GEOLOGIC, HYDROLOGIC, AND GEOCHEMICAL CONCEPTS AND TECHNIQUES IN OVERBURDEN CHARACTERIZATION FOR MINED-LAND RECLAMATION

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Stephen R. Moran, Gerald H. Groenewold, and John A. Cherry

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Lee C. Gerhard, Acting State Geologist
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CONTENTS

ILLUSTRATIONS

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EXECUTIVE SUMMARY

This study has determined the distribution of geologic materials, some of the geochemical properties of these materials, groundwater-flow patterns, and chemistry of groundwater at five existing or proposed coal mine sites in west central North Dakota. Data from the Falkirk, Indian Head, and Beulah-Hazen sites of the North American Coal Corporation, the Center Mine of Baukol-Noonan, and the Dunn Center site of the Natural Gas Pipeline Company of America have been used to identify the factors that control the distribution of salinity in soil and water in the overburden. These factors have an important influence on soil development and plant growth.

All five sites are located in upland areas. Groundwater movement is generally downward over most of each site. Lateral movement in the more permeable lignite and sand beds results in springs and seeps where these beds outcrop along valley slopes. The low permeability of silt and clay of the Sentinel Butte or Coleharbor Formation that underlies the surface throughout much of the area results in very slow groundwater movement. In some places in the Dunn Center and Falkirk sites, sand as thick as 100 feet overlies the lignite to be mined. In these areas groundwater flow is more rapid.

A comparison of saturation-extract analyses from samples of the overburden material with groundwater chemistry in the same materials indicates a general, although by no means complete, similarity. On this basis, we believe that the chemistry of saturation extracts can be described in terms of the same type of geochemical model that accounts for evolution of groundwater chemistry in the area. The chemistry of saturation extracts and groundwater appears to be controlled by the amount of calcium carbonate (calcite), clay minerals, and iron sulfide (pyrite and marcasite), and the soluble sulfate, gypsum, in the overburden materials and by the infrequent episodic occurrence of groundwater recharge. High sodium content, which is expressed as an elevated Sodium Adsorption Ratio (SAR), results when excess calcite is available to percolating waters and clay minerals containing exchangeable sodium are present in the material. Exchange of sodium from the exchange sites on the clays for dissolved calcium ions results in an increase in dissolved sodium and further dissolution of calcite, which in turn produces further exchange. Elevated salinity, which is expressed in terms of electrical conductivity (ECE), results from dissolution of gypsum. Gypsum is not present as a primary constituent of the overburden materials but is produced at or very near the land surface by oxidation of pyrite, which is a primary constituent of

the overburden. The presence of elevated sulfate and therefore salinity in saturation extracts and groundwater occurs beneath depressions, low in the landscape where surface water collects, in areas where fine-grained materials result in such low permeability that essentially no subsurface water movement occurs in the material, and in groundwater discharge areas. In all three types of areas low permeability materials accentuate the excess salinity by retarding water movement and permitting maximum evaporation. Acid pH values occur where oxidizable pyrite occurs in the absence of calcite. This condition is relatively common in the upper 10 to 20 feet at many sites.

An interpretive framework that relates potential pore-fluid chemistry to material type and setting in the subsurface flow system has been developed from the data on the five sites. At present, this framework is only semi-quantitative; laboratory studies and more detailed field studies will be required to refine it. The framework will facilitate the design of overburden investigations that assure sampling all relevant geological and hydrogeochemical material with a minimum of unnecessary or redundant sampling. Application of the interpretive framework in the development of land reclamation designs for a proposed mining site will provide a greater possibility of achieving a landscape that will be agriculturally productive on a long-term basis, than has previously been the case.

One of the most significant conclusions of this study is that existing analyses of overburden chemistry based on the saturation extract method do not adequately assess the potential chemical conditions in the material on a long-term basis. These tests only indicate whether calcite, gypsum, and sodium clays are present; they do not indicate the abundance of any of these constituents. Furthermore, they indicate only the *salinity* of material, the presence of soluble salts; they do not indicate the *salt generation capacity* of the material, which is a function of the abundance of potentially oxidizable pyrite. In order to assess the chemical conditions in overburden material on a long-term basis it will be necessary to develop analytical techniques to determine calcite content at very low levels of concentration, abundance of potentially oxidizable pyrite, and actual ion-exchange characteristics under field conditions.

1. INTRODUCTION

1.1 Overview of the Project

1.1.1 History and Terms of Reference of Study

During the past three to five years, growing demands for energy, combined with existing and projected shortages in petroleum and natural gas have led to an increasing interest in the vast reserves of low-rank coal in all parts of the western United States. New mines have been opened and existing mines enlarged in order to ship increasing quantities of this low sulfur coal to existing and newly constructed electrical generating stations as much as 1000 miles to the east, in the area of the Great Lakes. Other, increasingly large, electrical generating stations located at, or in close proximity to, the mines that provide the necessary energy have been constructed or are projected for the next several years. The electricity produced in these power plants is transported by a growing network of transmission lines over distances of hundreds of miles to the cities where it is used. The projected depletion of natural gas reserves has spurred attempts to develop the technology for large-scale conversion of low-Btu coal to high-Btu pipeline-quality gas. Large volumes of water are needed for this conversion process. Because most of the area underlain by these coal deposits is arid or semi-arid, the large volume of water stored in the reservoirs along the Missouri River make North Dakota of special interest for gasification development.

The growing interest in and pressure for development of the coal underlying the western states has been accompanied by a growing concern for the preservation of the environment in areas of proposed mining. In North Dakota, this concern has focused primarily on the need that coal development not permanently damage the agricultural productivity of the land. Because precipitation is small and potential evaporation is great, this area is always delicately balanced, even in wet years, on the brink of drought. The memory of the troubled years of the Dirty Thirties is still sharp in the minds of the leaders and people of the largely agricultural area. As a result, any change in the landscape, soil, or subsoil that might adversely affect the water holding capacity, erodibility, or fertility of the soil is regarded with great concern.

The states in the region as well as the federal government have responded to these concerns with legislation and regulations designed to minimize the impacts of coal development on the environment. Very little technical information has been available to guide the framers of these laws and regulations. As a result, the laws and regulations have been constantly changing to reflect the accumulating body of knowledge about procedures necessary to reclaim surface-mined lands. It became apparent to government and industry alike that the slow rate at which technical information on reclamation was being accumulated was unsatisfactory. Large projects that required lead times of five to ten years were being designed on the basis of laws that would in all probability be significantly revised three to five times before the mine would open. Very likely, these changes would require redesign of mine plans and reassessment of the economics of entire projects each time. Government officials and agencies were being asked to review plans for projects and, on that basis, grant or deny permits where the effectiveness of existing reclamation technology was largely unknown. In addition, as a result of changes in laws and regulations, many aspects of the project, as actually conducted several years in the future, would probably be sufficiently different from the projected design that the review would have to be repeated more than once.

Discussions between coal industry people, notably the North American Coal Corporation, and officials of the North Dakota state government over ways to alleviate this problem led to the creation by

Governor Arthur Link of the Mined Land Planning Group (MLPG) in the winter of 1973-74. The MLPG consisted of a group of scientists from universities and state and federal government agencies, who possessed expertise in reclamation of surface-mined land at that time or who possessed expertise potentially valuable in developing scientific-technical information on reclamation procedures. The MLPG consisted of geologists, soil scientists, biologists, and agronomists. This group was given a three-fold charge by Governor Link. (1) It was to advise the governor and the legislature on the state of the art of reclamation at that time to aid in the framing of legislation for the pending legislative session. (2) It was to keep the governor and legislature current on reclamation technology on a continuing basis. (3) It was to conduct research to determine the best methods to return mined land to productivity where such technology was not available.

During the winter of 1973-74 a series of preliminary proposals for research on various problems associated with reclamation were developed by members of the MLPG. The Governor's Office, State Planning Division, and the Reclamation Director of the Public Service Commission presented these proposals to the Old West Regional Commission (OWRC), which had indicated an interest in funding such a study. Through a series of meetings of the MLPG, both alone and with representatives of the OWRC, the proposals were modified into the final project proposal, which was funded July 1, 1974.

The final project consisted of four studies, the overall purpose of which was to determine methods to successfully return strip-mined lands to a level of vegetative productivity that is equivalent to or better than the pre-mining level. Three of the studies, which were conducted by the North Dakota Agricultural Experiment Station, were concerned with revegetation, root-zone hydrology and chemical and physical characterization of overburden materials. The fourth study, the results of which are reported here, was directed at developing geological techniques to aid in the design and planning of strip-mine reclamation.

1.1.2 Objectives and Scope

As was indicated in the previous section, the overall objective of reclamation of surface-mined land is to return the land to full vegetative productivity. In most areas in North Dakota, this means a return to agricultural productivity as great or greater than prior to mining. The overall objective of this study is to aid in this level of reclamation by developing a basis for prediction of soil and groundwater chemistry in reclaimed lands. This will provide a scientific basis for the design of engineered-cast overburden in a way that will lead to maximum agricultural productivity on a long-term basis. Before proceeding with the more specific objectives of this study, it is useful to examine the relationship between reclamation for vegetative productivity and subsurface-water chemistry.

In order to achieve the goal of productive revegetation in the short run, it is necessary to contour the cast-overburden to prevent erosion and permit access with farm equipment, to place a veneer of suitable plant-growth material over the land surface, and to seed the surface with an appropriate community of plants. On the basis of previous experience with reclaimed areas, this process, combined with suitable care for a period of a few years to permit vegetation to become well established, seems to assure the revegetation of the landscape. By and large, the chemical constituents that are beneficial or deleterious for soil development and plant growth have been identified. There is still considerable debate on the amount of "top-soil material" and "subsoil material" that is required to assure a return to optimum levels of production.

Keeping in mind the reservation that a soil is equal to more than the sum of its component parts, the assumption of the previous paragraph seems a reasonable first approximation. If, before mining we selectively remove the upper part of the landscape, the growth profile, and the material from immediately beneath it, and then replace this material in sequence over the cast-overburden, it appears that we have returned all the component parts of the soil back into place. If we then take steps to reestablish appropriate plant and animal communities and protect the landscape from erosion and premature, excessive agricultural use, this proto-soil could logically be expected to evolve through natural processes into a soil.

Within this short-range perspective, the objective of this study has been to evolve techniques to assist in identification of materials that contain mineral matter that would be beneficial or deleterious to revegetation if replaced near the land surface. We believe that the distribution of such chemical components in the landscape is systematically controlled by a series of geologic and hydrologic factors including texture, mineralogy, depth in the weathering profile, and direction and rate of subsurface-water movement through the materials. The study has been designed to develop an understanding of these factors so that they can be used to design a sampling program that efficiently and completely evaluates the chemical characteristics of the overburden prior to mining. As part of this sampling process, it is necessary to make generalizations about material between sampling points. This study is intended to provide a basis for such generalizations.

All of the preceding discussion has been directed at the short-range objective of reestablishment of vegetation. The problem of on-going, long-range maintenance of agricultural productivity has not been addressed. The process of mining and reclamation may result in a new form for the land surface in many areas. In addition, the material beneath the surface will have very different physical and, in some cases, chemical properties than the material present prior to mining. These changes can reasonably be expected to produce changes in the subsurface-water regime that, in some areas, will change location and frequency of groundwater recharge water table configuration, rates of groundwater and soil-water flow, and groundwater and soil-water chemistry. It is possible that through changes of this sort operating over a period of time, soils that were productive immediately after reclamation may become less productive because of leaching of desirable constituents or accumulation of undesirable ones. By the same token, it must not be forgotten that in other cases, these same kinds of changes in the subsurface-water regime will improve soil productivity. Leaching of undesirable constituents is the most probable mechanism to produce this type of change.

In order to assess the potential for long-range changes in soil productivity, it is necessary first to understand the physical and chemical interactions between soil, water, and rock within the existing landscape. With this knowledge, it becomes possible to predictively model the subsurface-hydrological regime in a reconstructed landscape and from this model to predict potential subsurface-water chemistry. A major objective of this report is to begin to explore the type of "pedo-hydro-geochemical" systems involved in this long-term approach to planning and design of mined-land reclamation. It should be evident that the complexity of this whole-landscape approach is so great that this study can only scratch the surface of the problem.

With this goal in mind, it seems useful to briefly outline the connection between plant growth and the evolution of subsurface-water chemistry to make clear the relationship between the overall objective and the more limited objectives of this report.

In order for a soil, whether natural or reconstructed, to support vegetation, it must have physical properties within a certain range. Water holding capacity, hydraulic conductivity, and crusting properties are just a few of these physical properties which are controlled in part by the texture and organic-matter content of the soil, but very largely by the dissolved chemical constituents in the soil-pore water. Sodium and calcium carbonate are two extremely important constituents in controlling the physical properties of the soil.

The chemical composition of the water in the pores in the soil also plays an extremely important direct role in controlling the type and condition of plants growing in the soil. Macro- and micro-nutrients, such as nitrogen, phosphorous, sulfur, and potassium, to name only a few, are essential for plant growth. Certain elements are toxic to plants, so that their presence precludes healthy growth. Where the total salinity of soil water is too high, plant growth is retarded or even prevented in extreme cases. From the above, it follows that vegetative reclamation of mined lands is intimately connected with soil-water chemistry.

The water chemistry in the soil at any given place in the landscape is determined by several factors, including composition of the soil, texture of the soil, frequency of infiltration, direction of water movement through the soil, and the rate of evapotranspiration.

The composition of the mineral matter and organic matter in contact with the water determines the water chemistry. The presence of minerals such as calcite ($CaCO_3$), dolomite ($(CaMg)CO_3$) and gypsum ($CaSO_4{\cdot}2H_2O$) influences pH and salinity. Oxidizable pyrite (FeS_2) can markedly alter pH and to a lesser extent salinity. The presence of sodic clays results in the replacement of Ca^{2+} by Na^+ in the water and drives the salinity up as further mineral dissolution occurs.

The texture of the soil plays an important role by regulating the rate of water flow through the soil. In coarse-grained, permeable sediment, water movement is relatively rapid resulting in the movement of many pore volumes of fluid through the soil during a short time. This results in strong flushing of chemical constituents. Fine-grained, less permeable sediment, on the other hand, results in slow velocity of water movement. This results in fewer pore volumes of fluid moving through the soil during the same time period and correspondingly less flushing.

The direction of water movement through the soil results in flushing of chemical constituents if the water moves downward through the soil, accumulation of chemical constituents, if water is moving up through the soil to the surface, or liberation and subsurface accumulation of chemical constituents, if water moves down into the soil and is removed through evaporation and transpiration.

It is thus evident that the long-term performance of vegetation in a reclaimed landscape is intimately tied up with the physical and chemical conditions in the subsurface water. It is understanding and predicting this subsurface-hydrological regime that is the focus of much of the present report.

In order to meet the long-range objectives of the study, it was first necessary to develop an understanding of the geologic, hydrologic, and geochemical controls on the soil-water and groundwater chemistry that exists under pre-mining (natural) conditions. Because two-thirds of the active mines in North Dakota were situated in Mercer and Oliver Counties, because the two most imminent new mines, both of which were to be very large, were situated in the same area, and because the North American Coal Corporation (NACCO) was active in initiating the study, the research project was designed to focus on two NACCO projects in this area, the Indian Head Mine at Zap and the proposed Falkirk Mine at Underwood. During the project three additional sites were added to increase the capability to generalize the results of the study. The proposed Dunn Center project of the Natural Gas Pipeline Company of America, the proposed Beulah-Hazen project of the Coteau Properties (North American Coal Corporation), and the Center Mine of Baukol-Noonan were studied in varying degrees of detail.

These five sites lie in an area about 30 miles north-south by 75 miles east-west that includes all but three of the mines currently active in North Dakota and all of the proposed developments, which appeared, at that time, to be potentially active before 1985 (fig. 1.1.2-1). Two of the three mines in North Dakota that are not in this area, the Husky Mine near Dickinson and Velva Mine near Velva, are small operations. The remaining mine, the Gascoyne Mine near Gascoyne was already under intensive study by the United States Geological Survey.

The five study sites include a range of conditions typical of nearly all existing or

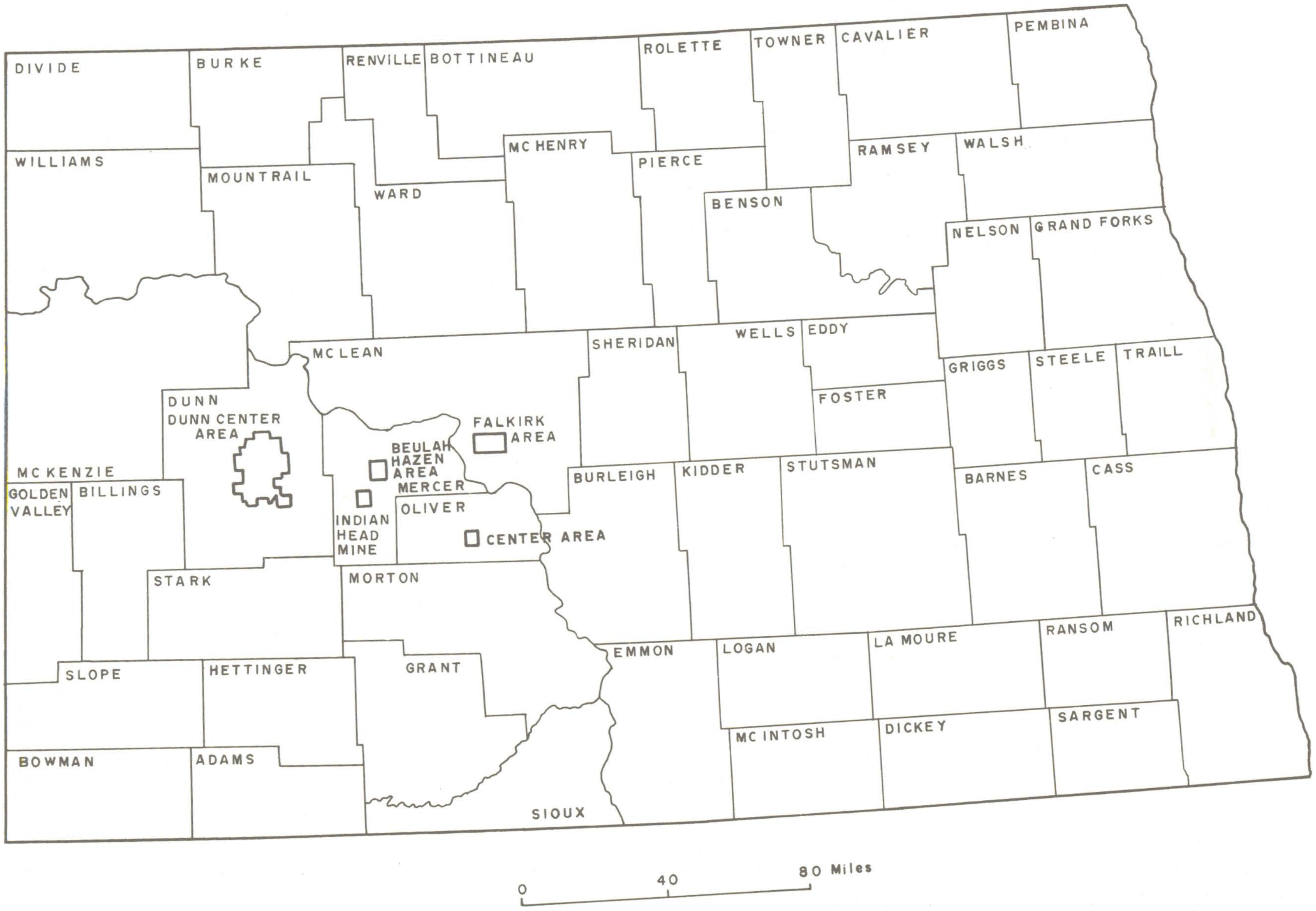

Figure 1.1.2-1. Map showing locations of the five study sites.

potential developments in the state. They all are in areas of semi-arid climate. They are all predominantly on uplands which appeared to be sites of groundwater recharge. The lignite being mined is in the Sentinel Butte Formation (Paleocene).

The character of the overburden and the details of the groundwater-flow system are the major variables among the sites. At the Falkirk site, nearly the entire site is covered by glacial sediment of the Coleharbor Formation (Quaternary), and this material constitutes the majority of the overburden in much of the site. Throughout much of the field, the Sentinel Butte Formation above the main lignite consists of sand. At Beulah-Hazen and Center the overburden is dominantly silt and clay of the Sentinel Butte Formation, although glacial sediment of the Coleharbor Formation is present over both of these sites and in places is quite thick. The Dunn Center site is characterized by thin sediment of the Coleharbor Formation limited to the northern part of the site. Nearly all of the overburden is sediment of the Sentinel Butte Formation. In parts of the site, the overburden is predominantly fine-grained silt and clay, and in others, it is predominantly sand. At the Indian Head site, glacial sediment, although present in very small isolated patches, is hardly ever identified in borings and the overburden consists predominantly of silt and clay of the Sentinel Butte Formation. The overburden is highly sodic.

The procedure used at each site was essentially the same, although variations did result as a consequence of differences in the procedures of the various mining companies. At all sites, drill-hole data that had been collected previously was made available to us. These data ranged from sketchy descriptive logs to high-quality geophysical logs and core samples. At each site, additional testholes were drilled, logged, and sampled by project personnel. At each of the five sites, samples were collected for standard geochemical testing and analyses. The samples ranged from forward circulation rotary cuttings, both wet and dry, to continuous cores of the entire overburden section. Potentiometric observation wells were installed in many of the testholes by placing a 1-inch or 2-inch plastic pipe that is screened at the lower end in the hole and sealing it in place with a cement grout. These wells were then used to collect water samples for chemical analyses and water-level data from the bed in which the screen was located. These procedures are described in greater detail in appendix A.

The sample, core, and geophysical log data from each site were synthesized to generate a detailed three-dimension "map" of the distribution of the various materials in the overburden at each site. These data were classified and grouped using several different procedures. Each classification scheme was evaluated to determine patterns. Based on these activities a semi-quantitative interpretive framework was developed. This framework has been successfully evaluated in terms of: (i) groundwater chemical data from the five detailed study areas, and (ii) standard overburden soil chemistry characterizations. For purposes of this investigation (i.e., for this report) this hydrogeochemical framework has been adopted as a basis for a landscape-overburden classification scheme.

A second intermediate goal of this study was to develop a scheme for landscape evaluation by which overburden could be classified into recognizable subdivisions based on characteristic, and possibly distinctive, geochemical properties. In other words, the goal was to develop a system whereby volumes of material in the landscape could be identified and described in terms of parameters that would serve as a basis for prediction of soil development and groundwater chemistry evolution in reclaimed land. We were seeking the simplest and fewest geologic, hydrologic, and hydrogeochemical parameters necessary to accomplish this task. With this objective in mind, the hydrogeochemical framework, which is based on geologic, hydrologic, and geochemical factors, has been used for selection and organization of terrain and sample descriptors. Data from the five study areas have been classified using this framework.

