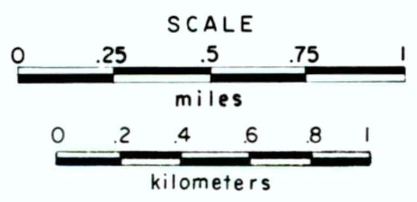
EXPLANATION

Coleharbor Group

🟥 Silt and clay
🟩 Sand and gravel
🟫 Pebble-loam

Sentinel Butte and Golden Valley Formations

🟦 Clay
🟩 Silt
🟩 Silty sand
🟨 Sand
⬛ Lignite



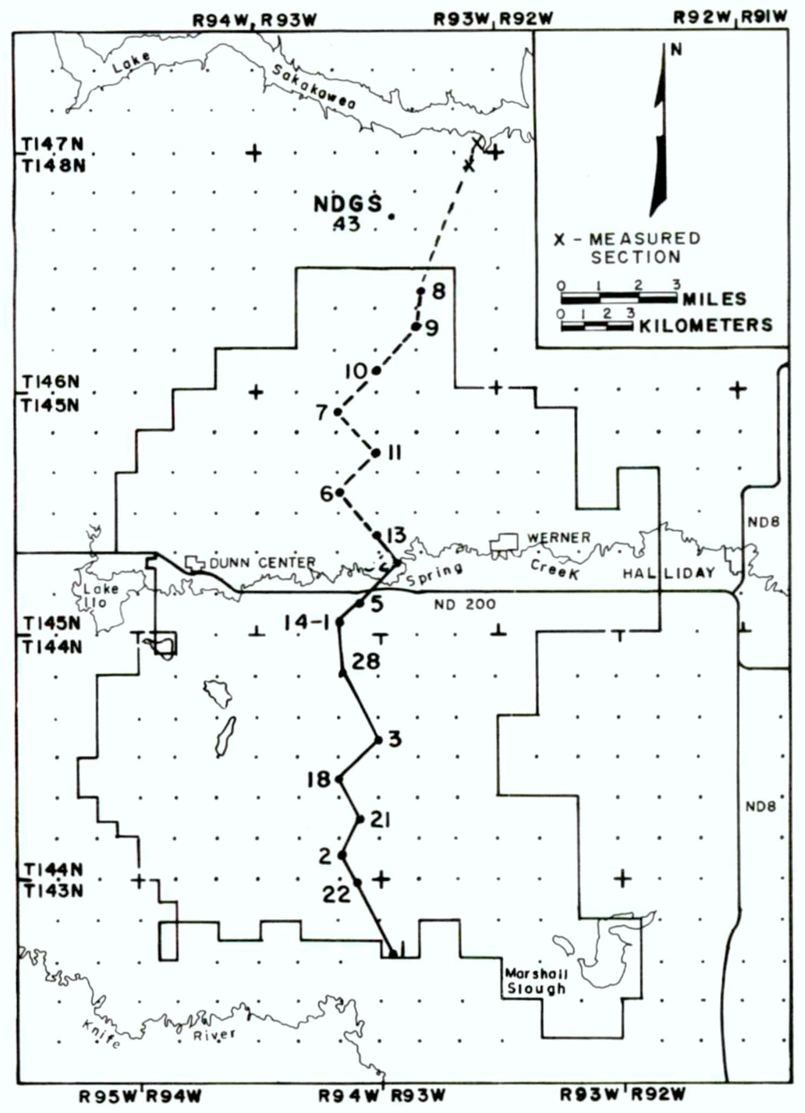


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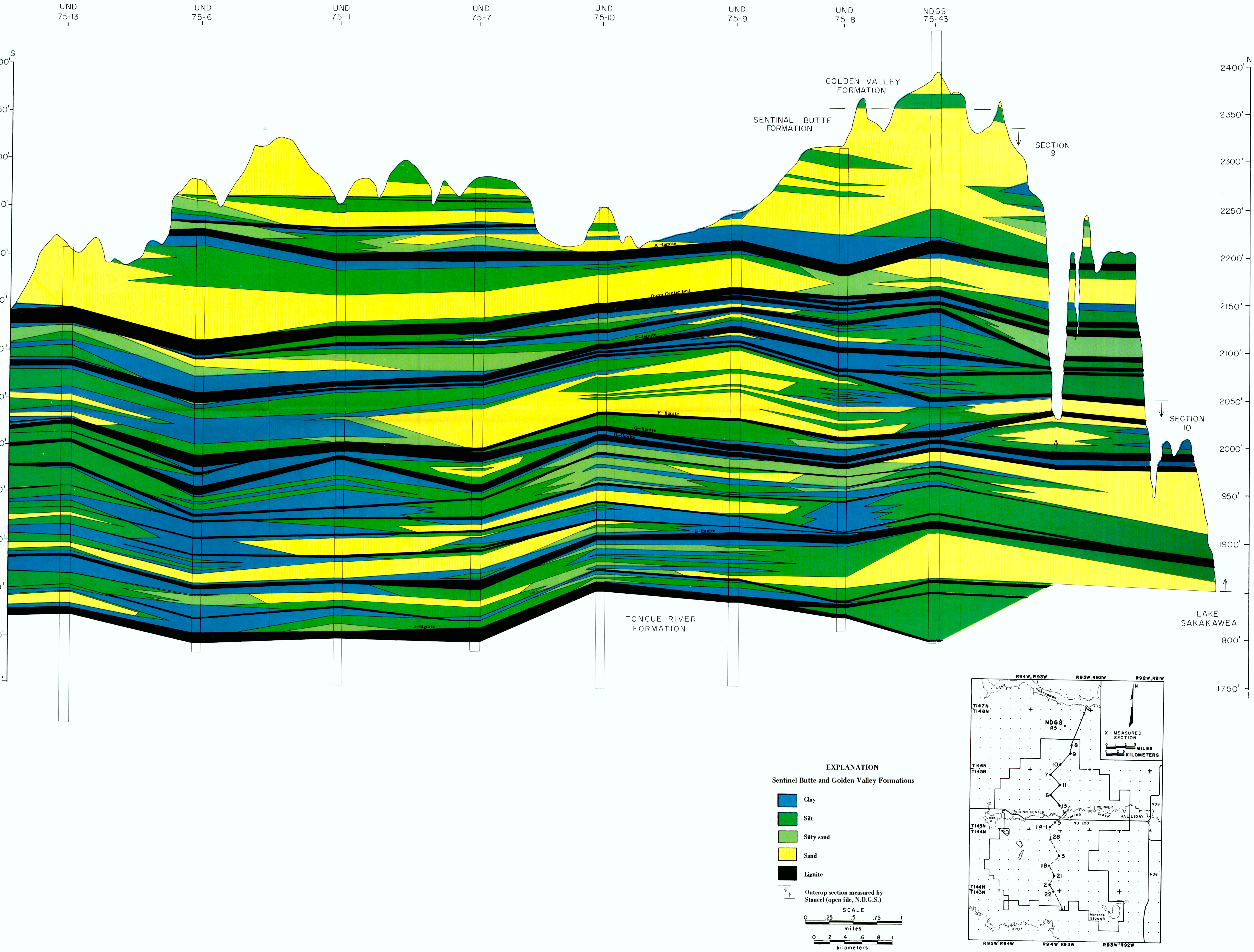
Plate 2

North-South Stratigraphic Cross Section of the Sentinel Butte Formation

Dunn Center Area

North Half



EXPLANATION

Sentinel Butte and Golden Valley Formations

🟦	Clay
🟩	Silt
🟩	Silty sand
🟨	Sand
⬛	Lignite
↓↑	Outcrop section measured by Stancel (open file, N.D.G.S.)