The hydrogeochemical model provides

a basis for understanding the soil-water and groundwater chemistry in the overburden under natural conditions. The framework or derivatives of it should serve as a basis for prediction of soil and groundwater chemistry in reclaimed lands, providing that it is refined and tested in a suitable manner in future years. The model is based on interpretation of geochemical processes that operate under specific geologic and hydrologic conditions. The landscape-classification system, however, is based on simple descriptive parameters rather than genetic parameters. If the parameters are properly chosen (i.e., if they relate in an appropriate manner to the hydrogeochemical model), they should serve as a basis for prediction. The key step, therefore, is to establish relations between the site and sample descriptors and the model. This has been done on a preliminary basis in this report. Recommendations for testing of some of the relationships are included in section 9.

1.1.3 The Whole-Landscape, Engineered-Cast-Overburden Concept of Reclamation

In the reclamation of surface-mined land we are engaged in the construction of a landscape. That landscape is constructed with a surface form and soil that are intended for a particular use; in North Dakota, that use is generally agricultural. In order to assure that the surface form and soil are able to continue to serve the intended use on a long-term basis, it is necessary to design the entire landscape such that it is physically stable and relatively inactive chemically. We have coined the term Engineered-Cast-Overburden (ECO) to refer to the approach to reclamation of surface-mined land, which concerns itself with the design of the entire landscape. This concept was termed "Landscape-Design Reclamation" by Moran and others (1975) where it was distinguished from the simpler concept "Soil Design Reclamation." In this section we begin by briefly discussing the reasons that the entire landscape, not just its surface form and soil, must be considered in reclamation; this is followed by a discussion of economic considerations in ECO reclamation. Finally we suggest some approaches that may lead to achieving ECO reclamation and discuss this report in the context of those requirements.

1.1.3.1 Focus on the Entire Landscape

Landscape, as we are using the term, includes the substance, as well as the form of the earth's surface. It includes the morphology of the surface, the soils on that surface, the structure of the rock and sediment beneath the surface, and the water that moves over and beneath the surface. The form of the surface, the soils on the surface, and the hydrologic regime beneath and upon the surface are more or less delicately balanced with the forces acting on and beneath that surface. When there is a big enough change in the forces acting on a landscape (for example during a climatic change), the landscape adjusts itself to become stable under these new conditions (Clayton and others, 1976). During the Dirty Thirties, when the climate was warmer and drier than it is today, vegetation cover was decreased on hillslopes throughout the semi-arid Great Plains. Although rainfall was less, runoff from the partially denuded hillslopes was greater, resulting in increased erosion on the slopes. The valley bottoms were clogged with sediment and gully cutting ceased as the floors of the arroyos were aggraded (Hamilton, 1967). Dust was blown from these valley floors and deposited on the flat upland surfaces. Through these changes in the rates and the processes of erosion and deposition, the form of the landscape was altered to one better adjusted to the new climatic conditions (Moran and others, 1975).

In the same way that a change in the forces acting on the landscape results in the establishment of a new stable landscape form, a change in the material making up the landscape may require an adjustment of the landscape. In areas of potential strip mining, the landscape consists of a surface that is the quasi-stable resultant of the interaction between the climate and the underlying structure, which consists of a series of alternating, relatively thin beds of sediment that differ from each other in physical, chemical, and hydrological properties. Where this landscape is disturbed by surface mining, the horizontal layering is destroyed, and a new, more complex and yet generally more homogeneous, structure results. In some cases, the characteristics of this new landscape may be sufficiently similar to the original landscape that the stable surface form will not be markedly different. However, in most cases, it seems probable that a different morphology will be required for stability.

The adjustments within the new landscape can take many forms. Slopes that are too steep will be flattened by erosion high on the slopes, and by deposition on the lower slopes, or by land sliding and slumping. Soils that contain organic matter in excess of the amount that can be maintained under the conditions will lose organic matter by oxidation or erosion.

Many of these changes in the landscape are complexly interlinked so that a seemingly minor alteration in one characteristic of the landscape may manifest itself in completely unexpected ways elsewhere in the landscape. For example, a change in the form or the permeability of the surface will generally produce a change in groundwater levels and flow patterns. This, in turn, can result in changes in slope stability or in water chemistry. These changes can then result in modifications in the landscape that will either amplify or nullify the original change in morphology. Changes in water chemistry and groundwater-flow patterns can result in marked changes in the characteristics of soils (Quirk and Schoefield, 1955; Reeve and Tamaddoni, 1965).

The goal of ECO reclamation is to design and construct a post-mining landscape that approximates, as closely as possible the stable landscape for the material as it is emplaced following mining. In this way, the natural adjustments that will be made to achieve stability will be minimized. Smaller natural adjustment involves less gullying surface subsidence, and landsliding, less soil erosion and destruction, less degradation of quality of groundwater and surface water, all of which results in better and cheaper reclamation (Moran and others, 1975).

1.1.3.2 Economic Considerations

The requirement for reclamation to achieve a return to agricultural productivity represents a very large added cost in the production of energy. Estimates range as high as $9900 per acre depending on various factors (Pundari and Coates, 1975). This requirement has its origin in a series of totally valid emotional reasons, which are beyond the scope of this report to discuss, rather than from an economic basis. As a society, we have elected to spend relatively large sums of money for which the returns lie in the realm of aesthetic and emotional satisfaction rather than in monetary reward. Although some of the land overlying potentially surface-mineable coal in the western United States is quite productive much of it is of very marginal agricultural capability. Even with optimum climatic conditions, much of this land will never return the investment made in it through reclamation if it is returned to its pre-mining state. In most cases, this is because the physical and chemical conditions created by the material that occurs at the land surface are, under the climate conditions of the site, inimical to soil development and plant growth. In many areas, however, it may be possible to rearrange the surface form, the underlying stratigraphy, or the surface permeability of the landscape and thereby alter the physical and chemical conditions of the surface of the landscape to conditions more favorable to vegetation. If this rearrangement can be accomplished for little or no additional cost within the context of existing mining and reclamation procedures then the potential exists to generate economic return on the money invested in reclamation in addition to the other benefits.

Two relatively straightforward examples should serve to illustrate this point. In much of the area where western coal occurs, considerable land, both cropland and hayland, has been lost to saline seeps, which overlie areas of groundwater discharge. The cause of these seeps appears to lie in three factors: (1) excess water entering the ground in recharge areas, (2) stratification of the rock such that permeable beds overlie less permeable beds, and (3) slope breaks where steeper slopes above join less steep slopes below. If, in the reclamation process, one or more of these causes is removed, the development of seeps in the new landscape can be prevented thereby improving the value of the land.

The second example involves a greater level of redesign of the landscape and makes the point more clearly. Soils that are saline or sodic are so because water flows into them and evaporates or because there is no flow through them at all. Let us assume an area of saline soils underlain by a bed of clay that overlies an extensive unit of sand resting on coal. The saline soils result from the low permeability of the clay subsoil material, which permits essentially no infiltration and therefore causes the accumulation of salts by evaporation. By inverting the overburden stratigraphy during mining so that the cast-overburden consists predominantly of sand overlying clay we have changed the entire mineralogic and hydrologic regime of the near surface environment. The relatively lower content of pyrite and sodic clay in the sand results in a lower salt generating capacity. Because of the higher permeability of the subsoil material, infiltration can occur and salts can be flushed from the soil. If sufficient water is available to permit irrigation the flushing can be accelerated. Once the salts are removed, the irrigation can be stopped or continued depending on costs of water and the intended use of the land.

It seems theoretically possible, in some settings, to significantly improve the agricultural quality of land through an ECO approach to reclamation. In the hypothetical example above, a saline, marginal pasture is modified to a condition suitable for irrigation farming. Through such a technique, it would be possible to realize real gains in agricultural productivity, and thus economic return, for the investment in land reclamation. This question must be explored from an economic standpoint to determine if the still greater costs of this increased step of ECO reclamation are small enough to increase the net return on the investment. It should be evident that this analysis must include all possible combinations of existing and potential techniques of overburden excavation and handling because ECO reclamation potentially involves a complete restructuring of surface-mining procedures. Because of the already large commitment of resources to reclamation and the increasing demand for the retention of agricultural values, we believe such an analysis is justified.

1.1.3.3 Prerequisites to ECO Reclamation

Before ECO Reclamation can be considered as a viable approach, several processes have to be understood and techniques developed. (1) Techniques must be developed to identify and evaluate the materials comprising the overburden; it is not possible to design a landscape until one knows what materials are available and their index properties. This overburden inventory involves soil mapping, geologic mapping, development of three-dimensional materials framework, hydrogeologic studies, and geochemical studies to delineate the properties of the materials. (2) The processes acting in the landscape must be understood. We must learn why the existing landscape is stable under existing conditions in order to be able to predict whether a redesigned landscape with different internal stratigraphy and surface form will be stable. (3) It is necessary to understand the form and internal structure of material deposited by various types of mining equipment and techniques. For example, if it is considered desirable to have a bed with certain characteristics at a particular place within the cast-overburden one must know whether, and if so, which, equipment and procedures can be used to deposit such a bed. (4) A model of the mining process is necessary to critically evaluate, in economic terms, the costs involved in each aspect of the mining and landscape construction process. (5) Finally, a series of landscape models must be developed or modified from existing models to permit the evaluation of newly constructed landscapes. The various materials available must be examined to determine how they will respond to the different physical and chemical environments that will result from each of the landscapes being considered. The types of interpretive frameworks that are used range from simple, nearly intuitive, qualitative, or semi-quantitative mental constructs to highly sophisticated digital computer models capable of handling large multicomponent arrays of interacting variables.

By analyzing the various components of alternative proposed landscapes, the morphology and stratigraphy that is most stable and best meets the requirements of alternative possible land uses will be determined. For example, if a certain surface morphology is constructed with a particular permeability distribution within the material, then the hydrological regime of the landscape is set. This hydrological regime will govern the amount of runoff and infiltration, the nature of stable soils, the mobilization and migration of soluble ions, along with a multitude of other factors. By changing either the morphology or the permeability distributions, the hydrological regime can be modified to a new equilibrium. The resultant equilibrium surfaces for a series of alternative designs can be evaluated, in this way, using the modeling approach to select the landscape that maximizes the three constraints, serving the intended use, being stable, and being economically feasible. Evaluation of the behavior of a proposed landscape under conditions of an extended drought or period of excessive precipitation is of very great importance in this modeling effort.

This report has been concerned primarily with development of techniques to inventory the geologic, and to a lesser extent hydrologic, conditions in overburden prior to mining. As a consequence of our evaluation of techniques to determine chemical properties of overburden, we have developed a model to describe in geochemical terms, the observed chemistry of groundwater and pore water. This model lies in the realm of the second area of concern, the understanding of processes sufficiently well to predict the results of change.

1.2 Sampling and Analytical Procedures

Before proceeding further it is useful to examine and evaluate the procedures used to analyze the geochemical properties of sediment (overburden) and groundwater. In this section, we describe the methods used in collection and analysis of samples from the five study areas.

1.2.1 Overburden Sampling

Overburden samples were obtained by four methods: (1) rotary coring, (2) hydraulic soil sample probing, (3) air-rotary cuttings, and (4) mud-circulation rotary cuttings. Some samples were obtained by rotary coring methods. Nearly all the samples at the Dunn Center site were obtained in this way. As the core barrel is rotated cutting its way through the material, a central plug, which ranged from 2 5/8 inches to 4 inches in diameter is fed up into the inner barrel. Drilling mud is circulated through the bit and up the annulus for cooling and cutting removal. When the desired length of core has been cut, the core barrel is returned to the surface by pulling the drilling rods and the core is extruded. The core segments are wrapped and sealed in plastic or sealed in plastic bags. These sealed cores were then transferred to the laboratory for analysis.

The principal problem with coring is that recovery of loose sand is often difficult. In addition, the possibility of penetration of drilling fluid into sand exists. Inspection of sand cores in the field suggested that fluid intrusion, if it were occurring at all, affected only the outermost cm of the core. This confirms the findings of Power and Sandoval (1976) who reported penetration of drilling fluid into sandy cores of only fractions of an inch. Various drilling additives are available commercially to bind loose sand and permit recovery. How they affect the chemical properties of the cores is not known. Extrusion of cores was difficult in some cases because of swelling in the barrel. Except in a few cases this was not a major problem. A possible solution to this problem is the use of a split inner liner in the core barrel. Our only experience with this type of barrel, which was at the Falkirk site, met with no success because of difficulty in obtaining recovery in sand with a drill crew not used to coring overburden. Considerably greater care and labor is required in disassembly, cleaning, and reassembly of this type of barrel; therefore, much of the advantage of ease in core removal seems to be counterbalanced.

A second coring method that was used for samples to a maximum depth of about 15 feet is a truck-mounted hydraulic soil sampler. This coring probe, which is manufactured by the Giddings Machine Co. of Ft. Collins, Colorado, provided excellent, uncontaminated samples of the soil and subsoil. It is unable to penetrate pebbles and compact sediment and rock and core recovery is nearly impossible in saturated sand. Extraction of clayey samples can be difficult and time consuming.

Most of the samples analyzed during this study were collected as cuttings from forward circulation rotary drilling. Most were collected with air or air-water mist circulation; some were collected with water-based mud circulation. The air samples were placed directly in plastic bags, which were sealed and transported to the lab. The wet rotary samples were washed free of drilling mud, in the field, before being placed in plastic bags. A comparison of analytical results obtained on both types of cutting samples collected at different times from the same site indicated small, but consistent differences between the two groups. The samples collected with water circulation contained consistently more Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, and Na^+, consistently less K^+, HCO_3^-, and $CaCO_3$, and had higher SAR, saturation limit, ECE, and pH than did the air samples (table 1.2.1-1). These changes appear to reflect the addition of chemical constituents from the drilling water rather than solution of material from the samples.

Table 1.2.1-1. *Analytical comparison of samples collected by two different drilling methods.*

	Units	n	$\bar{x}$[1]	s	Range
$CaCO_3$	weight percent	9	-1.28	1.29	-3.2 to 0.5
pH	pH units	9	0.07	0.08	0.0 to 0.2
ECE	mho's/cm	9	0.25	0.35	-0.12 to 1.10
SAR		9	0.37	0.15	0.2 to 0.6
Saturation Limit	percent	9	6.0	12.93	-8 to 32
HCO_3^-	meq/l	9	-0.02	0.16	-0.3 to 0.2
Cl^-	meq/l	9	0.19	0.36	-0.5 to 0.7
SO_4^{2-}	meq/l	9	6.06	7.78	-2.6 to 24.1
Ca^{2+}	meq/l	9	1.90	2.52	-1.6 to 6.8
Mg^{2+}	meq/l	9	3.18	4.15	-1.0 to 13.2
Na^+	meq/l	9	2.0	1.16	-1.1 to 4.8
K^+	meq/l	9	-0.09	0.08	-0.2 to 0.0

[1] **The mean is the mean difference of paired samples. $\bar{x} = (x_{ai} - x_{wi})$ where "a" and "w" represent air and water circulation, respectively.**

1.2.2 Standard Approaches in Soil and Sediment Analysis

1.2.2.1 The Saturation Extract Test

The saturation extract test is a procedure used to measure the content of salts in a soil or sediment sample. Whether the sample is a core or a cutting sample, it is removed essentially instantaneously from its original position. The pore fluid in the sample, whether the sample is completely or only partly saturated, does not have time to drain and is removed along with the sample. The sample is next transferred to the laboratory where it is dried.

After drying, water is added to the sample to form a very wet paste (United States Salinity Laboratory Staff, 1954, p. 84, 88). When the sample is dried, ions in the pore water are precipitated in the pore space. When the sample is resaturated with distilled water, the salts that were precipitated in the pore space are redissolved. If the water content of the sample were increased just to the natural water content, the concentration and composition of the pore water would be about the same as in the original sample. However, the water content of the saturated paste is considerably above the natural water content. In overburden samples in western North Dakota, water content from 30 percent to over 100 percent is required to reach the saturation limit.

Before discussing the chemical changes that may result from this excess water it is worthwhile to evaluate this effect from the standpoint of water volumes. If we assume that 100 grams of dry soil having a S.G. of 2.65 and a porosity of 30 percent are used for the test, we have 37.74 cm^3 of solids and 16.17 cm^3 of void space. If we then add water until 100 percent saturation is reached, the void space will be filled with water and the water content will be 16.17 percent. The saturation limit of most overburden materials in the study area ranges from about 30 percent to more than 100 percent with most values in the range of 40 percent to 60 percent. If we increase the water content of our hypothetical sample until a representative saturating limit of 50 percent is reached, we have a fluid weight of 50 percent of the dry sample weight or 50 grams of water. This represents 50 cm^3 of water or 300 percent of the original water content of the sample in the field. It can be seen that there is a large change in water volume.

The water added to the dried sample will cause the salts that precipitated on drying to redissolve. If these salts are the only soluble materials in the sample, the concentrations of the dissolved species derived from the salts will be lower than in the original pore water because the water to solids volumetric ratio is larger. The partial pressure of CO_2 in the water in the laboratory test will be equal to the partial pressure in the air ($10^{-3.5}$ atmospheres). Since the P_{CO_2} in groundwater is normally much higher than this value, carbonate minerals are more soluble in groundwater than in the test water. For example, 310 mg/l of calcite will dissolve in water with a partial pressure of 10^{-2} atm. Only 100 mg/l will dissolve in water in equilibrium with atmospheric CO_2. Therefore, even if the sample contains abundant calcite or dolomite, the concentrations of Ca, Mg, and HCO_3 derived from carbonate minerals will be much lower than in the original pore water.

If the solid material contains non-carbonate soluble minerals such as gypsum or halite, these minerals will dissolve until their saturation limit is reached or until their entire mass goes into solution. Since the water volume to solids ratio is larger in the laboratory test, there is a larger probability for the mass of soluble non-carbonate minerals to be depleted prior to attainment of mineral saturation in the test. If this occurs, the salt concentrations in the test water will be lower than in the original pore water.

Cation exchange is another process that can alter the pore water chemistry. In the natural soil water and groundwater systems Ca^{2+} is removed from the pore water by exchange reactions and is replaced in solution by Na^+ and to a lesser extent Mg^{2+}. This exchange process also acts to modify the pore water chemistry during the laboratory test. Cation exchange reactions are very fast. They alter the relative cation concentrations as cations enter the solution as a result of mineral dissolution. The exchange of Ca^{2+} for Na^+ causes more calcite, dolomite, and gypsum to dissolve if their presence has not already been exhausted by the initial dissolution stages.

Water used for the "saturated extract" tests is normally oxygenated prior to the test or becomes oxygenated during the test. The dissolved oxygen provides a potential for oxidation of iron sulfide (pyrite or marcasite) to produce SO_4^{2-} and hydrogen ions (i.e., acidity). The increase in hydrogen ion content can cause more dissolution of calcite and dolomite if these minerals are present.

In the preceding discussion the main geochemical processes that control the chemistry of water in saturated extract tests have been outlined. It is apparent that the pore water chemistry in the saturated extract can be much different than the chemistry of pore water in the sample under field conditions. To our knowledge these differences have not yet been evaluated by means of controlled laboratory experiments. As a qualitative or semi-quantitative indication of soil or subsoil salinity the standard saturated extract test is quite useful. As a basis for formulating quantitative predictions on the soil water and groundwater chemistry that will develop in areas of reclaimed land it leaves much to be desired. It should be kept in mind that the standard saturated extract test was not devised for mine-land reclamation studies. One of the objectives of mine-land reclamation studies is to develop knowledge of the chemistry of soil water and groundwater in reclaimed land. The usefulness of laboratory tests must be assessed relative to this and other specific objectives. Soil-water chemistry is important because it affects crop productivity. The chemistry of groundwater is important because groundwater can influence surface systems and soils and can serve for water supply. In the investigation reported on here, saturated extract data is compared to chemistry of groundwater samples obtained from wells in areas where samples were obtained and subjected to extract tests.

1.2.2.2 The Carbonate Test

The standard determination of carbonate content involves mixing a measured weight of sample with an excess of strong acid and measuring either weight loss as a result of solution of the carbonate or volume of CO_2 evolved in the reaction. The procedure used in determining carbonate content in the samples reported in this study is the standard agricultural technique of weight loss (Schroer, personal communication). This procedure calls for the reaction of 1.0 or 10 gm of sample with a weighed amount of HCl in a weighed flask (United States Salinity Laboratory Staff, 1954, p. 105). After the reaction has stopped and the weight of the flask, fluid, and sample has stabilized, the weight is recorded and the weight loss calculated.

If we assume that the balance used is accurate to ±0.001 gm we can calculate the minimum level of detection of this technique. A weight loss of 0.002 gm, the minimum reading that can be made with confidence using our balance, is a $CaCO_3$ equivalent of 0.46 percent in a 1 gm sample or 0.046 percent in a 10 gm sample. This is equivalent to 4.55×10^{-5} moles of $CaCO_3$. If we assume that the sediment has a porosity of 0.3 and the solids have a specific gravity of 2.65, then 1 gm of undisturbed saturated solids will be in contact with 0.162 ml of water. The equilibrium concentrations of Ca^{2+} and HCO_3^-, which occurs at a pH of about 9, are 23 and 70 mg/l, respectively. The amount of carbonate present in the 1 gm sample is adequate to saturate about 890 pore volumes with respect to calcite and yet is right at the lower limit of detection. Using the 10 gm sample improves the picture to the extent that the sample can saturate about 89 pore volumes with respect to calcite.

Using the standard type of gasometric procedure used in geological studies (for example, Dreimanis, 1962) gives results of the same order of magnitude. The lower limit of detection using a Chittick apparatus is about 1 ml. This is a calcium carbonate equivalent of about 0.45 percent for a 1 gm sample of 0.045 percent for a 10 gm sample and represents 4.46×10^{-5} moles of $CaCO_3$. This is enough carbonate to saturate about 110 pore volumes with respect to Ca^{2+} and HCO_3^- at a pH of 8.4.

From the preceding analyses it is obvious that neither weight loss nor gasometric techniques of carbonate determinations are sensitive enough for the needs of geochemical evaluation of subsurface water.

1.2.2.3 Determination of Ion-Exchange

The cation-exchange-capacity is determined according to a scheme of analysis as outlined by United States Salinity Laboratory Staff, 1954. The procedure is as follows: (1) A sample of soil is extracted with an excess of neutral normal ammonium acetate solution. The milliequivalents of the various cations removed per 100 ml of soil are determined. If carbonates of calcium and magnesium are known to be present in the soil, determination of these cations is omitted. The determination of calcium is also omitted if the soil is known to contain gypsum not completely soluble in the saturation extract. Lacking prior knowledge of calcium and magnesium carbonate and gypsum contents of the soil, the calcium and magnesium determinations are disregarded if the sum of the values for exchangeable cations is greater than the cation-exchange-capacity of the sample. (2) A saturation extract of the soil is prepared and milliequivalents of the various soluble cations per 100 gm is determined. (3) Exchangeable cation contents of the sample are calculated by subtracting the amounts of the various cations dissolved in the saturation extract from the amounts extracted by the ammonium acetate solution. (4) The cation-exchange-capacity is determined by measuring the milliequivalents of sodium adsorbed per 100 gm of soil after treating the sample with an excess of normal sodium acetate solution of pH 8.2.

Soil samples having low permeabilities are leached by shaking and centrifuging with successive portions of the extract and wash liquids.

1.2.2.4 Sodium-Adsorption-Ratio—SAR

The Sodium-Adsorption-Ratio is a parameter derived from major-ion analysis of the saturation extract from overburden samples. It is defined as "a ratio for soil extracts. . .used to express the relative activity of sodium ions in exchange reactions with soil." (United States Salinity Laboratory Staff, 1954, p. 156).

$$SAR=\frac{Na^+}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}}$$

where the ionic concentrations are expressed in milliequivalents per liter.

Examination of this expression indicates that the SAR is a function of salinity as well as ratio of Na^+ to Ca^{2+} and Mg^{2+}. Thus, at the same relative proportions, the Na^+ in a more saline soil is more effective in determining the properties of the soil than in a slightly saline soil.

1.2.3 Methods of Groundwater Monitoring, Sampling and Analysis

Sampling of groundwater in the five study areas was accomplished by the installation of standpipe potentiometric observation wells. The specific procedures used to install the wells are given in appendix A. After a testhole was drilled and logged, a section of PVC pipe, long enough to reach the desired bed, was assembled and lowered into the hole. The lower 1.5 to 5 feet of the pipe consisted of an intake, which was either a slotted section of pipe, or a wrapped PVC well screen. The intake zone was gravel packed and then a concrete seal was poured above the gravel. The well was pumped by air lift with a compressor until the water was clean, the pH had stabilized to ±0.1 pH units, and the conductivity had stabilized to ±10 percent.

The water level in the wells was measured periodically to determine the hydraulic head in the various aquifers. These data were used to develop an interpretation of the groundwater-flow pattern in each area.

Water samples from some of the wells were obtained by pumping the well by air lift. In other wells, after pumping for a period of time, the water level was allowed to recover to the static level and a sample was bailed from the well using a section of pipe with a foot valve at its base. Oxygen 18 isotope studies on wells at the Dunn Center site (Moran and others, 1976) indicated that extended pumping periods are required in some wells to remove water that was introduced during drilling of the well. We have seen no evidence in any of our analyses of contamination of the water by the concrete used to seal the well. Pumping wells by air lift (or any other gas, which is bubbled through the water) appears to alter the chemical composition of the water so that it is not representative of the in-place groundwater. The bubbles permit rapid degassing of dissolved CO_2. This produces an increase in pH which in turn causes the water to become supersaturated with respect to calcite. Precipitation of calcite alters the Ca^{2+} and HCO_3^- concentration in the water. Certain analyses must be done in the field at the time of sampling and the samples must be properly preserved to prevent alteration of the water chemistry. The temperature, pH, and electrical conductance must be measured as soon as the sample is collected. The samples must be preserved in various ways for various analyses. The procedures for sample preservation outlined in Methods for Chemical Analysis of Water and Wastes (EPA, 1973) have been adopted as part of our standard procedures. All samples are filtered in the field using a filter bottle pressurized with a nitrogen cylinder (Ghering, 1976, p. 24-25). Samples for heavy metal analyses are acidized. Samples for major ions are chilled. Samples for nitrogen analyses are sterilized.

The importance of proper and careful sampling and treatment of groundwater samples cannot be stressed enough. As this study as well as concurrent and subsequent studies, has progressed it has become increasingly obvious that meaningful chemical analyses are extremely difficult to acquire. Very careful attention to the field sampling aspect of the problem can increase the probability of acceptable results. On the other hand, careless or incorrect technique in the field can render meaningless the most carefully performed laboratory analysis.

1.3 Description of Study Sites

1.3.1 Location of Study Sites

The Falkirk area consists of about 50 square miles located in southeastern McLean County (fig. 1.1.2-1). The area includes part of townships 145 and 146 north and ranges 81, 82, and 83 west (fig. 1.3.1-1).

The Indian Head site includes the area of the Indian Head Mine near Zap, in Mercer County, North Dakota, as well as land adjacent to the mine where mining is planned during the next 12-15 years (fig. 1.1.2-1). The study area includes about 7 square miles in sections 30, 31, and 32 of T144N, R88W, and sections 24, 25, 26, 35, and 36 of T144N, R89W (fig. 1.3.1-2).

The Beulah-Hazen study area consists of about 20 square miles in T145N, R87W in north-central Mercer County (figs. 1.1.2-1 and 1.3.1-3).

The Dunn Center area is located in west-central North Dakota in approximately the center of Dunn County (fig. 1.1.2-1). It consists of an area of about 172 square miles in townships 143, 144, 145 and 146 north and ranges 93, 94, and 95 west (fig. 1.3.1-4). Mine Area No. 1 consists of approximately 40 square miles in the center of the Dunn Center area that includes the southernmost sections in township 145 and the northern 2/3 of township 144 (fig. 1.3.1-4). Mine Area No. 1 was studied much more intensively than the remainder of the Dunn Center area.

The Center site consists of about 16 square miles near Center, in Oliver County, North Dakota. It consists of portions of townships 141 and 142 north, range 84 west (fig. 1.3.1-5).

1.3.2 Physiography and Topography of Study Sites

All five of the study sites are located in the glaciated portion of the Missouri Plateau section of the Great Plains Physiographic Province (fig. 1.3.2-1).

The Falkirk site is largely an area of nonintegrated drainage on the south edge of a low, glaciated, upland drainage divide. The western edge of the site is drained by small unnamed creeks that flow into the Missouri River. The southern and eastern edges of the site drain into the Weller Slough complex of lakes on the surface of a buried preglacial valley. These lakes drain by an intermittent stream to the east and south, ultimately into the Missouri River.

Except where late glacial or post-glacial erosion has exposed the underlying Sentinel Butte Formation along the sides of the small valley trending southward from Underwood and along the valley of Coal Lake Coulee, sediment of the Coleharbor Formation underlies the surface. The Coleharbor Formation is generally from 10 to 150 feet thick.

Around the town of Underwood the surface is generally undulating to rolling and north of Underwood is characterized by numerous prairie-pothole sloughs. East, west, and south of Underwood the hummocky constructional glacial topography is replaced by longer slopes and the better integrated drainage of the underlying bedrock topography. Except in very small areas, the bedrock is obscured by a blanket of glacial drift and the landscape is inherited from prior to the last glaciation. Post-glacial erosion has been very minor in most of the area.

Most of the area is cropland. Pastureland is generally limited to steep slopes along the valley sides and on the major north-south trending glacial thrust ridge that lies about two miles east of Underwood.

The Indian Head site is situated on an upland area between Spring Creek and the Knife River. Although the area has been glaciated, most glacial sediment has been eroded. The topography is generally rolling to very steep with occasional small areas of "badlands" topography along surface drainages.

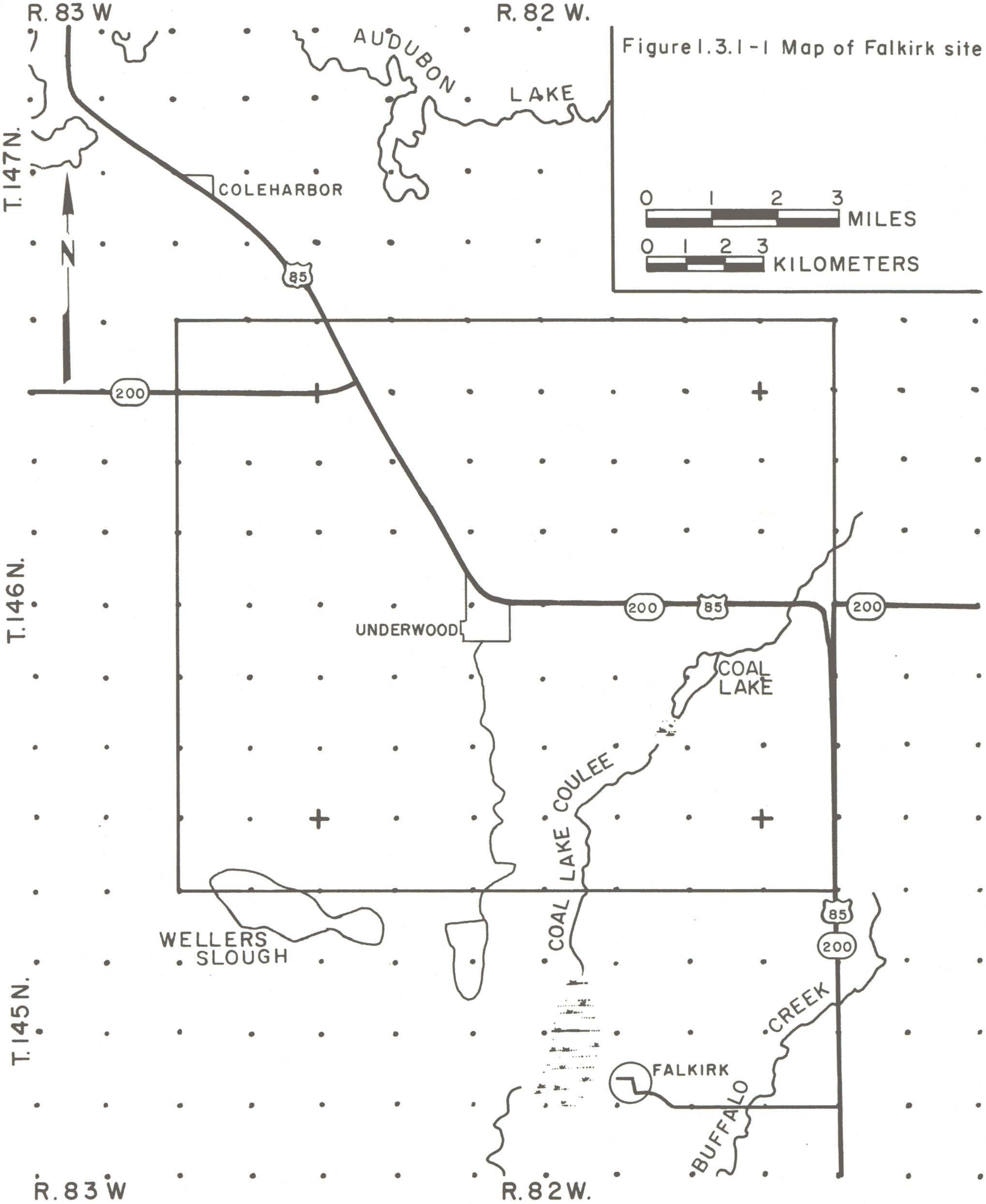

Figure 1.3.1-1. Map of Falkirk site.

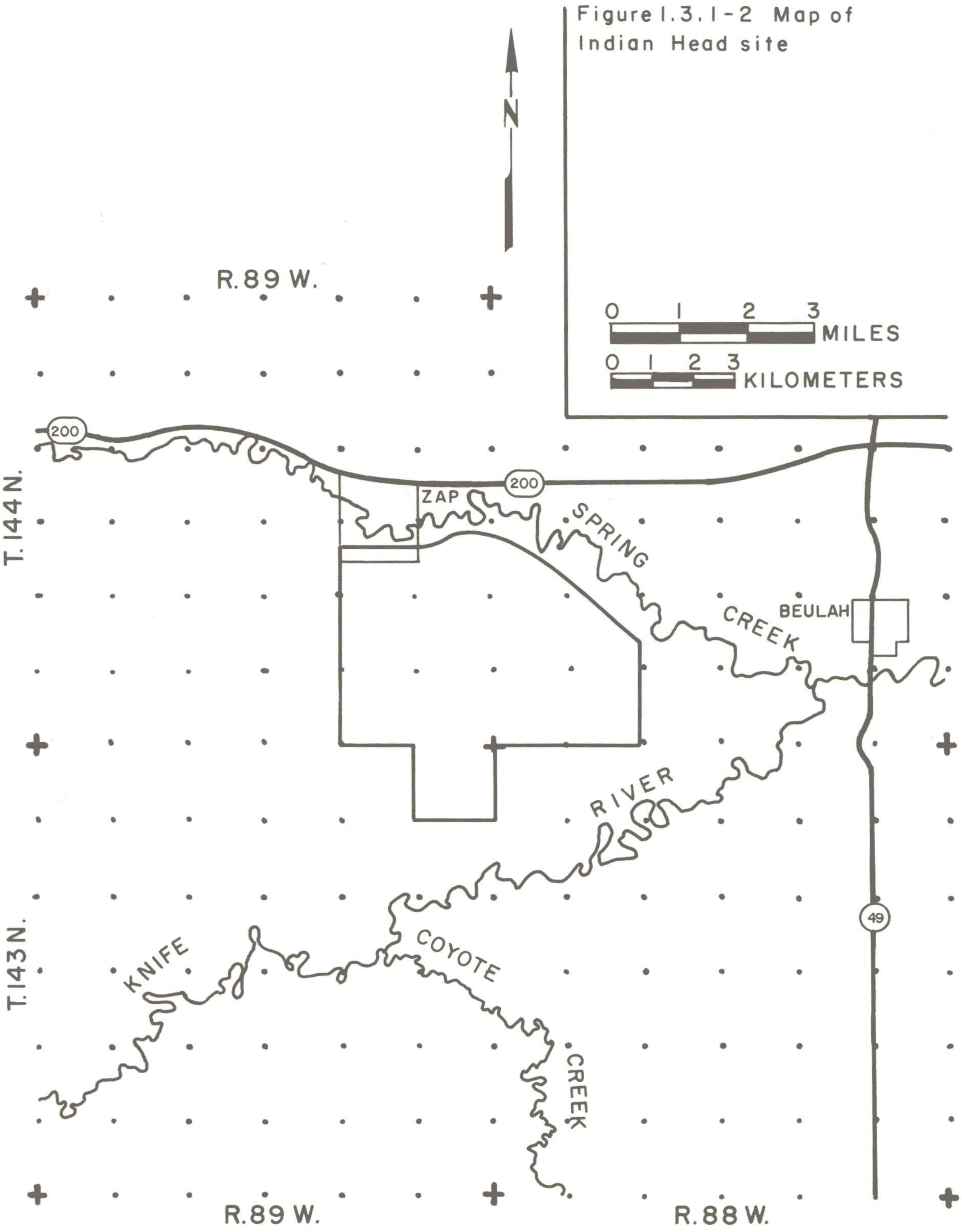

Figure 1.3.1-2. Map of Indian Head site.

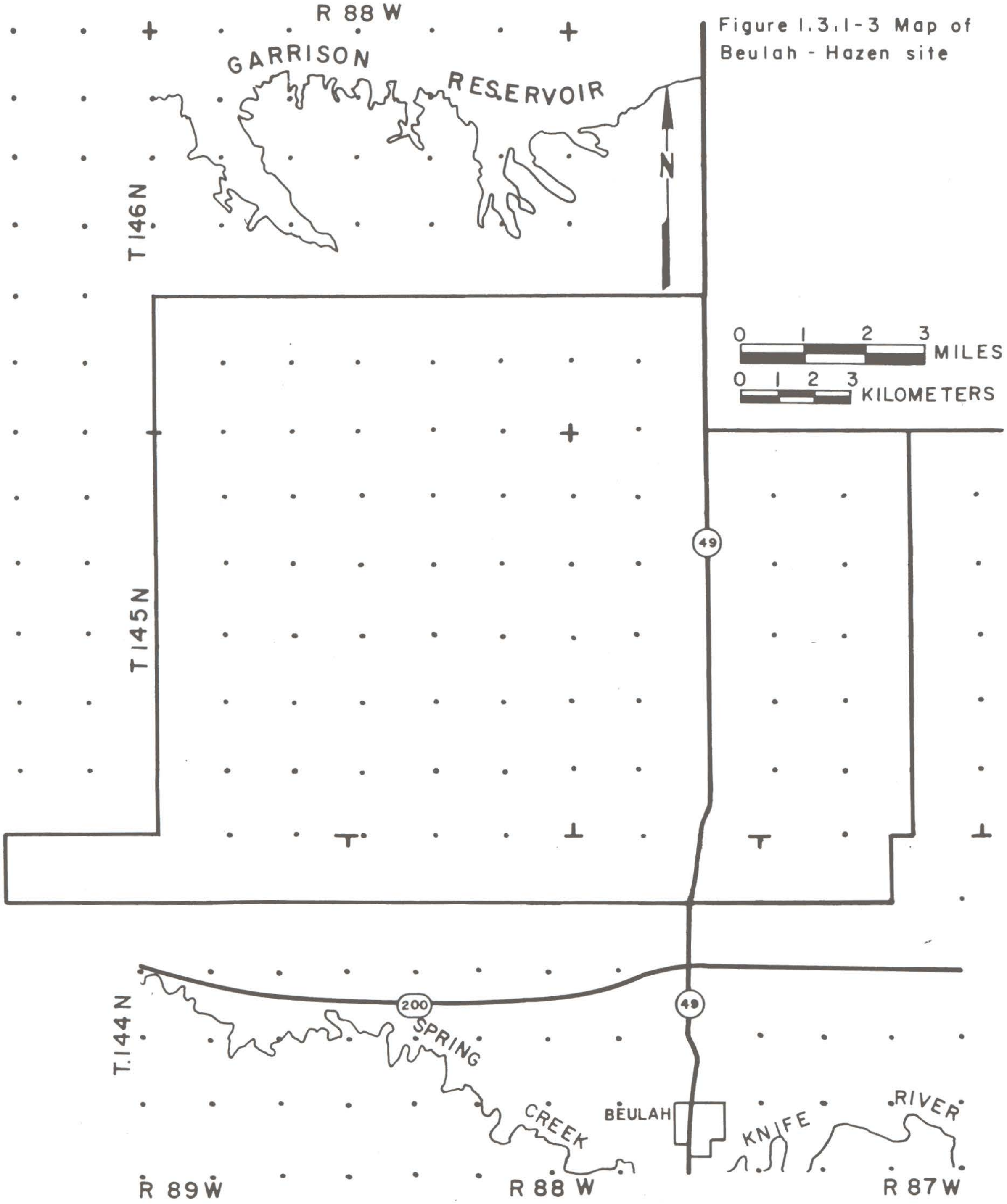

Figure 1.3.1-3. Map of Beulah-Hazen site.

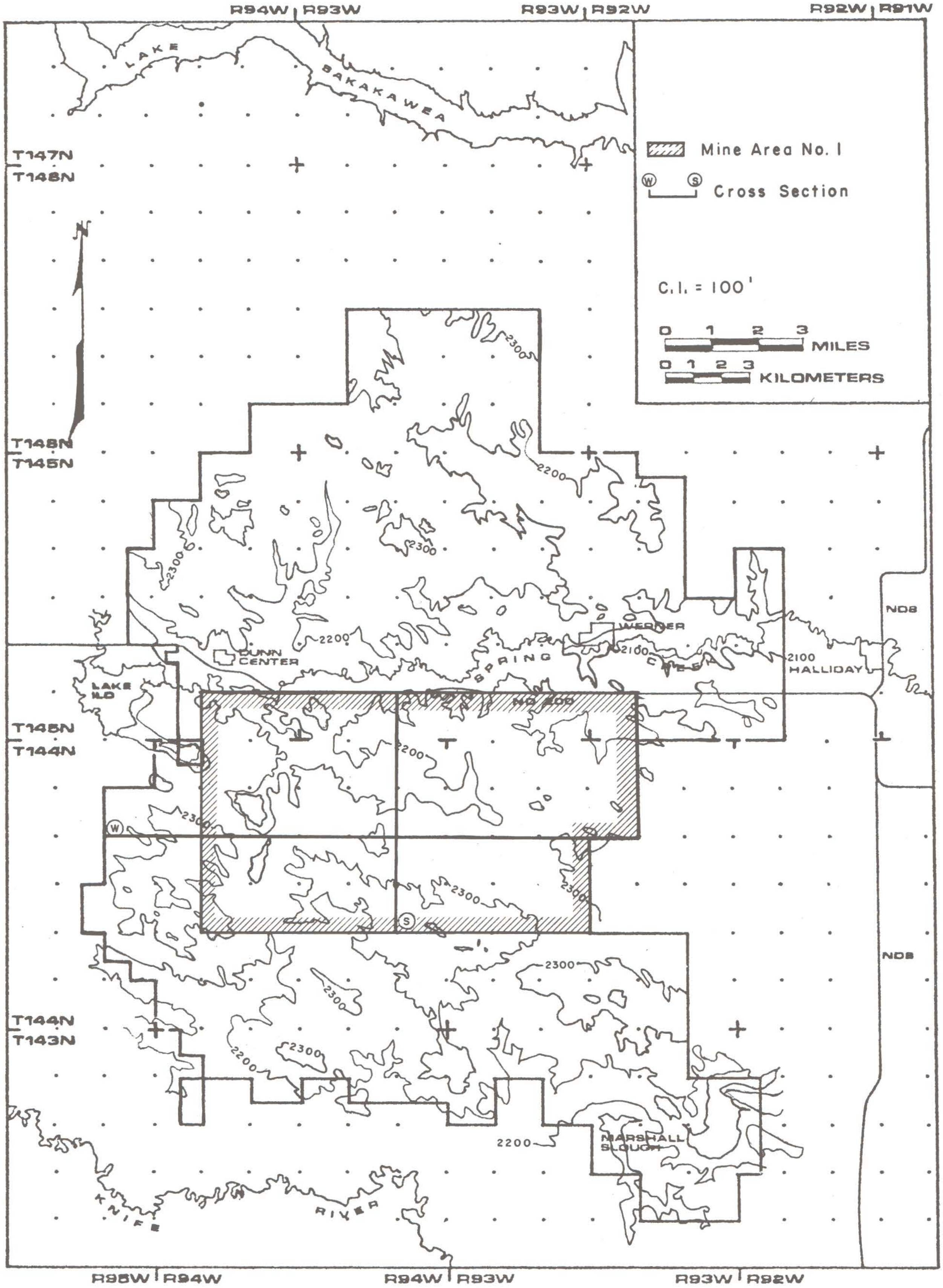

Figure 1.3.1-4. Map of Dunn Center area.