SCALE
0 .25 .5 .75 1
miles
0 .2 .4 .6 .8 1
kilometers

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Plate 3

East-West Stratigraphic Cross Section of the Sentinel Butte Formation

Dunn Center Area

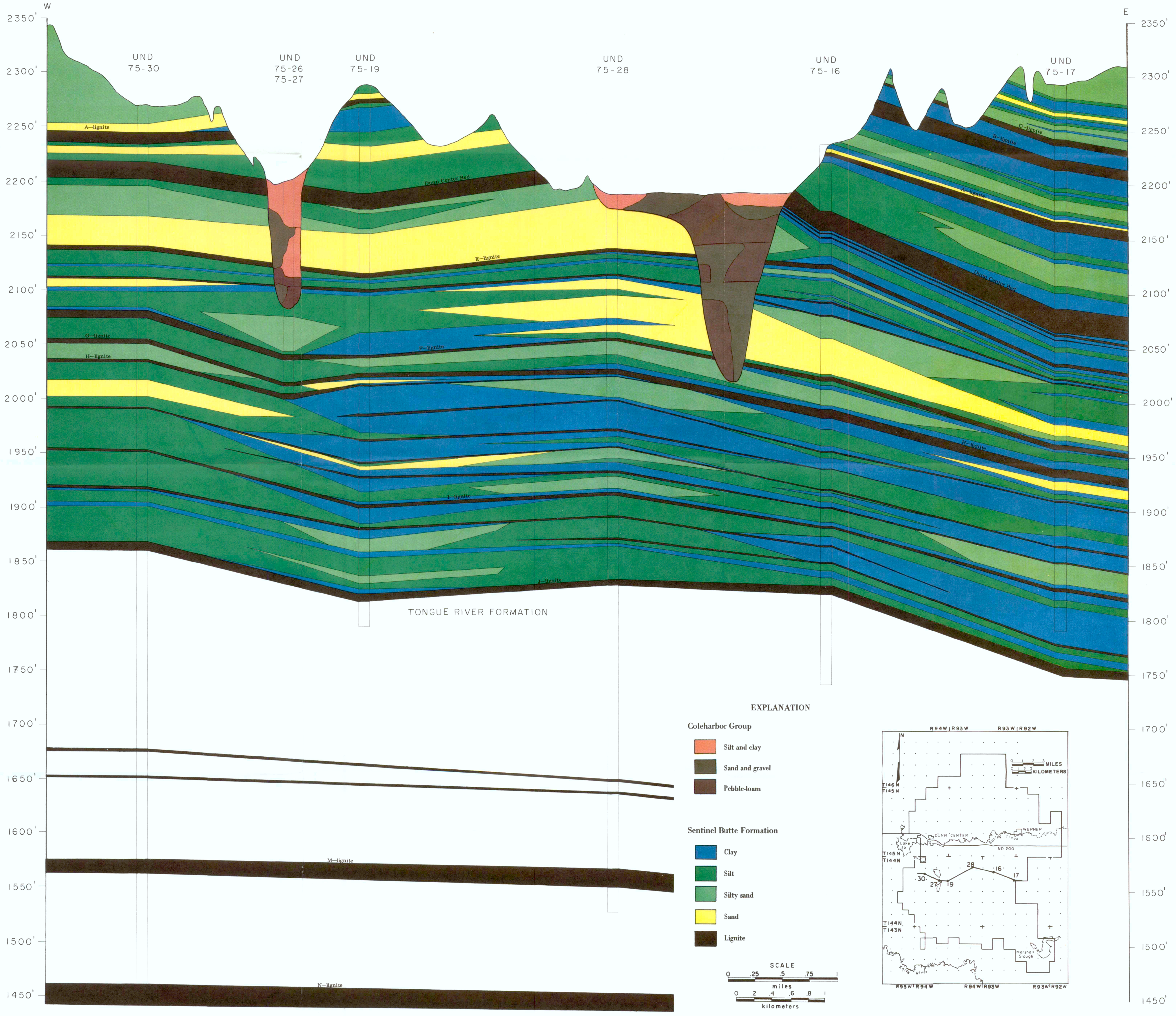

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Plate - 4

STRATIGRAPHIC CROSS SECTION OF THE SENTINEL BUTTE FORMATION IN THE LITTLE MISSOURI BADLANDS, LOST BRIDGE TO WOLF CHIEF BAY, DUNN COUNTY, NORTH DAKOTA