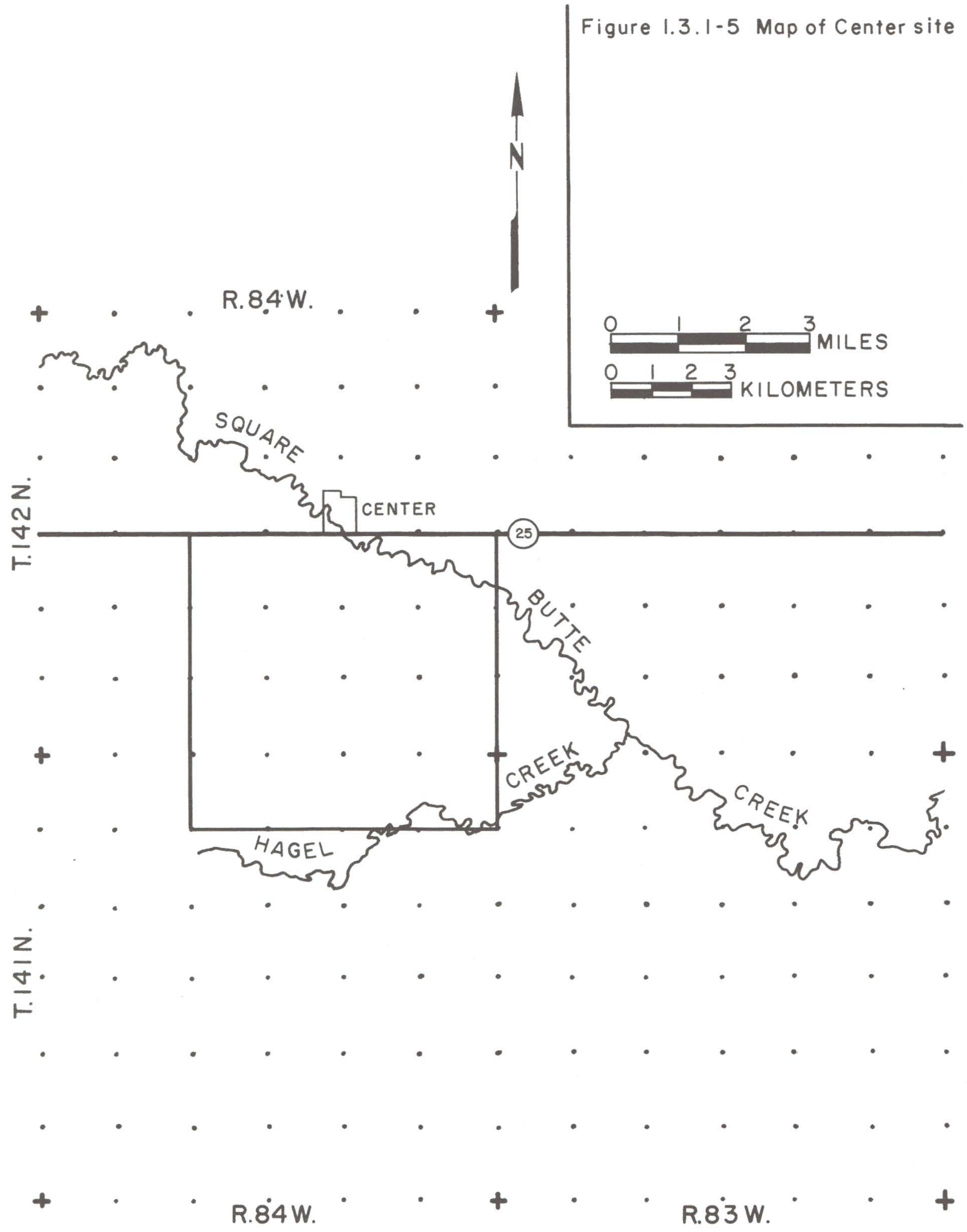

Figure 1.3.1-5. Map of Center site.

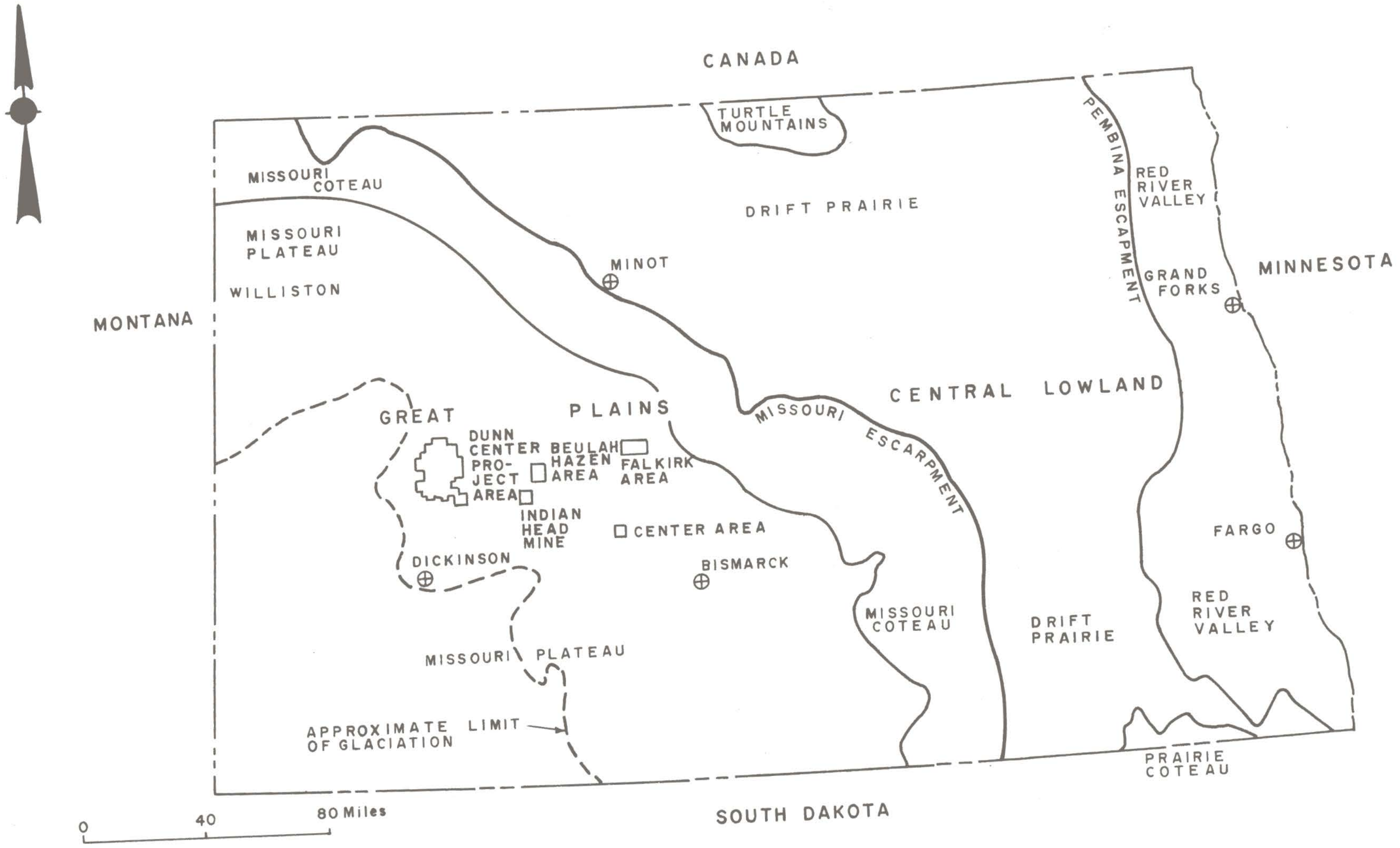

Figure 1.3.2-1. Map showing physiographic setting of the study sites.

The area is predominantly pastureland. Cropland is limited to areas of gentle slopes.

Scattered about the area are surface-subsidence features that consist of groups of circular depressions 50 to 100 feet across, which have resulted from the collapse of abandoned, underground-mine workings.

The Beulah-Hazen area is situated on a broad, glaciated upland that is bisected by a northwest-southeast trending glacial meltwater trench. The site, which lies on the divide between the Missouri River and Spring Creek, is characterized by undulating topography with 20 to 40 feet of local relief and poorly integrated drainage. Numerous shallow prairie-pothole sloughs occupy the depressions. The pebble loam of the Coleharbor Formation that veneers the upland surface is typically 5 to 40 feet thick.

The meltwater trench which bisects the area, the Beulah Trench, was cut during a temporary diversion of the Missouri River when its eastward course was blocked by glacial ice. The generally flat floor of the trench is about ½ mile wide and lies as much as 250 feet below the upland surface.

The Dunn Center area is located within the Knife River Upland straddling the valley of Spring Creek, a tributary of the Knife River (fig. 1.3.1-4). The valley here is about 15 miles wide and 200 to 300 feet deep. The valley of the Little Missouri River lies about four miles north of the project area (fig. 1.3.1-4). 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 two to three miles. About two to four 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 an elevation above 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 Dunn Center area is characterized, for the most part, by integrated drainage typical of the Great Plains. Approximately 3/4 of the area is classified 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 (Moran and others, 1976). Most of the nearly level topography in the project area lies on the nearly flat floors of two partially-filled glacial meltwater 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.

Throughout most of the project area, the land surface is covered by boulders. In most areas, the boulders are few and scattered, but in some places they are so abundant that a man could walk across an entire quarter section and never have to step on the ground. 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 meltwater valleys. All of the large lakes in the project area, including Lake Ilo and Marshall Slough, are of this latter type.

The Center site is situated on an upland area between Square Butte Creek and Hagel Creek. Sediment of the Coleharbor Formation underlies the surface in most of the western half of the site. Post-glacial erosion has removed most of the sediment of the Coleharbor Formation in the eastern part of the study site.

The topography is generally rolling

with occasional small areas of steep topography. The site is predominantly cropland. Pastureland is generally limited to steep slopes along drainages.

In order to provide the reader with a more thorough understanding of the characteristics of the study area to aid him in generalizing the results of this study, we have included discussions of soils, vegetation, and climate of the study sites in appendix B.

1.3.3 Geologic Setting of the Study Sites

The area of the study sites is underlain by 11 000 to 14 000 feet of sedimentary rock lying on a basement of Precambrian igneous and metamorphic rock. The sedimentary column consists of alternating beds of limestone, dolomite, shale, sandstone and evaporite having varying thickness and attitude (Carlson and Anderson, 1970). The uppermost units, the Coleharbor, Golden Valley, and Sentinel Butte Formations, either will be disturbed by the proposed mining activity or contain aquifers that are part of the local and intermediate groundwater-flow systems. Aquifers in the Bullion Creek Formation (Clayton and others, 1977), which underlies the Sentinel Butte Formation, and thick aquitards of the underlying Cannonball Formation are also part of the intermediate groundwater-flow system.

The Cannonball Formation consists of an alternating succession of silt and clay beds that is about 300 feet thick in the eastern part of the area and thins to about 200 to 250 feet in the western part of the area. It contains two or three sand beds as much as 30 feet thick. The silt and clay beds are offshore marine deposits and appear to be laterally continuous across the entire area. The Cannonball Formation, therefore, serves as a regional aquitard, which separates the shallow, intermediate groundwater-flow system from the flow system in the underlying Fox Hills and Hell Creek Formations.

The Bullion Creek Formation (Clayton and others, 1977) ranges in thickness from about 250 feet in the eastern part of the area to as much as 650 feet in the western part of the area. In the eastern part of the area, the formation consists of two distinct lithologic units. The upper unit is 80 to 100 feet of interbedded silt, clay, sand, and lignite (Hemish, 1975). The lower unit consists of as much as 150 feet of fine-grained, poorly sorted, bluish sand overlying a few tens of feet of silt, clay, and lignite (Hemish, 1975). The sand thins to the west and has not been definitely identified in the western part of the area (Moran and others, 1976; Croft, 1973). However, hydraulic head data from the western part of the area indicate that there is a groundwater drain in the lower part of the Bullion Creek Formation strongly suggesting that the sand is present. The upper contact of the Bullion Creek Formation in the Dunn Center area now appears to be about 100 to 125 feet lower than the arbitrarily defined contact of Moran and others (1976). Throughout the area this contact is marked by a lignite bed, which is from three to seven feet thick (Hemish, 1975), and by a color change from bluish gray and olive gray (Munsel 5Y colors) in the Sentinel Butte Formation to brownish gray and yellow brownish gray (Munsell 2.5Y and 10YR colors) in the Bullion Creek Formation.

The Sentinel Butte Formation consists of alternating beds of silt, clay, sand, and lignite. 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 Sentinel Butte Formation contains 11 major lignite beds. The lower beds can be traced throughout the area; the upper beds are progressively truncated by erosion toward the east. In each study site, one or more lignite beds overlie the main bed. The Beulah-Zap bed, which is the fourth major lignite bed below the top of the formation, is mined at Indian Head Mine and will be mined at the Beulah-Hazen site. The main lignite to be mined at Dunn Center was referred to as the Dunn Center bed (Moran and others, 1976). More recent work, however, indicates that it, too, is the Beulah-Zap bed. The Hagel bed, which is the sixth major lignite below the Beulah-Zap bed, is the main bed at Center and Falkirk.

The structure of beds in the Sentinel Butte Formation is variable. In the western part of the area, the beds in the Sentinel Butte Formation dip generally eastward. From the Zap area eastward, the beds generally dip westward or northwestward. Small-scale structures are superimposed on this regional pattern as a result of original topographic irregularities on the depositional surface, differential settlement as a result of consolidation (compaction), and in some areas, subsidence resulting from or solution of salt beds at depth. These small-scale structures commonly produce elevation changes of as much as 40 feet in half a mile on individual beds. As a result, dips are locally very much steeper or reversed.

The Golden Valley Formation caps isolated buttes north of the Dunn Center 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. It is extensively exposed on both sides of the Spring Creek valley west of the Indian Head Mine and the Beulah-Hazen site. 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).

The Coleharbor Formation (Bluemle, 1972), 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 contains sand, silt, and clay which are stratigraphically above the type Coleharbor Formation, in the Oahe Formation (Clayton and others, 1976; Clayton and others, 1977). The Coleharbor Formation is used in this 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.

Sediment of the Coleharbor Formation occurs in three distinct settings in the project area: (1) thick layers covering uplands and obscuring pre-existing topography; (2) thin, discontinuous patches on the uplands, largely restricted to the western and southern part of the area; and (3) thick, linear bodies filling glacial meltwater channels.

The thick layers of the Coleharbor Formation that cover upland areas generally consist of silty pebble loam, but in some places, nearly the entire thickness of the formation is sand and gravel. Thick pebble loam of the Coleharbor Formation is limited to the Falkirk, Center, and Beulah-Hazen sites. The thickness of the pebble loam ranges from a few feet to as much as 150 feet in the northern part of the Falkirk site. In at least two places at the Falkirk site, blocks of sediment from the Sentinel Butte Formation, which are as much as 80 feet thick and several tens of acres in area, have been thrust up into the pebble loam of the Coleharbor Formation. Thrust features of this type have been identified about two miles northeast and about three miles south-southeast of Underwood.

In numerous testholes that have been drilled in the Falkirk site and in surface exposures throughout the area, it has been possible to recognize subdivisions of the Coleharbor Formation. Sediment that is correlative with the Medicine Hill Formation and the Snow School or Horseshoe Valley Formations of Ulmer and Sackreiter (1973) were identified in several locations. At least one additional unit appeared to be present beneath the Medicine Hill Formation in the eastern part of the Falkirk area. Sand and gravel beds in the lower parts of these units form small but potentially significant aquifers in local areas. Because the subdivisions of the Coleharbor Formation have not been recognized throughout the project area they have not been mapped and the Coleharbor Formation has not been elevated to group status.

Thin patches of the Coleharbor Formation that generally consist of clayey to silty pebble loam (till), which contain scattered boulders, occur on uplands in the northern part of the Dunn Center area. 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 thin patches of pebble loam, which range in area from a few hundred square feet to a few acres, will be encountered through the southern part of the project area, at the Dunn Center, Indian Head, and Center sites. Isolated patches of gravel, from one to three feet thick, which are too thin and too small to map also occur in this area.

The third major occurrence of sediment of the Coleharbor Formation is in thick, complex valley fills. The maximum thickness of these valley fills ranges from about 120 to about 250 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. In some places, several layers of sand and gravel are separated by layers of pebble loam or lacustrine clay. In a few places, sand beds were found in the upper, generally fine-grained, part of the fill, very near the surface. Valleys of this type include the large preglacial valley underlying the Weller Slough complex south of the Falkirk site, the Beulah Trench and other major meltwater trenches in the vicinity of the Beulah-Hazen site, and the meltwater trenches that cut across the central, eastern, and western parts of the Dunn Center site. In most cases, these valleys are eroded below the main lignite and will not be disturbed by mining.

A thin veneer of windblown silt of the Oahe Formation (Clayton and others, 1976; Clayton and others, 1977) blankets upland surfaces throughout the area. It is probably no more than three feet thick in the Beulah-Hazen and Falkirk sites but becomes as much as 15 feet thick at the top of the bluffs along Lake Sakakawea in the northern part of the area.

1.3.4 Hydrogeology and Groundwater Hydrology of the Study Area

The study area is largely an upland recharge area where water moves downward through low permeability material until it encounters more permeable sand and lignite beds. Much of the water is transmitted along these beds to nearby outcrops where it is discharged in springs. Groundwater that stays in the system by penetrating deeper is carried toward the Missouri River by widespread sand units that underlie the area.

The level of knowledge about the hydrologic setting at the study site varies considerably. Each site is discussed individually in this section.

1.3.4.1 Hydrogeology of the Falkirk Site

The Falkirk site consists of a bedrock divide that is capped with pebble loam of the Coleharbor Formation. The site is ringed on three sides, the south, west, and north, by deeply incised preglacial valleys that have been partly or completely filled by sediment of the Coleharbor Formation. To the east, the site is bordered by a glacial meltwater trench that completes the hydrologic isolation of the shallow aquifers underlying the site. The entire area of the site is dominated by downward flow of groundwater, and, therefore, is generally an area of groundwater recharge.

The hydraulic conductivity of the gravel, sand, and lignite aquifers beneath the site is several orders of magnitude greater than that of the pebble loam, silt, and clay confining beds. As a result, the flow system is characterized by a strong anisotropy. Flow in the confining beds is nearly vertical, and nearly everywhere downward; flow in the aquifers is horizontal and nearly everywhere radially outward from the apex of the upland beneath the city of Underwood. Because of the low hydraulic conductivity of the pebble loam that underlies nearly all of the site, groundwater recharge is very slow or nonexistent over most of the site.

Groundwater recharge appears to be restricted to a few areas where the pebble loam is absent or very thin and fractured and where thick sand beds in the Sentinel Butte Formation occur at or very close to the surface. Observations of water levels in shallow wells, the behavior of numerous large surface water bodies, and, not uncommon, mineralized fractures in cores of fine-grained material suggest strongly that the area around the city of Underwood is the site of much, if not most, of the recharge to the shallow groundwater regime.

The two lignite beds that will be mined, as well as the sand beds above the Hagel bed and below the B bed, outcrop subaerially or subcrop against permeable sediment of the Coleharbor Formation all around the site. As a result, nearly all the groundwater in these shallow aquifers is discharged as springs or into the major valley-fill aquifers. Little to no water that is recharged in the Falkirk site appears to reach the thick sand aquifer in the lower part of the Bullion Creek Formation, which underlies the entire site. Hydraulic head data suggest that this aquifer is recharged east of the site and discharges in the Missouri River valley west of the site.

1.3.4.2 Hydrogeology of the Indian Head Site

The movement of groundwater in the sand and lignite aquifers in the Indian Head site is generally horizontal. The predominant movement of groundwater in the fine-textured sediments is vertically downward in response to the decrease in hydraulic head with increased depth. The movement of water within the Beulah-Zap bed is predominantly away from the area of high head along the partly drift-filled valley that crosses section 36.

The major area of recharge to the Beulah-Zap bed, in the mine area, appears to be in the vicinity of this partially buried valley. The dissipation of hydraulic head beneath adjacent uplands indicates that the Beulah-Zap bed is receiving little or no recharge in the upland areas.

A widespread sand unit lies approximately 50-80 feet above the Beulah-Zap bed beneath upland areas. This unit appears to be saturated in at least two locations (sites X-2 and 149). Site X-2 is close to site X-1 where the Beulah-Zap bed is dry. Springs and seeps are common in areas where this sand unit outcrops. It appears, therefore, that the sand contains perched water, and that the unit functions independently of the Beulah-Zap bed. Whether the groundwater conditions in the Indian Head site are representative of the entire surrounding area is uncertain. The study area is relatively small, and thus, these conditions may be highly site specific.

1.3.4.3 Hydrogeology of the Beulah-Hazen Site

Limited information is available concerning the hydrogeology of the Beulah-Hazen site. The Beulah-Zap bed is a water supply for a few domestic wells in the area. However, saturation of this bed appears to be highly variable and is commonly under water table conditions (Woodward-Clyde, 1975).

In general, the flow system in the study area can be characterized as being very sluggish. The overburden above the Beulah-Zap bed is predominantly fine-grained bedrock (silt and clay) and glacial till (Woodward-Clyde, 1975). Potentiometric head values indicate downward movement of groundwater in the fine-grained materials and predominantly lateral movement in the more permeable lignite and sand units. Most recharge in the area is highly localized resulting from leakage from scattered sloughs and ephemeral streams. Scattered springs and seeps occur along the sides of the Beulah Trench in locations where the Beulah-Zap bed is exposed. Leakage rates into and out of the Beulah-Zap bed from overlying and underlying units appear to be very low due to the presence of relatively thick clay and silt units.

1.3.4.4 Hydrogeology and Groundwater Hydrology of the Dunn Center Site

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 two 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 ($1x10^{-3}$ to $1x10^{-5}$ cm/sec) is several orders of magnitude greater than that of the silt and clay confining beds ($1x10^{-6}$ to $1x10^{-9}$ cm/sec). 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 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 slope 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.

1.3.4.5 Hydrogeology of the Center Site

The three stratigraphic units of major hydrological concern are the upper lignite, the lower lignite (Hagel bed) and a silty sand which lies approximately 50 feet below the lower lignite (pl. C.5-1).

The distribution of hydraulic head values in these units indicates a general trend toward decreasing head values with increasing depth below the surface. The lowest hydraulic head values in the two lignites occur around the margins of the study area. The highest head values in these units occur, in general, in the vicinity of the areas of highest surface topography.

The head values in the upper lignite indicate that it is transmitting very little water throughout much of the southwestern portion of the study area. To the northeast, at site 379, the upper lignite is dry. The only area where the upper lignite appears to be transmitting considerable water is in the vicinity of sites 367, 368, and 371. The Hagel bed, on the other hand, appears to be a major aquifer throughout most of the study area.

The hydraulic head values in the sand unit show a much different trend than those in the lignites. The head values in this unit show a general decrease across the study area from the southwest to the northeast. There is no apparent relationship to surface topography as is the case with the lignites.

In general, the movement of groundwater in the fine textured materials (aquitards) is vertical. On the other hand, movement of groundwater in the sand and lignite aquifers is essentially horizontal or lateral. The decrease in hydraulic head with depth, as mentioned previously, indicates that flow within the aquitards is downward.

In general, downward movement of groundwater through the various aquitards supplies water to the aquifers. The aquifers, in turn, both lose water to underlying aquitards and transmit water laterally to discharge areas along slopes.

The major recharge areas for both lignites correspond closely with upland areas. Discharge from the two lignites is along valley slopes, particularly along Hagel Creek and Square Butte Creek. Thus, essentially all groundwater flow within both the upper lignite and the lower lignite is local, originating and terminating with the study area.

Groundwater flow within the sand is apparently related to a larger flow system than that which controls shallow aquifers. The general decreasing trend in hydraulic head values across the study area from southwest to northeast indicates that flow within this unit is probably controlled by the Square Butte Creek valley. Thus, the major discharge area for the sand is probably in the buried sand and gravel below Square Butte Creek. The major area of recharge to this unit is apparently to the southwest of the study area.

2. INVENTORY OF OVERBURDEN COMPOSITION

In the preceding sections and appendix B, the location, topography, vegetation, soils, climate, geology, and groundwater regime of the study area and sites have been described. The information on the groundwater regime was developed in part through this study using methods outlined in appendix A but largely through other studies that were conducted prior to, concurrently with, or subsequent to this study. The geologic information both in section 1.3.3 and appendix C was developed largely during this study. These data serve as the basic physical framework within which to develop an inventory of overburden composition.

This section consists of a discussion of the observed geochemical characteristics of the overburden in the study area discussed on a site by site basis. More than 500 analyses of the chemistry of saturation extracts from core and cutting samples were made by the Soils Reclamation Laboratory at North Dakota State University as part of this and related projects. In order to organize these data in such a way that they can be discussed and handled conceptually, they have been grouped within each site on the basis of the stratigraphic units described in appendix C and are listed in appendix D. A description of the units within each group is included.

Several significant trends regarding the chemical properties of overburden materials can be noted from these anlayses. (1) Materials having a higher clay content have a greater tendency to be sodic. (2) The proximity of the materials to the land surface, regardless of texture, has a strong influence on the chemical characteristics of the materials. Weathering in the near-surface zone results in the release of various ionic species into the system. (3) The direction of groundwater movement in the near-surface zone in large part controls the chemical characteristics of the materials. For example, areas of groundwater infiltration are flushed and characterized by low salinity and SAR. Areas of groundwater exfiltration are characterized by high salinity and variable SAR's. (4) It is very likely that geochemical variations in the materials, related to the original environment of deposition and interacting with number (3) above, can have a strong influence on the chemical characteristics of the overburden materials.

This section summarizes the analytical data on the overburden of the study sites. In the first part of the section the data from each site are grouped on the basis of their stratigraphic position. Each unit that was sampled is discussed in terms of its ability to meet the requirements of suitable plant-growth material in North Dakota, SAR < 10, ECE < 4.

It is immediately evident from a review of these data and discussions that considerable variation exists within these stratigraphically based groupings. Much of the variation appears to result from differences in landscape position and subsurface-water-flow patterns. In order to take this variation into account, the second part of this section begins with a reclassification of the analytical data into groups that are defined on the basis of the data. The distribution of these groups in the landscape forms several consistent patterns. These patterns are then used to characterize the overburden.

2.1 Stratigraphic Grouping of Analytical Data

The analytical data from each site are summarized by stratigraphic unit in appendix D. Each site is described in the following section.

2.1.1 Falkirk Site

2.1.1.1 Coleharbor Interval

The Coleharbor interval consists of pebble loam, sand and gravel, and silt. Numerous samples of the pebble loam were analyzed. Seven samples of the sand and gravel were analyzed.

2.1.1.1.1 Unit 530.—All pebble loam was included within unit 530. In all but one case, the samples were calcareous. The electrical conductivity of these materials ranged from less than 0.5 to greater than 11. Most values were less than four. The SAR values were very low, generally less than two.

2.1.1.1.2 Unit 510.—Seven samples were analyzed from unit 510. This unit consists of sand and gravel. The ECE values ranged from 0.95 to 4.0. The SAR values ranged from 0.6 to 2.6.

2.1.1.2 Hagel Interval

The Hagel interval consists of the material between the Hagel bed and the overlying Coleharbor Formation.

2.1.1.2.1 Unit 280.—Twenty-eight samples from unit 280 were analyzed. The unit consists of interbedded silt and clay. Some sand is also included in this unit. The ECE values ranged from 0.62 to 5.9. Most values were less than 3.0. The SAR values ranged from 0.6 to 13.0. The SAR values were generally less than 6.0.

2.1.1.2.2 Unit 270.—Seventy-eight samples from unit 270 were analyzed. The unit is predominantly sand with minor amounts of silt included. The ECE values ranged from 0.67 to 5.00. Most values were less than 2.5. The SAR values ranged from 0.4 to 30.1. Most SAR values were from 0.5 to 1.5.

2.1.1.2.3 Unit 240.—Fifty samples from unit 240 were analyzed. This unit consists of interbedded clay and silt very similar to unit 280. The ECE was generally about 1 to 2 and ranged from 0.27 to 4.6. The SAR values ranged from 0.4 to 13.5 with the majority of values about 1 to 3.

2.1.1.2.4 Unit 230.—Thirteen samples from this unit were analyzed. Unit 230 consists of clay that in some places is carbonaceous. The ECE values were generally about 1.5 to 3.0 and ranged from 0.83 to 6.2. The SAR values were generally about 0.5 to 1.5. Three samples had high SAR values (12-20). All three samples were from greater than 80 feet in depth.

2.1.1.3 The B-Interval

The B-interval includes all intervals between the B-bed and the Hagel bed.

2.1.1.3.1 Unit 190.—Eight samples of unit 190 were analyzed. The unit consists of clay that in some places is carbonaceous. The ECE values ranged from 1.46 to 3.2. The SAR values ranged from 0.3 to 6.2 generally about 0.5 to 1.5.

2.1.1.3.2 Unit 180.—Ten samples of unit 180 were analyzed. The unit consists of silt, silty sand, and sand. The ECE values ranged from 1.25 to 2.9. The SAR values ranged from 0.5 to 1.9.

2.1.1.3.3 Unit 140.—Seven samples of this unit were analyzed. The unit consists of clay and silty clay. The ECE values ranged from 1.00 to 2.5. The SAR values ranged from 0.7 to 8.0, generally falling between 1 and 2.

2.1.1.3.4 Unit 110.—Only one sample from unit 110 was analyzed. The unit consists of clay that in some places is carbonaceous. The ECE was 1.85. The SAR was 8.8.

2.1.2 Indian Head Site

2.1.2.1 Coleharbor Interval

The materials in the Coleharbor interval consist of pebble loam, silt, and sand and gravel. The Coleharbor interval is absent over most of the study site.

2.1.2.1.1 Unit 590.—Nine samples from unit 590 were analyzed. The unit consists of organic silt and clay. Sand is also included in a few samples. The ECE values were highly variable, ranging from 0.6 to 13.0. The SAR values ranged from 4.0 to 23.7 and were generally between 10 and 20.

2.1.2.1.2 Unit 570.—Sixteen samples from this unit were analyzed. Unit 570 is predominantly silt but in some places also includes clay and sand. The ECE values ranged from 1.19 to 10.9, generally falling between 6 and 10. The SAR values ranged from 15 to 27.1.

2.1.2.1.3 Unit 530.—Only three samples from this unit were analyzed. Unit 530 consists of pebble loam. The ECE values ranged from 2.2 to 6.0. The SAR values ranged from 4.5 to 5.3.

2.1.2.2 Schoolhouse Interval

The Schoolhouse interval includes all materials between the Schoolhouse bed and the Coleharbor interval.

2.1.2.2.1 Unit 260.—Only two samples of unit 260 were analyzed. The unit consists of sand and silty sand. The ECE values ranged from 0.75 to 5.7. The SAR values ranged from 1.1 to 7.1.

2.1.2.2.2 Unit 240.—Seven samples were analyzed from unit 240. The unit consists of interbedded silty sand and silty clay. The ECE values ranged from 1.8 to 10.0. The SAR values ranged from 8.2 to 21.1.

2.1.2.2.3 Unit 210.—Twelve samples from unit 210 were analyzed. The unit consists of interbedded silt and clay. The ECE values ranged from 1.2 to 8.0. The SAR values were generally very high, ranging from 6 to 33.0.

2.1.2.3 Beulah-Zap Interval

The Beulah-Zap interval includes all materials between the Beulah-Zap bed and the Schoolhouse bed.

2.1.2.3.1 Unit 190.—Only two samples from unit 190 were analyzed. The unit consists of clay. The ECE values ranged from 9.0 to 9.1. The SAR values ranged from 10.0 to 11.4.

2.1.2.3.2 Unit 180.—Five samples were analyzed from unit 180. The unit consists of fine sand. The ECE values ranged from 3.6 to 12.9. The SAR values ranged from 11.0 to 21.1.

2.1.2.3.3 Unit 170.—Seventeen samples were analyzed from unit 170. This unit consists of interbedded sand, silt, and silty clay. The ECE values ranged from 1.1 to 10.0. The SAR for the various samples ranged from 9 to 38.4.

2.1.2.3.4 Unit 160.—Six samples were analyzed from unit 160. The unit is predominantly clay. The ECE values ranged from 1.2 to 6.2. The SAR values ranged from 6 to 44.5.

2.1.2.3.5 Unit 150.—Thirteen samples were analyzed from this unit. The unit consists of clay and silty clay. The ECE values ranged from 1.0 to 7.25. The SAR values ranged from 13 to 48.

2.1.2.3.6 Unit 140.—Eleven samples were analyzed. Unit 140 is predominantly sand. The ECE values ranged from 1.69 to 3.6. The SAR values ranged from 24 to 63.

2.1.2.3.7 Unit 130.—Thirty samples from unit 130 were analyzed. The unit consists of interbedded silt and clay. The ECE values ranged from 1.2 to 8.1. Most values were about 1.5 to 3.5. The SAR values were generally very high, ranging from 6.6 to 50.

2.2.1.3.8 Unit 120.—Thirty samples were analyzed. The unit is predominantly sand and silt. The ECE values ranged from 1.03 to 5.5. Most values were between 1.0 and 3.5. The SAR values ranged from 5.1 to 57.7. The SAR values were generally greater than 15.

2.1.2.3.9 Unit 110.—Seven samples were analyzed from unit 110. The unit is predominantly clay. The ECE values ranged from 1.57 to 6.6. The SAR values ranged from 6.4 to 52.

2.1.3 Beulah-Hazen Site

2.1.3.1 Coleharbor Interval

The Coleharbor interval consists of gravel, pebble loam, and clayey silt. The Coleharbor interval is present over most of the study site.

2.1.3.1.1 Unit 570.—Six samples were analyzed from unit 570. The unit consists of clayey silt. The ECE values ranged from 0.27 to 5.10. Most values were about 0.2 to 0.5. The SAR values ranged from 0.3 to 2.

2.1.3.1.2 Unit 530.—Thirty samples were analyzed from unit 530. All the various pebble loams are included in this unit. The ECE values ranged from 0.5 to 6.5. The values generally showed a sharp increase below five feet in depth. The SAR values ranged from 0.2 to 5.

2.1.3.1.3 Unit 510.—Ten samples were analyzed from unit 510. The samples consisted of sand and gravel. The ECE values ranged from 0.5 to 1.26. The SAR values ranged from 0.3 to 7.

2.1.3.2 Schoolhouse Interval

The Schoolhouse interval includes all materials between the Schoolhouse bed and the Coleharbor interval.

2.1.3.2.1 Unit 240.—Twenty-six samples were analyzed from this unit. The samples consisted of silty sand and silty clay. The ECE values ranged from 0.62 to 8.5, being distributed bimodally. Testholes 74-80 and 74-82 had ECE values generally between 0.5 and 2. Testhole 74-81 had ECE values generally between three and six. The SAR values were fairly consistent for all the testholes, ranging from 0.7 to 4.

2.1.3.2.2 Unit 210.—Only five samples were analyzed from this unit. The samples consisted of clay. The ECE values ranged from 0.8 to 3.78. The SAR values ranged from 0.4 to 3.

2.1.3.3 Beulah-Zap Interval

The Beulah-Zap interval includes all materials between the Beulah-Zap bed and the Schoolhouse bed.

2.1.3.3.1 Unit 190.—Only two samples were analyzed from this unit. Both samples were clay. The ECE values ranged from 1.28 to 1.71. The SAR values varied greatly, ranging from 4 to 23.

2.1.3.3.2 Unit 170.—Twelve samples were analyzed from this unit. The samples consisted of interbedded silt and sand and lesser amounts of silty clay. The ECE values ranged from 1.44 to 4.7. The SAR values ranged from 0.7 to 33, most values lying between 0.7 and 1.5.

2.1.3.3.3 Unit 160.—Only two samples were analyzed from this unit. Both consisted of clay. The ECE values varied from 1.87 to 2.53. The SAR values varied from 0.8 to 8.0.

2.1.3.3.4 Unit 140.—Five samples were analyzed from this unit. All five samples consisted of sand. The ECE values ranged from 1.38 to 1.73. The SAR values ranged from 20 to 37.

2.1.3.3.5 Unit 130.—Only two samples were obtained from this unit. Both consisted of silty clay. The ECE values varied from 1.72 to 1.79. The SAR values varied from 12 to 36.

2.1.3.3.6 Unit 120.—Four samples were obtained from this unit. The samples consisted of sand and silty sand. The ECE values ranged from 1.49 to 1.64. The SAR values ranged from 32 to 34.

2.1.3.3.7 Unit 110.—Nine samples were obtained from unit 110. All the samples consisted of clay. Value for ECE ranged from 0.67 to 2.30. SAR values ranged from 5 to 41.

2.1.4 Dunn Center Site

2.1.4.1 C-Interval

The C-interval consists of thin alternating beds of silt, clay, and sand and has not been subdivided. Eleven samples of the C-interval from two sites were analyzed; four are sandy loam and loamy sand, and the remainder are silt loam, silty-clay loam, silty clay, and clay (app.

D). Site 18 is located on an upland in a groundwater recharge area; site 17 is located on a flat near the base of Horse Nose Butte in an apparent groundwater exfiltration zone.

Except for one sample, a clay at 30.3 to 30.6 feet at site 17, the C-interval appears to be noncalcareous. The one calcareous clay contains 3.1 percent $CaCO_3$.

The electrical conductivity of material in the C-interval appears to depend on the dominant direction of subsurface water movement through the site. In infiltration zones over areas of groundwater recharge such as site 18, the conductivity is low, everywhere below 4.0 and at depths below 10 feet, below 2.0. In exfiltration zones, over areas of groundwater discharge, such as site 17, the electrical conductivity is higher, especially near the surface. Values in excess of 4.0 occur from the surface to at least 15 feet. Below 15 feet the conductivity drops below 4.0.

The dominant direction of movement of subsurface water also appears to influence SAR in the C-interval. In infiltration zones, such as site 18, the SAR remains low to greater depths than in exfiltration zones such as site 17. At site 18, the SAR is 2.1 at 10 feet, about 4 at 20 feet, and 19 at 35 feet. At site 17, the SAR is 3.4 at about 10 feet and 9.5 at 12 to 15 feet.

In general, where the C-interval is in a recharge area, it appears to be suitable plant-growth material. In some places, this generalization may not be true as a result of a build-up of salts in the upper ten feet, producing an increase in conductivity above 4.0. Where the C-interval is in a discharge area, it appears to have SAR values low enough to be acceptable; but the electrical conductivity is so high that suitable plant-growth material, if present at all, is limited to the upper few feet.

2.1.4.2 B-Interval

Two of the three units in the B-interval were sampled. Only two samples each were obtained from units 320 and 310.

2.1.4.2.1 Unit 320.—Two samples were analyzed from unit 320. Both were from site 17. Neither is from near the surface, so there is no information on the characteristics of this unit where it has been altered by weathering. The samples analyzed were clay and silty clay loam from 58 to 60 feet deep. They were noncalcareous. The electrical conductivity averages just below 2.0 and the SAR is just under 10.0 (app. D).

The fine-grained sediment of unit 320 appears to have limited sampling and the SAR is just at the upper limit of suitability. This unit should be further studied before being considered for use as suitable plant-growth material.

2.1.4.2.2 Unit 310.—Like unit 320, only two samples of unit 310 were analyzed. One, from 6 to 12 feet at site 19, the other from 55 to 60 feet at site 18. Both samples are fine sandy loam; some loamy sand was present in the sample at 55 to 60 feet. The unweathered sample from site 18 was noncalcareous; the electrical conductivity was less than two and the SAR about five (app. D). The sample near the surface, from site 19, appears to indicate a build-up of calcareous material, salts, and sodium (app. D).

Except near the land surface, material of unit 310 appears to meet the criteria of suitable plant-growth material. Near the surface, however, it may become too saline and possibly too sodic, as a result of a build-up of soluble salts.

2.1.4.3 A-Interval

Fifty-nine samples of the A-interval were analyzed. In general terms, the materials of the A-interval appear to be undesirable materials to have near the final land surface after mining. This generalization is less applicable where the materials have been altered by exposure near the surface. Although limited in extent, the use of these materials should be carefully considered in the mine plan.

2.1.4.3.1 Unit 260.—Unit 260 consists generally of silt, but some beds of sand and clay are present. Four samples from site 29 were analyzed. All were in the interval from 20 to 30 feet below the ground surface and therefore are unaltered by weathering. None of the samples are acceptable as suitable plant-growth material. Two are too sodic. The other two are marginal by the SAR criterion, but are too saline.

2.1.4.3.2 Unit 250.—Unit 250 consists largely of sand and sandy silt, although some beds of finer-grained material are also included. Nine samples, five from site 6, two from site 18, and two from site 4417JA were analyzed. Those from site 6 and 4417JA ranged in depth from 5 to 21 feet; those from site 18, from 82 to 92 feet.

The only samples of this unit from considerable distance below the surface were atypical of the unit, silt loam and silty clay. One was slightly calcareous, the other noncalcareous. The electrical conductivity varied from 0.9 to 1.3 and the SAR from 19 to 21. Two samples of sandy loam, typical of the unit, which were deep enough to be unaltered, had ECE's of 2.6 and 2.7 and SAR's 13.7 and 21. Where it is closer to the surface, material of unit 250 is generally noncalcareous. The electrical conductivity varies from 0.3 to 5.0. The higher values appear to reflect salt accumulations associated with low permeability beds overlain by sandier material. Near the surface, SAR values range from 1.2 to 4.8.

The dominant lithology of unit 250, sand and silty sand appears to meet the requirements of suitable plant-growth material where it occurs near the surface; at depth it appears to be too sodic. The fine-grained beds are generally not acceptable, either because of high SAR where they occur at depth or because of a build-up of salinity where near the surface.

2.1.4.3.3 Unit 240.—Five samples of unit 240 were analyzed. Four samples of clay, silty clay, and clay loam from 20 to 27 feet at site 4417JA and one sample of clay from 81.0 to 81.4 feet at site 17 are probably typical of unaltered material from the unit. They are slightly calcareous (6.4 percent $CaCO_3$); have electrical conductivity values that range from 1.1 to 5.0 and an excessive SAR (13 to 21.7). Unaltered material of unit 240 is apparently not suitable plant-growth material because of its high SAR.

2.1.4.3.4 Unit 230.—Twenty-one samples from unit 230 were analyzed. The samples include sandy loam, sandy clay loam, silt loam, silty clay loam, silty clay, and clay. Fourteen samples of essentially unaltered material are included. Two are noncalcareous, and two contained about 7 percent $CaCO_2$. The electrical conductivity was generally about 2 or 3 and ranged from 0.9 to 5.0; SAR was generally 20 or above and ranged from 8.8 to 37. Seven samples from within 15 feet of the surface contained considerable calcareous material, 5.4 to 9.9 percent $CaCO_3$. The electrical conductivity ranged from 2.8 to 11.1, with a maximum from 2.5 to 6.0 feet below the surface. The SAR varied from 12 to 28 feet.

None of the material of unit 230 is suitable plant-growth material. The unaltered material from deep in the section is highly sodic (SAR of 22 to 37), or too highly saline (ECE of 5.0). Because site 30 is probably in an exfiltration zone above a groundwater discharge zone, the high values of electrical conductivity and SAR (app. D) for the shallow samples may not be typical for the unit. They may reflect an accumulation of salt and sodium related to evaporation of upward moving subsurface water. Until this qualification is studied, all materials of unit 230 should be considered unusable as suitable plant-growth material.

2.1.4.3.5 Unit 220.—Seven samples from unit 220 were analyzed. They include loamy sand, sandy loam, sandy clay loam, silty clay, and clay. The samples are noncalcareous; the electrical conductivity ranged from 0.9 to 5.5, and the SAR ranged from 1.6 to 35.1. At depths less than 50 feet the SAR is below 10; at greater depths it is considerably above 10.

The fine-grained beds in unit 220 appear to be unusable as suitable plant-growth material because of excess salinity or excess sodium at greater depths. The sandy material of the unit ranges from acceptable (ECE 1.0 and 1.3, SAR 3.6 and 2.4) to unacceptable (SAR 35.1). The samples were collected at two different sites in different hydrologic settings. The acceptable samples are from an upland recharge, flushed zone, whereas the unacceptable sample is in a lower position near a groundwater discharge zone.

2.1.4.3.6 Unit 210.—Thirteen samples

from six sites in unit 210 were analyzed. They include silt loam, silty clay loam, silty clay, clay loam, and clay. Eleven samples are from more than 40 feet below the surface. Two are noncalcareous, two contain about 7 percent $CaCO_3$, and two contain about 13 percent $CaCO_3$. One sample, the shallowest, from about 40 feet at site 19, has an electrical conductivity of 5.0. The remainder of the deep samples have conductivity of 3.6 or less. The SAR of eight of the eleven ranges from 13 to 34; two samples in the interval from 58 to 63 feet at site 14 and one sample from 167 to 168 feet at site 18, have SAR values from 0.3 to 1.6. Two near-surface samples from unit 210 were analyzed; both were silt loam from site 16. They contain 7.2 and 2.3 percent $CaCO_3$, have electrical conductivity of 0.6 and 5.0, and a SAR of 6.2 and 5.0.

In general, the silt of unit 210 seems unusable as suitable plant-growth material because of its elevated sodium content. Near the surface, where the SAR is lower, the soluble salt content is generally too high. At very shallow depths, three to five feet at site 16, both the SAR and electrical conductivity are low enough to make the unit 210 suitable plant-growth material. Three samples from deep in the section are suitable plant-growth material. All are situated in upland recharge areas and probably reflect flushing of soluble sodium by downward and outward moving groundwater.

2.1.4.4 Dunn Center Interval

Fifty-eight samples from four units of the Dunn Center interval were analyzed. The usability of these materials as suitable plant-growth material is highly variable.

2.1.4.4.1 Unit 130.—Twelve samples of silty clay, silty clay loam, clay and silt loam from unit 130 were analyzed. They were collected at four sites at depths ranging from 10.5 to 76.3 feet. The unit contains some beds of noncalcareous material and some that are fairly calcareous (about 19.7 percent $CaCO_3$). The electrical conductivity is low except near the land surface. Except in two samples, the SAR is within the acceptable limits for suitable plant-growth material. Those samples, from site 4417JA, were collected in the down gradient portion of the groundwater-flow system. In summary, the materials of unit 130 seem, in general, to be suitable plant-growth material.

2.1.4.4.2 Unit 123.—Four samples of silt loam and silty clay loam from two sites were analyzed. They are slightly calcareous, about 6 to 6.5 percent $CaCO_3$; the electrical conductivity is low; the SAR ranges from 6.0 to 27. The fine-grained material characteristic of unit 123 is generally highly sodic and is not suitable plant-growth material. However, in sites where the unit occurs in upland recharge areas, the SAR is low enough to permit the material to be acceptable.

2.1.4.4.3 Unit 120.—Twenty samples of loamy sand, sandy loam, and sand and four of loam and silty clay loam were analyzed from seven sites. Most ranged from noncalcareous to about 3.5 percent $CaCO_3$, but two contained about 24 percent $CaCO_3$; the electrical conductivity varied from 0.2 to 11.0; the SAR varied from 0.2 to 12. Twelve percent of the samples are unusable as suitable plant-growth material because they are excessively saline or sodic or both. All of these samples are from site 19. An additional 12.5 percent of the samples, although usable, are marginal with values of electrical conductivity or SAR just below the maximum acceptable limits. In general, the material of unit 120 is acceptable as suitable plant-growth material, but enough of it is not acceptable or marginal that further study of the unit is needed.

2.1.4.4.4 Unit 110.—Eighteen samples of silt loam, silty clay, and clay from eight sites were analyzed. The material ranged from being noncalcareous to containing 23.6 percent $CaCO_3$. The electrical conductivity was generally about 2 but ranged from 0.2 to 8.0; the SAR was generally about 30 and ranged from 0.9 to 45. Only one sample is suitable plant-growth material. Most of the rest of the samples are too sodic; one sample that was marginally acceptable from the standpoint of SAR was too saline. In general, material of unit 110 is not acceptable as suitable plant-growth material.

2.1.5 Center Site

2.1.5.1 Coleharbor Interval

Materials included within the Coleharbor interval are predominantly pebble loam and silt to sandy silt. The Coleharbor interval overlies most of the study site.

2.1.5.1.1 Unit 580.—Four samples from unit 580 were analyzed. All four samples consisted of silt. In three of the samples the values for ECE were very low, ranging from 0.3 to 0.8. The fourth sample had an ECE value of 6.0. SAR values for the first sample were also low, ranging from 0.3 to 1.9. The SAR for the fourth sample was 8.0.

2.1.5.1.2 Unit 530.—Fifty samples from unit 530 were analyzed. All samples consisted of pebble loam. The ECE values ranged from 0.25 to 8.5, but were generally between 0.5 and 4.0. The SAR values ranged from 0.3 to 14.3, generally falling between 1 and 4.

2.1.5.2 Hagel Interval

The Hagel interval included all materials between the Hagel bed and the Coleharbor interval.

2.1.5.2.1 Unit 180.—Fourteen samples were analyzed from unit 180. All samples consisted of interbedded silt and clay. Values for ECE varied considerably ranging from 0.32 to 9.7. SAR values ranged from 0.6 to 12.8.

2.1.5.2.2 Unit 170.—Seventeen samples from unit 170 were analyzed. All samples consisted of sand. The ECE values ranged from 0.52 to 6.5, most falling between 0.5 and 3.0. The SAR values ranged from 0.6 to 5.8, generally falling between 0.6 and 2.0.

2.1.5.2.3 Unit 160.—Eight samples from unit 160 were analyzed. The samples consisted of lignite, silty clay, and carbonaceous clay. The ECE values ranged from 1.1 to 8.0. The SAR values ranged from 0.7 to 7.4.

2.1.5.2.4 Unit 150.—Eighty-six samples from unit 150 were analyzed. The samples consisted of sand and sandy silt, and minor amounts of clay. The ECE values were generally between 0.5 and 3.0, ranging from 0.23 to 6.7. The SAR values were generally between 0.2 and 3, ranging from 0.2 to 15.7.

2.1.5.2.5 Unit 140.—Seventy samples for this unit were analyzed. The samples consisted of interbedded silt and clay and lesser amounts of sand. The ECE values generally were between 0.5 and 3, ranging from 0.33 to 7.3. The SAR values were highly variable, ranging from 0.3 to 45.4.

2.1.5.2.6 Unit 130.—Fourteen samples from unit 130 were analyzed. All samples consisted of clay, occasionally carbonaceous. The ECE values ranged from 0.92 to 3.6. The SAR values were highly variable, ranging from 1.0 to 29.2.

2.1.5.2.7 Unit 110.—One hundred fifty-four samples from this unit were analyzed. The sample consisted of interbedded clay, silty clay, silt, and sand. Values for ECE ranged from 0.36 to 6.7 with the vast majority of the samples between 1 and 3. The SAR values were highly variable, ranging from 2.0 to 50.8.

2.2 Chemical Grouping of Data

The analyses have been grouped on the basis of five simple descriptive and chemical properties: texture, oxidation state, pH, ECE, and carbonate content. These properties were selected because they are readily determined and, as is developed in considerable detail in a later section, they can be related to hydrologically and geochemically important parameters.

Texture is subdivided into two classes: (1) sand, and (2) silt and clay. Sand includes both fine-grained sand of the Sentinel Butte Formation and coarse-grained sand, gravelly sand, and sandy gravel of the Coleharbor Formation. Silt and clay include thinly bedded to unbedded silt and clay beds of the Sentinel Butte Formation and the pebble loam and minor silt and clay of the Coleharbor Formation. The oxidation state of the material is subdivided on the basis of color into two classes: (1) unoxidized, and (2) oxidized. Carbonate content is subdivided into two classes: (1) calcareous, and (2) noncalcareous. Samples that are classified as calcareous either effervesced with acid or had laboratory-determined carbonate content values. As is discussed in section 1.2.2.2 and below, it cannot be assumed that samples in the noncalcareous class contain no carbonate minerals. Both pH and electrical conductivity (ECE) are classified into three groups: low, intermediate, and high. The boundaries between classes for pH were 7.0 and 8.0, the latter being arbitrarily selected. The boundaries between classes for ECE are 2.0 and 4.0, which are the boundaries established in North Dakota regulations for the two classes of suitable plant-growth materials.

This combination of properties gives a theoretical maximum of 72 groups. The actual numbers of groups are less, however, because some did not occur in the study areas. In addition, calcareous samples with pH values less than seven seem extremely unlikely, so the theoretical maximum number of groups is actually 60.

In addition to the defining properties of carbonate content, pH, and ECE, values for sample depth and SAR were recorded for each group of analyses. Inspection of the numerical values revealed that in most groups these latter two parameters fell within a relatively narrow range. In some groups, however, there were two distinct subdivisions of SAR or depth. These subdivisions were used to define subgroups. The data were summarized by calculating a mean and standard deviation for each property within each group or subgroup. Visual inspection of data indicated that little difference existed between calcareous and noncalcareous samples in terms of the numerical properties in most groups.

As these data were being compiled, it was noted that the same analysis groups occurred in the same relative position in several testholes. To evaluate this relationship, the values of ECE, SAR, and pH were plotted against depth for each testhole. Examination of these plots indicated that seven distinct patterns were present in the five study sites.

Class I sites are characterized by evaluated values of salinity and low values of pH from about 2 feet to about 22 feet (fig. 2.2-1). The pH quickly increases so that only values in excess of 8.0 are found beneath 30 feet. Conductivity decreases more slowly with intermediate values (between 2.0 and 4.0) found to nearly 90 feet and values less than 2.0 from about 40 feet on down. Elevated values of SAR are the rule in class I sites. The depth at which SAR values in excess of 10 are encountered ranges from 2 to about 25 feet.

Class II sites are characterized by a salinity bulge similar to that in class I, but lack the depressed pH values. The upper 30 feet in these sites are characterized by intermediate to high salinity and intermediate to high pH (fig. 2.2-2). Like class I sites, pH is elevated below 30 feet and ECE gradually decreases. Elevated SAR values are common in class II sites. SAR values in excess of 10 are encountered within 3 feet of the surface at some sites and from 20 to 55 feet in others.

Class III sites are characterized by low salinity throughout and pH values that are generally in the intermediate range (fig. 2.2-3). In some sites values of pH in excess of 8.0 occur from 5 to 20 feet below the surface and from 60 to 110 feet. Intermediate ECE values occur in some testholes from about 60 to 80 feet. A variant of class III, called class IIIa, was observed. Here, a thin interval of fine-grained sediment about 12 to 15 feet beneath the surface gave ECE values in excess of 4.0. The upper part of the hole was all sand and this thin saline interval is believed to represent a zone of accumulation of salt derived from the overlying material. SAR values in excess of 10 occur no higher than 80 feet beneath the surface.

Class IV is represented by only one testhole at the Dunn Center site. It is characterized by a thick interval of elevated salinity that extends from 7 to 90 feet and low pH values from 40 to 75 feet below the surface (fig. 2.2-4). SAR values in excess of 10 are found about 30 feet below the surface.

Class V is represented by several testholes at the Falkirk, Beulah-Hazen, Dunn Center, and Center sites. It is similar to class I in having a raised salinity and depressed pH in the upper part of the profile (fig. 2.2-5). Unlike class I, however, the conductivity does not exceed 4.0. Like class III, the salinity in the remainder of

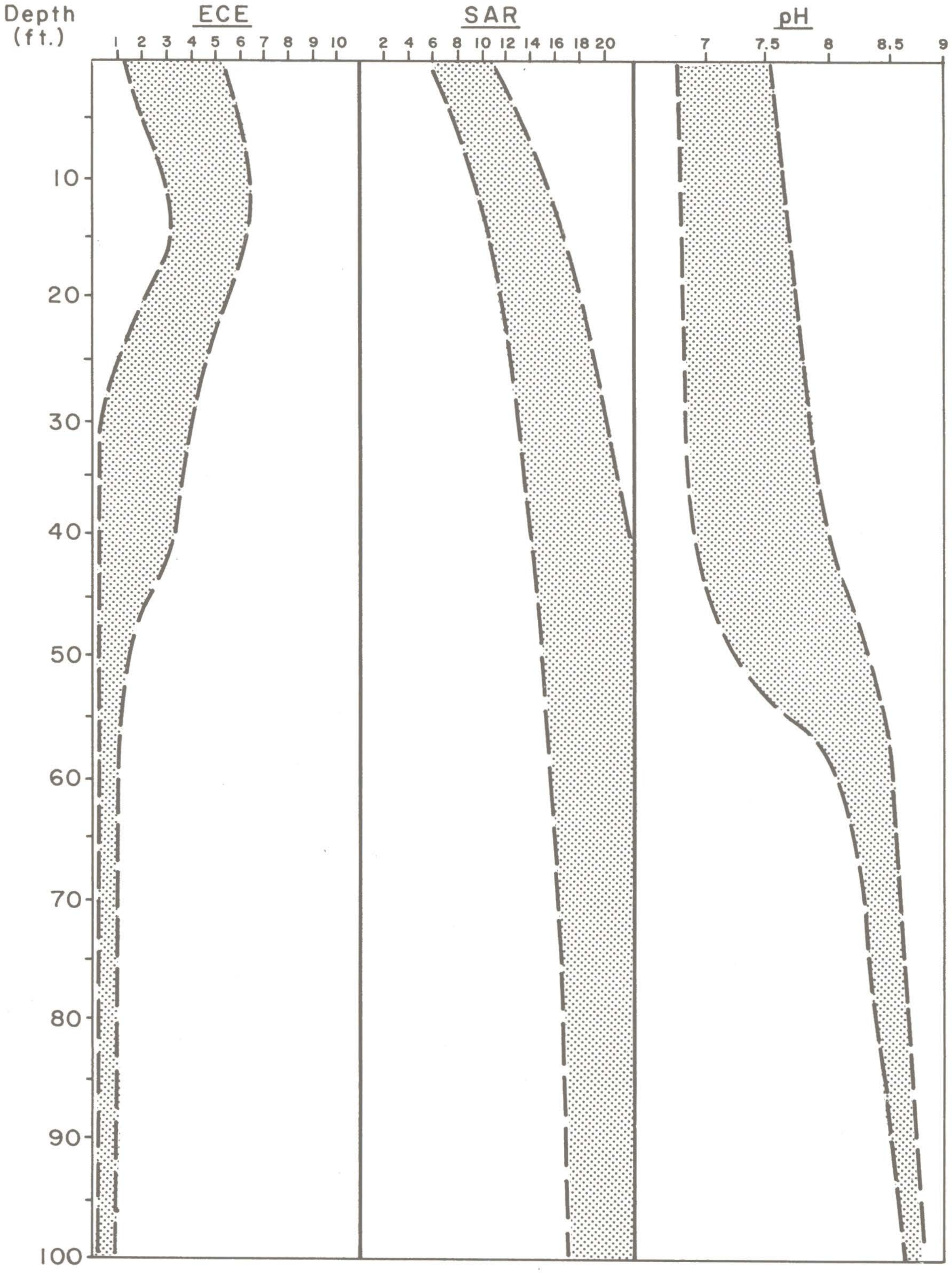

Figure 2.2-1. Class I overburden chemical profiles.

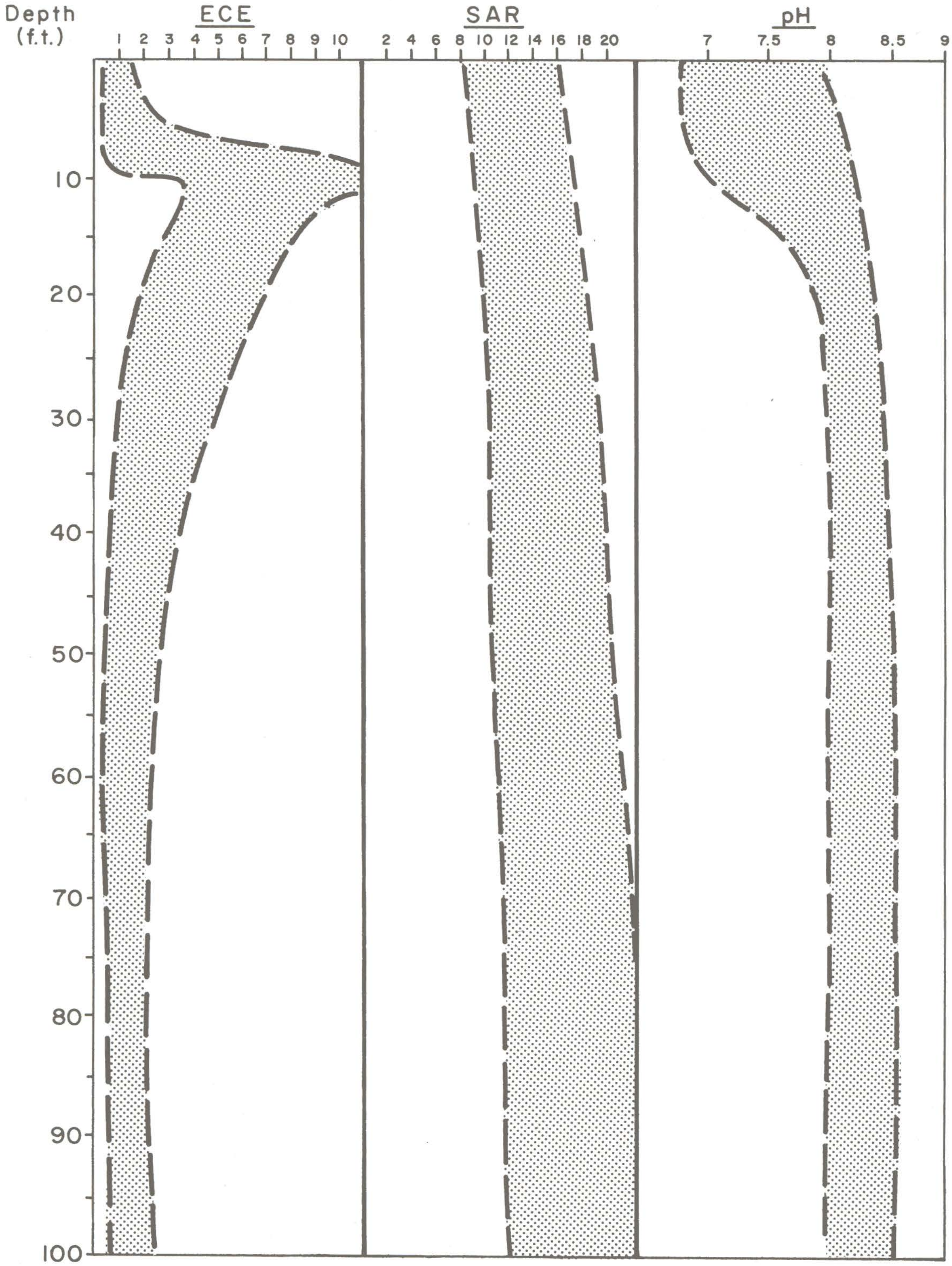

Figure 2.2-2. Class II overburden chemical profiles.

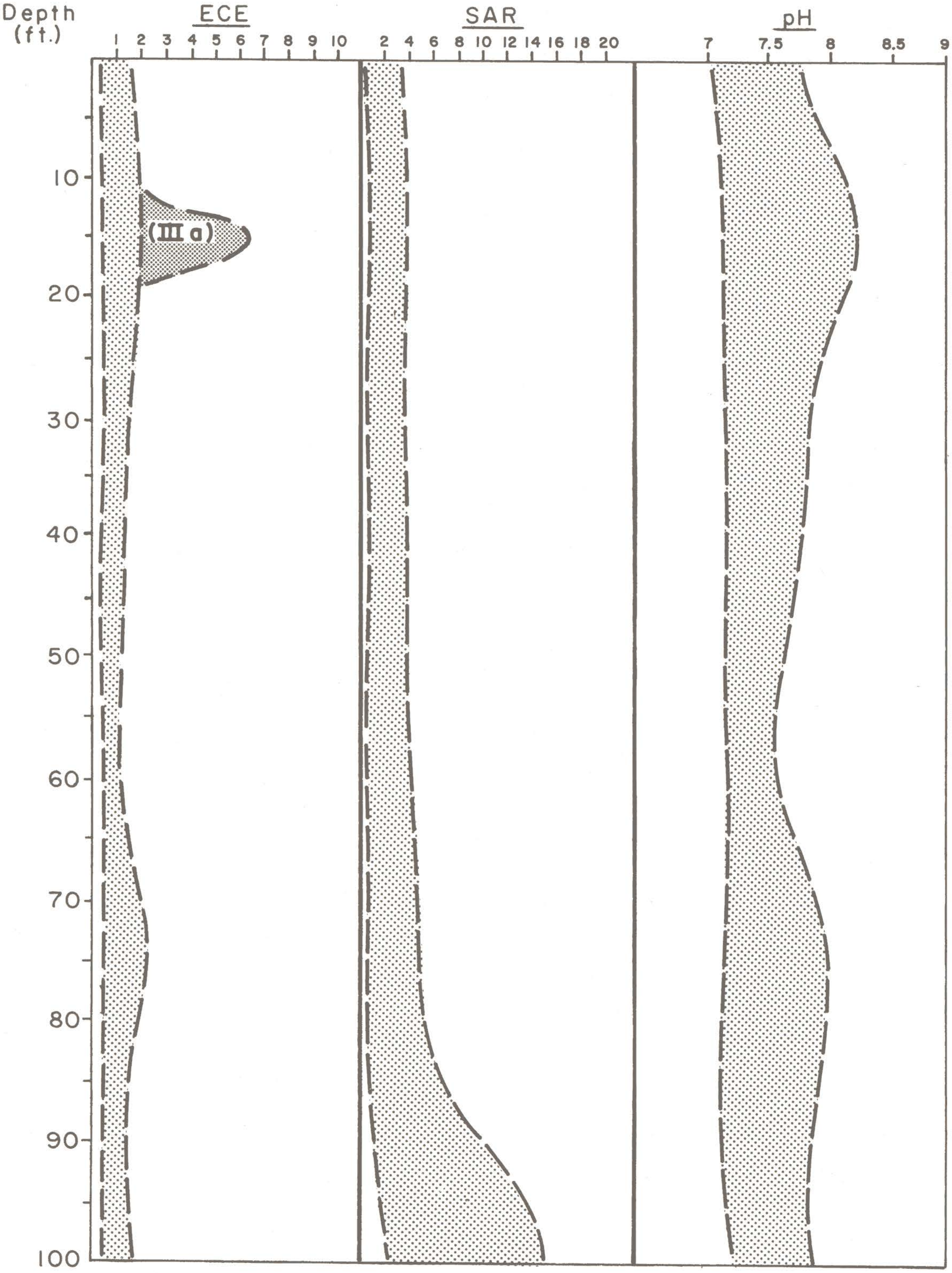

Figure 2.2-3. Class III overburden chemical profiles.

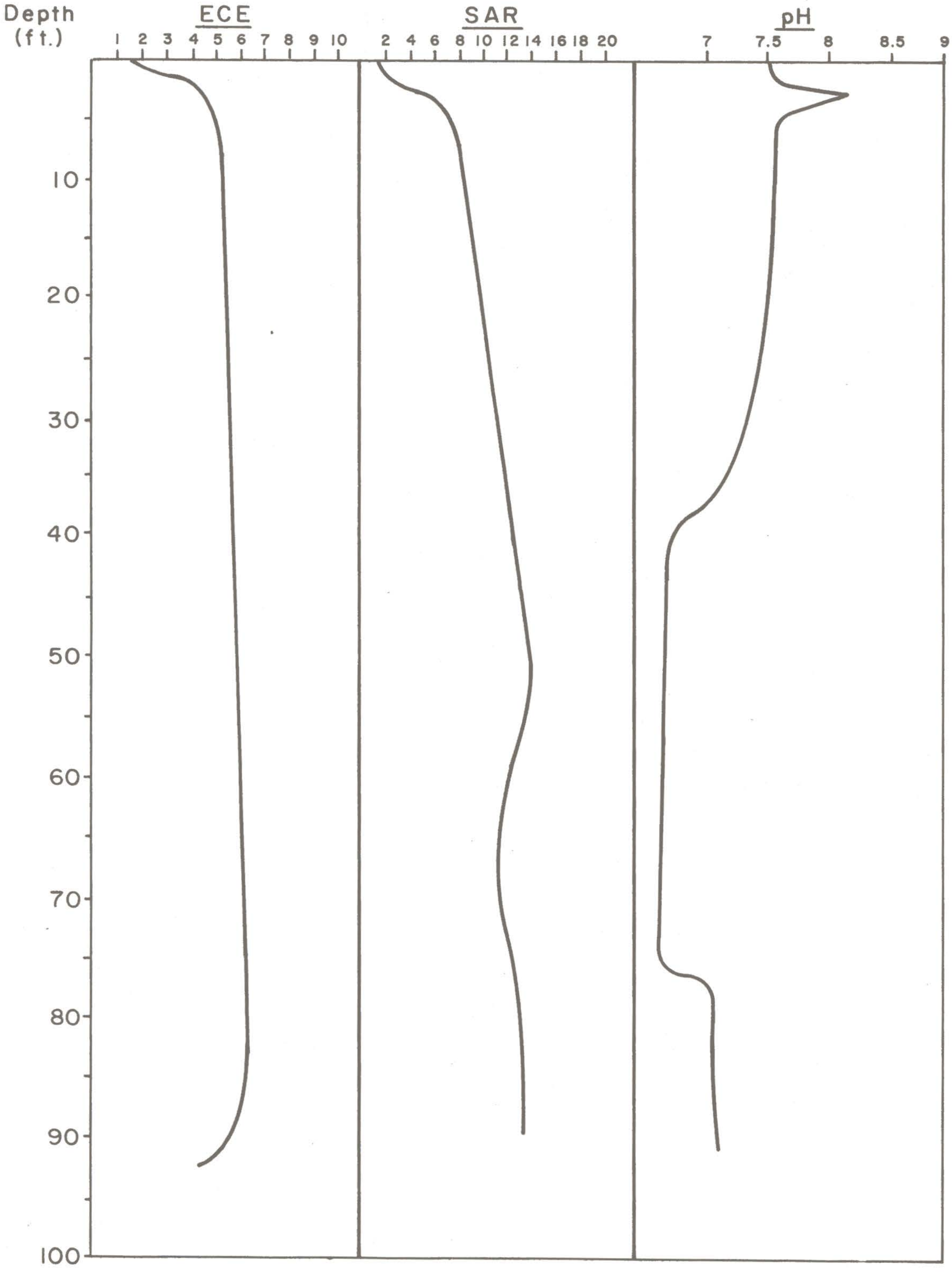

Figure 2.2-4. Class IV overburden chemical profiles.

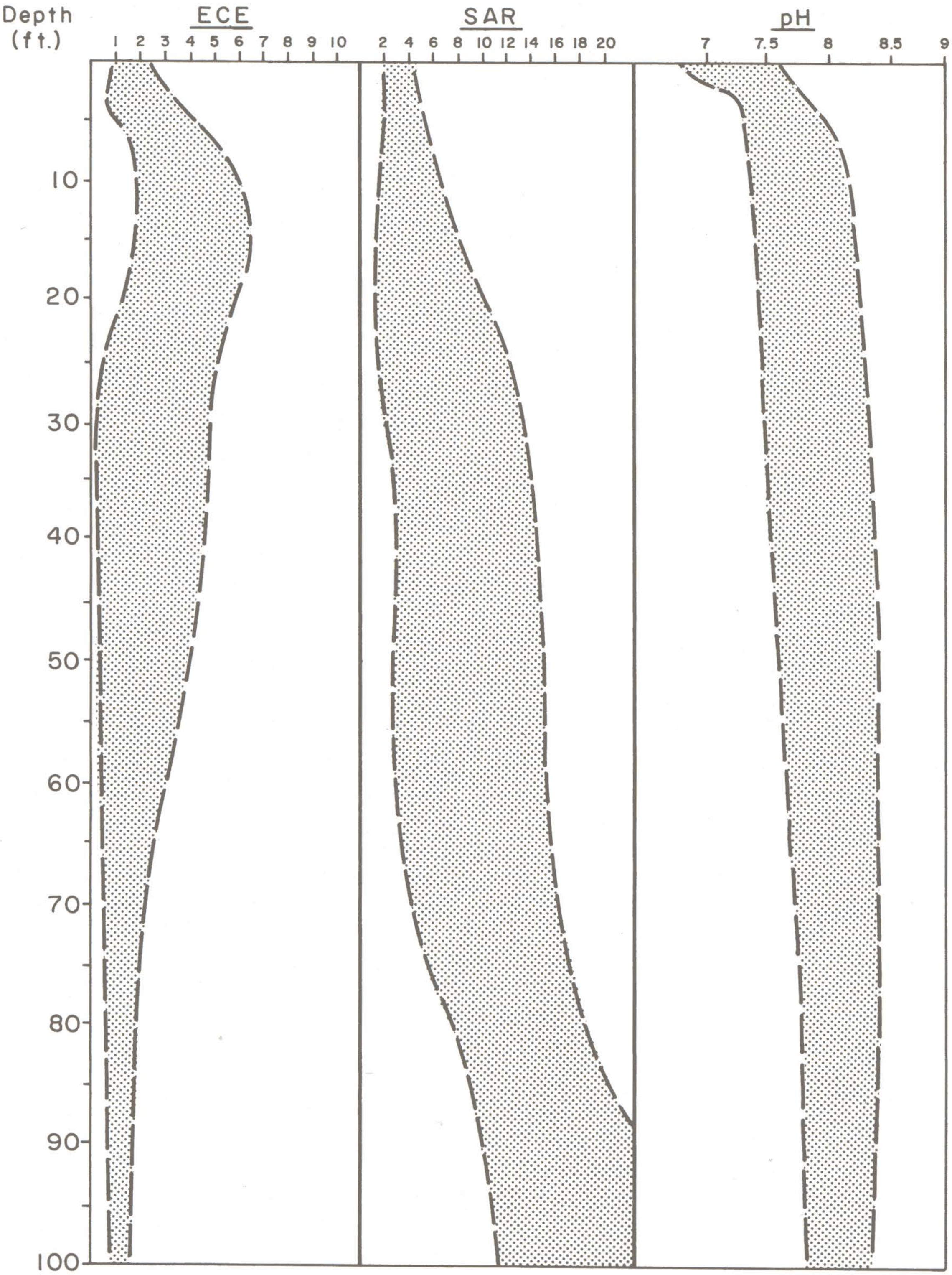

Figure 2.2-5. Class V overburden chemical profiles.

the hole is low, but like classes I and II the pH is high rather than intermediate as in class III. Elevated SAR values occur below about 25 to 35 feet.

Class VI is represented by numerous testholes at the Falkirk and Center sites. It is very similar to class V in most respects (fig. 2.2-6). It differs from class V in that the materials are glacial till rather than bedrock silt and clay, and the SAR values are typically low rather than high as is common in class V profiles.

Class VII is represented by only two testholes. It is characterized by high salinity values in the upper 10 to 20 feet of the profile (fig. 2.2-7). Below that level the salinity values are low. The pH is moderate to slightly high throughout the profile. SAR values are high in the upper 15 to 20 feet of the profile, decreasing rapidly with depth. Class VII profiles are located in the same landscape positions as class I profiles.

2.2.1 Landscape Classification by Overburden Characteristics

Although the land surface of the study areas is everywhere sloping, the surface descends from the butte-capped uplands in a series of steps that are controlled by more resistant beds. Most of the area is characterized by a rolling upland separated from a second, lower surface by steeper topography. This second, mid-slope surface is truncated more or less abruptly by the steeper slopes of the glacial meltwater channels (fig. 2.2.1-1).

Examination of the position in the landscape of the seven overburden classes indicates that each has a characteristic setting (fig. 2.2.1-1).

Class I and VII sites occur on the upper part of the mid-slope surface and lower slopes and floors of glacial meltwater channels (fig. 2.2.1-1). In these sites, weathering of the material beneath the surface releases salts which are augmented by salts infiltrating from above.

Class II, III, and IV sites occur in the lower part of the mid-slope surface and the upper part of the side slopes of meltwater channels and their post-glacial tributaries (fig. 2.2.1-1). In these sites, surface ponding does not generally occur and there is therefore little salt accumulation at the surface. Where the material is fine-grained, weathering releases salts which generally remain in place since infiltration is minor. These sites form class II. Removal of sediment and weathering products by physical erosion may also be a factor in the characteristics of these sites. Where the surface material is coarse-grained, there is little to no salt build-up; these sites form class III. The low salt content of class III sites probably reflects the small amount of ions liberated by the weathering of sand relative to clay and silt as well as flushing of salt downward by infiltration. The conditions necessary for generation of class IV sites are not understood.

Class V and VI sites appear to be restricted to the upland surface (fig. 2.2.1-1).

3. INVENTORY OF CHEMICAL COMPOSITION OF GROUNDWATER

This section summarizes the major-ion chemistry of groundwater in the five study areas. The Indian Head and Beulah-Hazen sites are grouped together for purposes of discussion because of the little data in the Indian Head area and the similarity of the setting. At some of the sites, the groundwater chemistry is summarized by aquifers. This basis of systemization is used at the relatively simple sites such as the Falkirk, Center, and Beulah-Hazen sites. At the larger, more hydrologically complex Dunn Center site, the analyses have been grouped into groups of similar analyses and are discussed with respect to their position in the landscape.

3.1 Falkirk Site

Forty-eight complete chemical analyses are available from wells in the Falkirk area, nine from the Coleharbor Formation, three from the sand above the Hagel bed, 15 from the Hagel bed, seven from the B bed, three from the sand beneath the B bed, two from the sand above the TR bed, one from the TR bed, and eight from the Hensler sand (table 3.1-1).

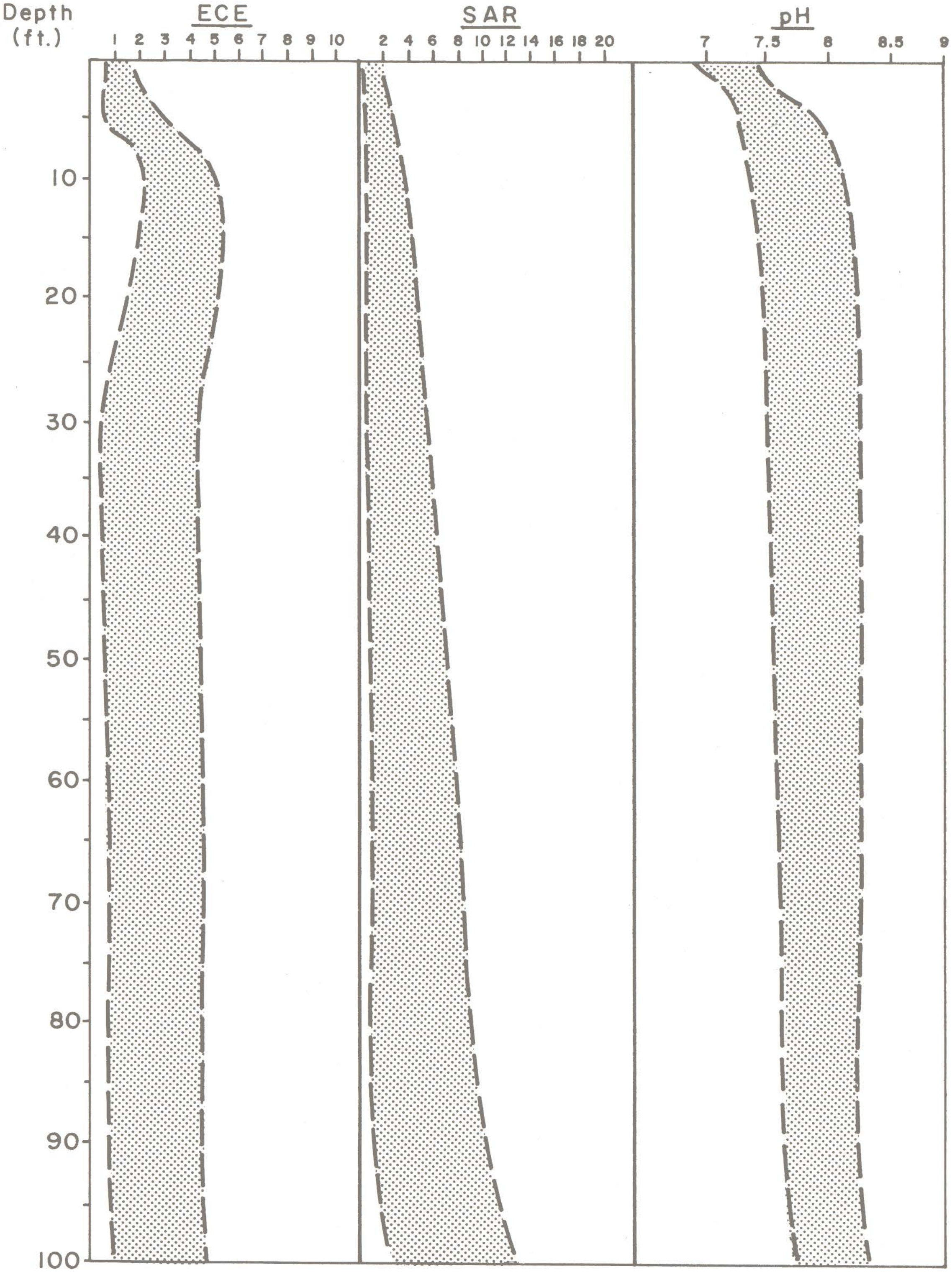

Figure 2.2-6. Class VI overburden chemical profiles.

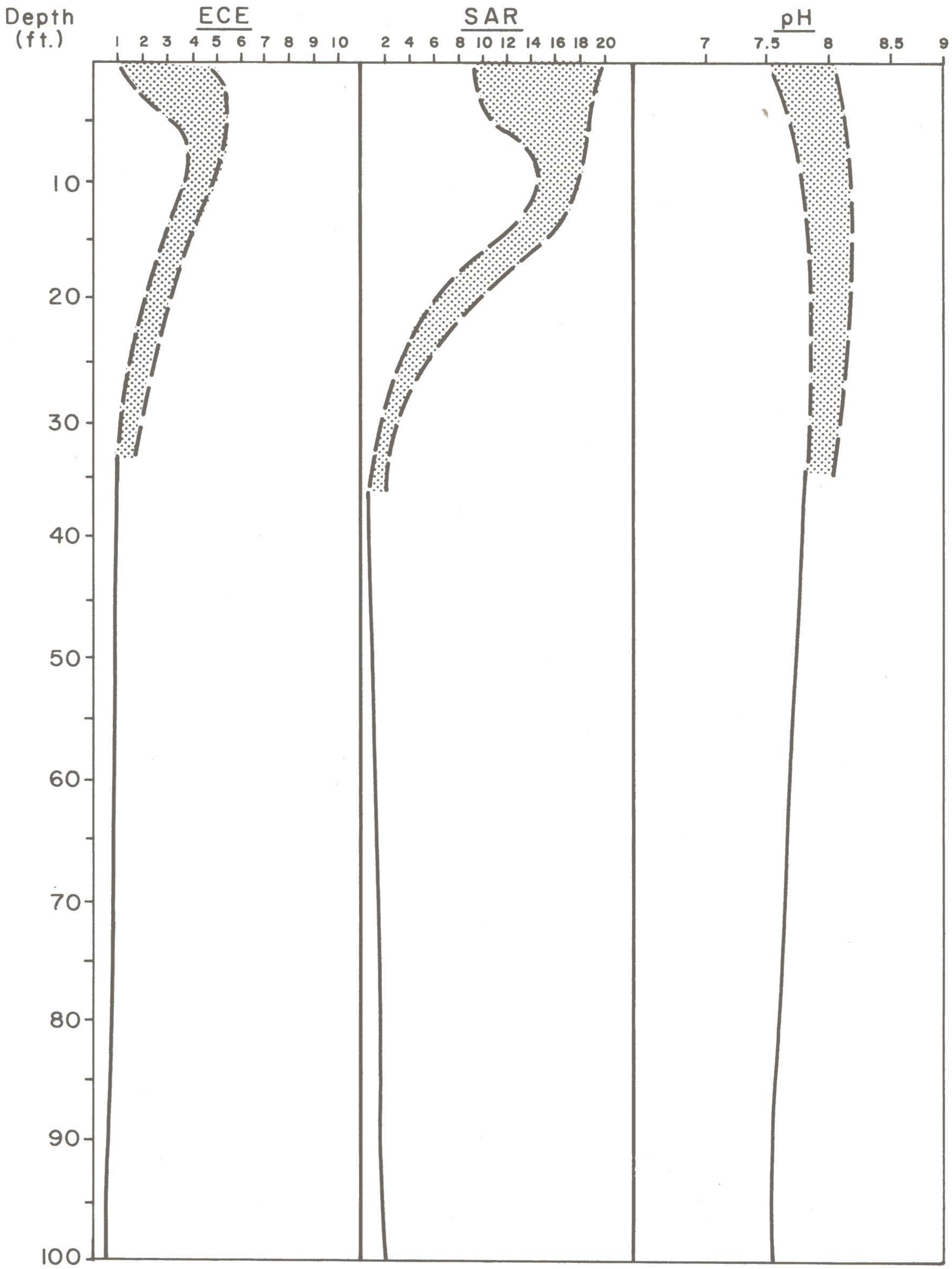

Figure 2.2-7. Class VII overburden chemical profiles.

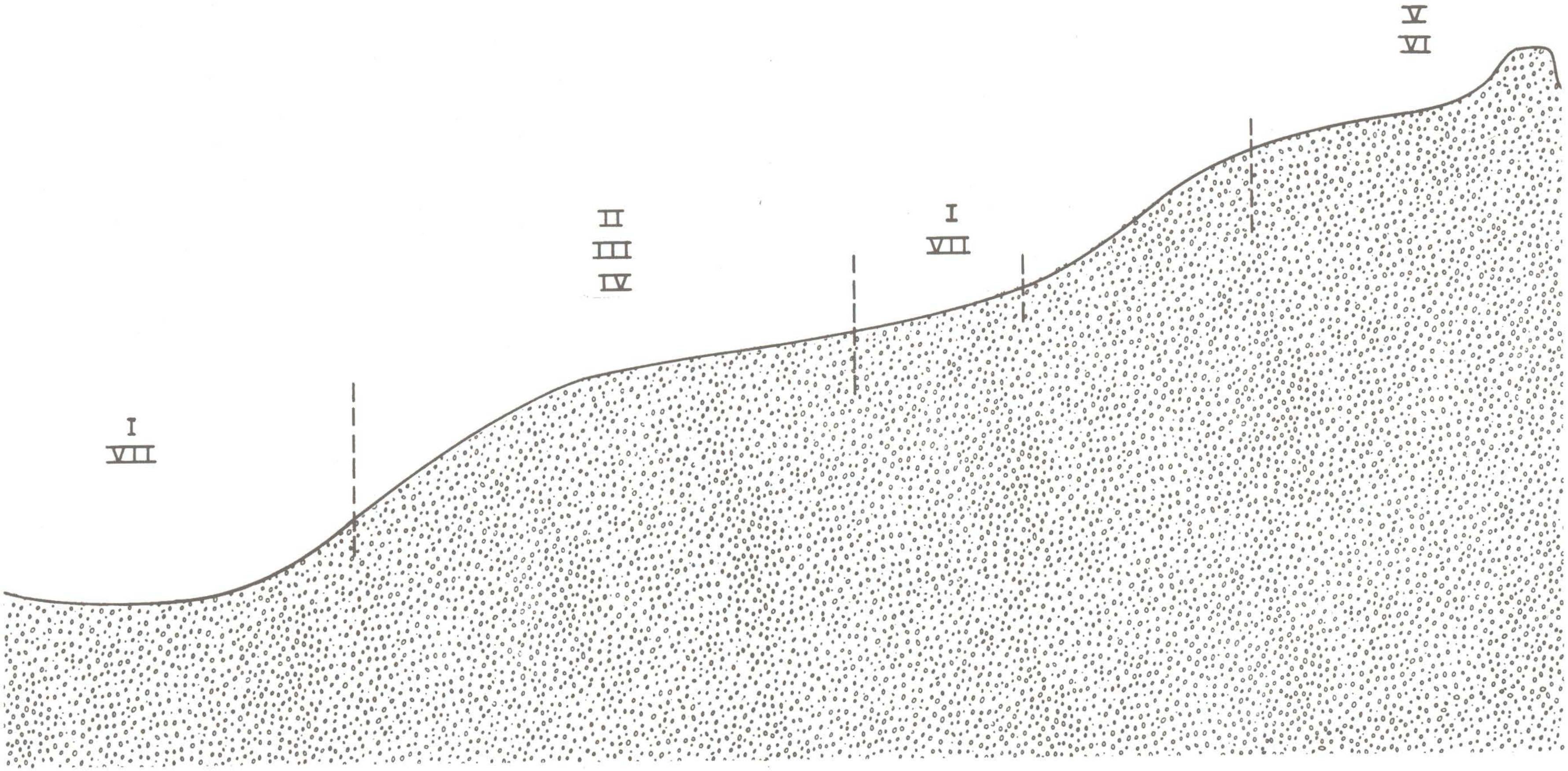

Figure 2.2.1-1. Position in landscape of overburden chemical profile classes.

Table 3.1-1. *Chemical Analyses of Groundwater–Falkirk Area.*

Location	Well No.	Depth (ft)	Lab pH	Lab Cond.(1)	TDS(2)	Alkalinity(2)	Hardness(2)	Ca(2)	Mg(2)	Na(2)	K(2)	HCO_3(2)	CO_3(2)	Cl(2)	SO_4(2)
Coleharbor Formation															
145-82-04 CDC	FA 76-3-2	12	8.2	1128	972	380	583	184	30	62	5.5	463	—	15	251
145-82-07 DAA	NDSWC 2858	241	8.1	1320	867	—	350	77	38	192	8.3	712	0	2.7	188
145-82-08 ADD	FA 75-101-3	47	7.6	752	450	—	231	14	48	31	6.6	467	—	0.63	129
145-82-08 ADD	FA 75-101-2	241	7.8	1396	910	679	235	50	27	156	7.7	828	—	13	295
145-82-08		232-252	8.2	1150	1106	623	—	238	6	179	7.7	721	39	5	400
145-82-08		236-256	8.0	1850	1208	666	—	165	8	285	7.5	766	46	8	390
146-82-34 ADD	NDSWC 3911	80	7.9	701	417	—	398	89	32	20	3.5	376	—	—	85
146-82-34 CBC	FA 76-2-1	49	7.4	2970	240	153	159	63	1.0	1.2	6.6	187	—	1.5	18
146-83-15 CCC	NDSWC 4036	284	7.9	2620	1730	—	125	33	10	629	4.4	1230	—	17	464
Sentinel Butte Formation															
Upper Sand (sand above A bed)															
146-82-16 CCB	FA 76-9-1	63	8.3	1113	810	366	399	154	3.6	63	10.3	446	—	138	231
146-82-21 CCC	FA 76-8-3	19	8.2	847	546	318	351	67	45	36	7.3	388	—	126	13
146-82-21 CCC	FA 76-8-1	58	7.8	1230	806	574	582	234	0.0	81	7.0	701	—	137	39
Hagel bed (A bed)															
146-82-20 CBB	FA 75-81	116	7.9	1086	748	431	549	40	75	49	9.2	526	—	16.0	148
146-82-20 CCC	FA 75-82	122	7.5	519	1132	468	509	32	104	78	7.2	571	—	7.1	13
146-82-21 CBB	Underwood Well 3	90					300	73	29	18	3.1	329	0.0	15	28
146-82-21 BBD		95	7.7	2050	1400	—	1382	245	80	96	9.5	608	0	199	308
146-82-21 CBB		82	7.9	605	369	—	300	76	24	20	3.7	341	0	11	27
146-82-21 CCC	FA 75-106-6	82	7.8	1571	1436	—	960	15	50	18	4.6	292	—	37	619
146-82-27 BBC	FA 75-41	62	7.2	475	1262	305	163	66	0.0	1.3	6.7	372	—	8.9	22
146-82-27 CCC	FA 75-40	81	7.3	658	404	318	283	48	29	12	7.2	387	—	2.1	77
146-82-28 CCC	FA 75-105-6	61	7.7	723	465	—	345	6.0	80	25	7.9	482	—	2.8	52
146-82-28 CDD	FA 75-79	72	7.5	875	1468	556	548	96	75	71	10.7	678	—	21	119
146-82-34 BCC	FA 75-39	50	7.3	866	558	375	352	32	66	45	9.8	457	—	10.5	155
146-83-24 BBB	FA 75-83	144	7.8	2371	2006	741	368	56	55	338	14	905	—	19	142
146-83-24 CCC	FA 75-84	134	7.3	1650	2110	796	694	154	75	116	15	971	—	80	340
146-83-36 BCC	FA 75-85	—	7.3	1310	1798	245	285	7.9	65	101	11	299	—	20	201

(1)Micromhos
(2)Mg/l

Table 3.1-1. *Chemical Analyses of Groundwater–Falkirk Area.*–Continued

Location	Well No.	Depth (ft)	Lab pH	Lab Cond.$^{(1)}$	TDS$^{(2)}$	Alkalinity$^{(2)}$	Hardness$^{(2)}$	Ca$^{(2)}$	Mg$^{(2)}$	Na$^{(2)}$	K$^{(2)}$	$HCO_3^{(2)}$	$CO_3^{(2)}$	Cl$^{(2)}$	$SO_4^{(2)}$
B bed															
145-82-04 DAA	FA 75-37	37	7.4	1351	1280	442	743	99	121	12	7.0	539	—	20	334
145-82-05 CBB	FA 75-92	63	7.4	1521	2128	447	492	67	79	135	9.8	546	—	12	341
145-82-05 DBA	FA 75-113-2	51	6.3	1249	1308	212	658	196	41	31	10.6	259	—	16	508
145-82-05 DBB	FA 75-112-2	58	6.4	1529	1506	303	841	244	56	38	10.2	369	—	22	680
146-82-20 CBB	FA 75-80	161	7.8	514	34	262	123	17	20	78	9.3	320	—	6.3	511
146-82-30 CCC	FA 75-86	108	7.5	1015	1572	336	348	58	49	41	8.8	409	—	2.2	132
146-82-31 DAA	FA 75-90	58	7.1	1683	2306	485	484	223	—	99	12	592	—	8.7	323
A & B beds															
148-82-05 DAB	FA 75-114	57	8.9	3021	4890	90	2201	587	178	79	20	109	—	19	1023
Sand Below B bed															
145-82-04 AAA	FA 75-107-2	57	7.6	1289	940	687	309	9.8	69	248	11	838	—	7.8	92
145-82-05 DAA	FA 75-102-3	82	7.5	1287	896	648	211	1.4	50	175	10	791	—	9.6	143
146-82-28 CCC	FA 75-105-2	109	7.8	678	430	350	56	5.1	11	88	5.0	427	—	0.9	20
Sand Above TR bed (TR sand)															
145-82-03 CDD	FA 76-4-1	13	7.7	1445	1206	491	726	262	18	90	9.6	599	—	14	389
145-82-05 DAA	FA 75-102-2	154	8.4	1975	1333	—	58	5.6	3.4	361	6.5	1175	—	23	181
Bullion Creek Formation															
TR bed															
145-82-04 CDC	FA 76-3-1	40	8.0	1523	1114	710	212	65	12	213	7.6	866		9.4	163
Hensler Sand															
145-82-04 AAA	FA 75-107-1	237	7.5	1658	465	—	84	13	7.9	308	9.1	1089	—	661	64
145-82-05 DAA	FA 75-102-1	269	8.0	1371	888	—	34	4.2	2.6	16	5.3	819		9.3	98
146-81-18 CDD		187	7.9	1020	631		510	107	51	58	7.3	546	0	?	144
146-82-05 CCC		324	8.6	1770	1180	—	44	12	3.4	441	3.1	888	43	2.7	181
146-82-21 BDC		395	8.8	1190			24					502	52	7.0	92
146-82-21 BDD		385	8.9	1210			10	6.0	4.0	308	5.0	528	67	0.0	91
146-82-21 CCC	FA 76-137	97.5-109.7		1090	896		12	3.1	1.1	350	1.7	762	35	0.4	74
146-82-28 CCC	FA 75-105-1	259	8.3	1193	882		45	2.3	9.6	225	3.8	770		9.3	84
146-82-32 CDC		311	8.6	1550	1000		14	4	1.0	385	2.0	781	39	1.6	142

$^{(1)}$Micromhos
$^{(2)}$Mg/l

3.1.1 Coleharbor Formation

The electrical conductivity of samples from the Coleharbor Formation varies from about 700 to about 3000 µmhos/cm with a mean and standard deviation of 1557 and 785, respectively. In general terms the lower values occur in the upper part of major buried valley fills with intermediate to high values in the deeper part of the same fills. Minor buried valleys cutting across the bedrock upland contain yield values of conductance.

Four groups of water types occur in the Coleharbor Formation. Four samples form a group of $(CaMg)HCO_3$ type waters that run the full range of conductivities found in the unit. Three of these wells are among the most recently installed and these analyses may reflect contamination from drilling water or grout. Three analyses form a group of $Na(CaMg)HCO_3SO_4$ type water with intermediate to high conductivity. These samples are all from deep wells in major valley fills. A single sample of $(CaMg)NaHCO_3SO_4$ type water was collected from a deep well in a major valley fill. Another sample of $NaHCO_3SO_4$ type water was collected from a major valley fill just west of the project area.

3.1.2 Upper Sand

Three analyses from the upper sand indicate a relatively fresh $CaMgHCO_3SO_4$ to $CaMgSO_4HCO_3$ type water. The mean conductivity is 963 µmhos/cm with a standard deviation of 257. All three samples are from wells located in the center of the bedrock upland around Underwood.

3.1.3 Hagel Bed

Specific conductance of water from the Hagel bed varies systematically with values less than 500 µmhos/cm along the axis of the thick linear ENE-WSW trending upper sand and values in excess of 2000 to the south and north (fig. 3.1.3-1). Beneath the sand body values of conductance are nearly everywhere less than 1000. These analyses, which are $CaMgHCO_3$ type water, have a mean conductance of 705 µmhos/cm with a standard deviation of 436. Three analyses of $CaMgSO_4$ type water have a considerably higher conductivity. These samples occur where the overburden above the Hagel bed is thin and generally clayey. They appear to represent additions of dissolved gypsum to the more typical water found in the Hagel bed. A single sample of $NaCaMgHCO_3$ type water with a conductance of about 2300 µmhos/cm is from a well to the northwest of the principal recharge area of the aquifer. The overburden here is thick and predominantly fine-grained.

3.1.4 B Bed

A single sample from the B bed is a relatively fresh (560 µmhos/cm) $NaCaMgHCO_3$ type water. This sample is from beneath the upland where recharge is greatest. Three samples located along the southwestern flank of the bedrock upland are $CaMgNaHCO_3SO_4$ type water with a mean conductance of about 1400. Four samples are from wells along the southern edge of the bedrock upland, where the overburden is thin and generally fine-grained. These samples range from $CaMgHCO_3SO_4$ type water with conductance of 1350 µmhos/cm, through two samples of $CaMgSO_4HCO_3$ type water with mean conductance of 1390 µmhos/cm, to a single sample of $CaMgSO_4$ type water with conductance of 3020 µmhos/cm.

3.1.5 Sand Beneath B Bed

Like the overlying units, the conductivity of water from the sand beneath the B bed is lowest beneath the central part of the bedrock upland and increases both to the north and south. Values of conductivity in this $NaCaMgHCO_3$ type water range from about 700 to about 1300 µmhos/cm.

3.1.6 TR Bed and Overlying Sand

Samples from this interval are restricted to wells along the southern edge of the bedrock upland; specific conductance varies from about 1450 to 1975 with a mean of 1648 µmhos/cm and a standard deviation of 234. The water varies from $CaMgHCO_3SO_4$ type through $NaCaMgHCO_3SO_4$ type, to $NaHCO_3$ type.

3.1.7 Hensler Sand

Specific conductance of water from

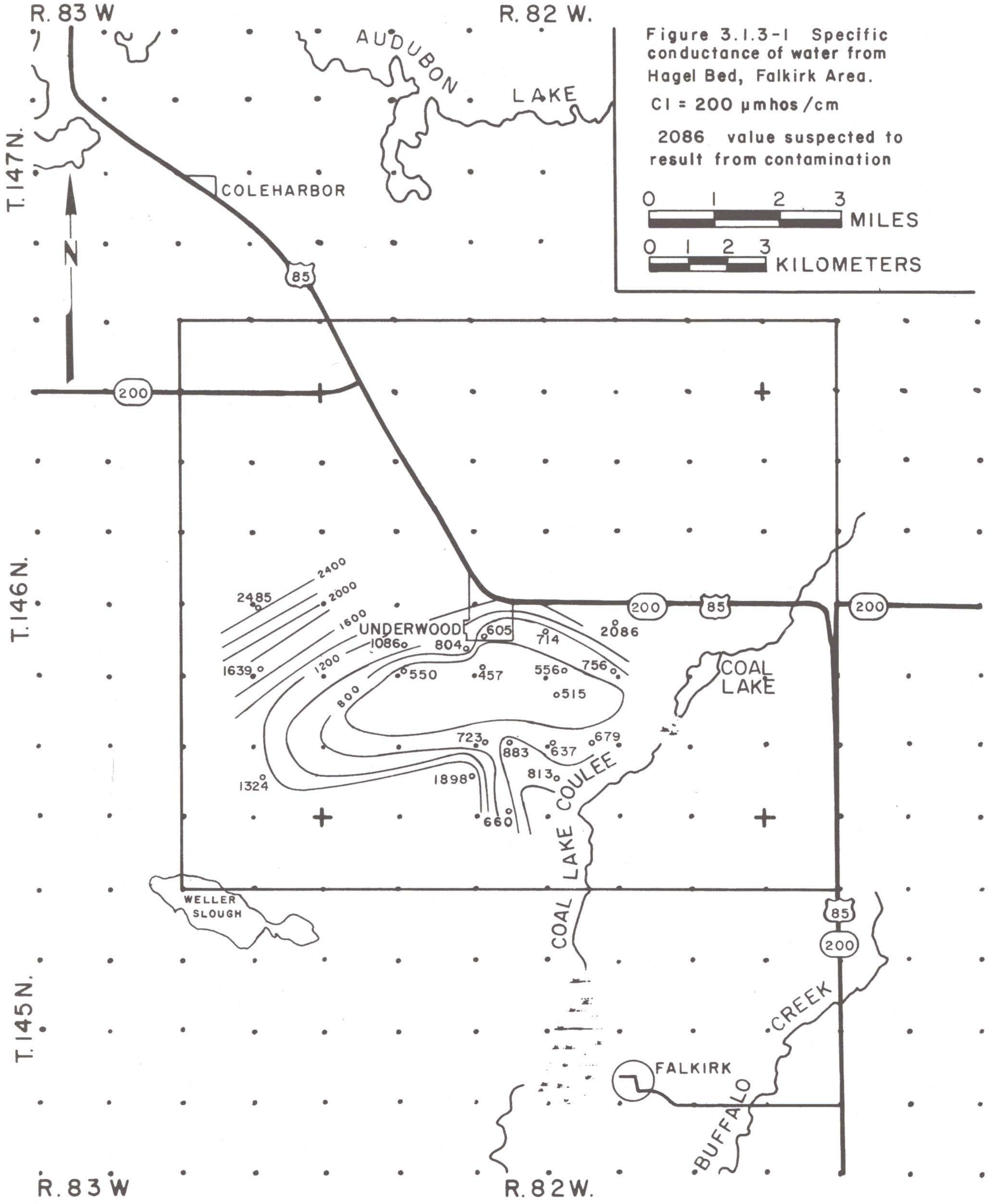

Figure 3.1.3-1. Specific conductance of water from Hagel bed, Falkirk area.

the Hensler sand appears to increase from east to west and from the central part of the bedrock upland both toward the north and south. Values range from about 1000 to about 1800 with a mean of 1358 μmhos/cm and a standard deviation of 242. One sample is $CaMgHCO_3$ type water; the remainder are $NaHCO_3$ or $NaHCO_3SO_4$ type water. The one anomalous sample is from a well where a buried valley fill lies directly on the Hensler sand.

3.2 Indian Head and Beulah-Hazen Sites

Due to the proximity of the Indian Head and Beulah-Hazen sites it is possible to include these two sites within a single discussion. The major source of groundwater chemical data for these sites is Woodward-Clyde, 1975. These data are from several wells in the Beulah-Hazen and Zap areas.

Analyses from wells in the Coleharbor Formation are shown in table 3.2-1. The prominent cation is typically sodium. Sodium concentrations range from 19 to 289 mg/l. In one well calcium is more abundant than sodium. In all cases, bicarbonate is the principal anion. Sulfate concentrations are highly variable, ranging from 6 to 426 mg/l. The pH values range from 7.18 to 7.99.

Analyses from wells in lignite aquifers in the Sentinel Butte Formation are shown in table 3.2-1. These data indicate that the water quality of the lignite aquifers is somewhat variable. The prominent cation in all samples is sodium, with concentrations ranging from 99-867 mg/l. Calcium is the second most common cation in all samples. Calcium concentrations range from 24 to 400 mg/l. The principal anion varies between bicarbonate and sulfate. Bicarbonate is the principal anion in the deeper wells. Sulfate is the principal anion in shallow wells (less than 50 feet), reaching a maximum concentration of 3010 mg/l. The pH values range from 6.98 to 8.77. Iron concentrations are generally high in the lignite aquifers.

3.3 Dunn Center Area

The chemical analyses of water samples in the Dunn Center area are grouped by water type and stratigraphic unit in table 3.3-1. 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 3.3-1, 11 groups of analyses are evident (figs. 3.3-1 to -9). The values of these ratios are referred to as the relative Na and relative 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 relative Na-HCO_3 composition of 0.39-0.44. 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 μmhos/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 three analyses of $(CaNa)HCO_3$ type water with a mean relative Na-HCO_3 content of 0.50-0.82. 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 relative Na-HCO_3 composition of 0.27-0.58, from five units, the Coleharbor

Table 3.2-1. *Chemical Analyses of Groundwater—Beulah-Hazen Area.*

Location	Well No.	Depth (ft)	pH	Cond.$^{(1)}$	TDS$^{(2)}$	Hardness$^{(2)}$	Ca$^{(2)}$	Mg$^{(2)}$	Na$^{(2)}$	K$^{(2)}$	$HCO_3$$^{(2)}$	Cl$^{(2)}$	$SO_4$$^{(2)}$
Coleharbor Formation													
146-088-21 DDD	G01	229	7.99	1080	673	209	31	33	180	9.7	793	5.6	6.4
144-086-19 ABA	G05	224	7.82	310	—	—	—	—	19.8	—	178	—	—
144-088-25 CCC 03	G06	156	7.66	770	808	302	74	33	150	11.2	691	9.6	136
145-088-03 ACC	G10	155	7.42	1850	1410	568	153	56	289	9.9	1030	2.4	426
145-088-25 ABB	G17	200	7.75	750	1471	368	148	48	43	6.7	527	6.4	79.2
144-087-14 AAA	G28	230	7.99	590	375	216	51	20	59	5.1	427	6.8	5.6
144-088-17 BCD	G60	225	7.35	700	576	302	—	—	—	—	305	11	94
144-086-08 DDD 01	G92	41	7.18	460	—	—	—	—	—	—	377	36	—
144-088-25 CCA	Beulah	46	7.5	850	590	283	72	37	85	4.8	539	5.6	95.6
144-086-18 ADA	Hazen Composite		7.45	1100	746	335	76	29	150	5.8	661	13	149
Sentinel Butte Formation													
146-088-22 CBB 01	G02	36	7.72	2850	2200	231	49	34	590	8.6	827	4.0	827
145-087-18 BAA	G04	120	8.45	1225	—	—	—	—	285	—	594	36	594
145-087-30 ADB	G09	100	7.28	1275	1530	660	85	71	250	9.2	652	8.8	652
144-089-24 BCC	G12	25	7.05	3800	5570	1803	400	158	867	19	1093	15	1093
146-087-22 CDC	G15	113	7.79	1000	—	—	—	—	—	—	637	36	—
146-087-27 ACC	G16	140	6.98	1190	934	529	87	53	115	9.2	590	15	256
146-087-21 CDC	G23	120	7.88	1000	741	369	73	36	126	7.3	564	5.6	142
145-087-19 CCB	G25	110	8.77	650	482	143	24	20	99	7.4	242	5.6	123
145-087-28 CDD	G57	335	7.37	285	—	—	—	—	—	—	110	36	—

(1) Micromhos
(2) Mg/l

Formation, A-interval, A-lignite, Dunn Center interval, and E-interval (fig. 3.3-1). The relative sodium content of the group ranged from a mean of 23 for two samples from the A-lignite to 246 for a single sample from the E-interval. The relative bicarbonate content varied from a mean of 329 for two samples from the A-lignite and five samples from the Coleharbor Formation to a mean of 0.63 for two samples from the A-lignite. The electrical conductivity of samples in group II was 842 μmhos/cm and 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 and A-lignite, respectively.

The distribution of analyses in group II is shown in figure 3.3-2. Except for two 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

Table 3.3-1. *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 3.3-1. *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 3.3-1. *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

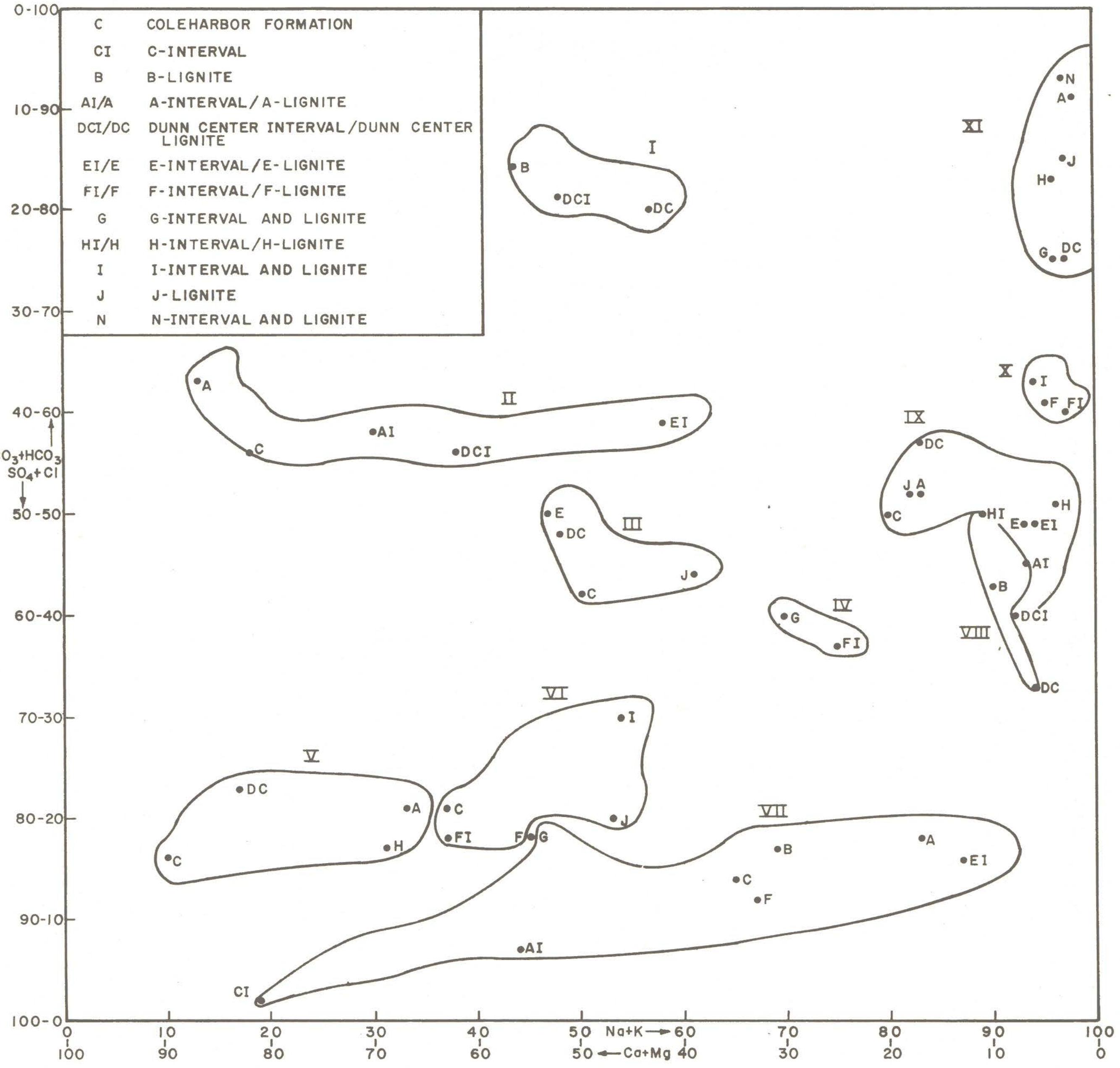

Figure 3.3-1. Plot of mean values of the ratios Na+K/Ca+Mg to CO_3+HCO_3/SO_4+Cl of groundwater in the Dunn Center area grouped by water type and by stratigraphic unit. The analysis group is shown by Roman numerals. The analyses are summarized in table 3.3-1 and their distribution is shown in figures 3.3-2 to -9.

Coleharbor Formation and sandy sediment in the upper part of the Sentinel Butte Formation.

Group III consists of 34 samples, with a mean relative Na-HCO_3 composition of 0.49-0.47, from four units, the Coleharbor Formation, Dunn Center bed, E-lignite, and J-lignite. The relative sodium content varies from a mean of 0.47 for seven samples from the E-lignite to 0.61 for a single sample from the J-lignite. The relative bicarbonate content varies from a mean of 0.42 for seven samples from the Coleharbor Formation to a mean of 0.50 for seven samples from the E-lignite. The mean electrical conductivity and pH of this (CaNa) (SO_4HCO_3) type water are 1535 μmhos/cm and 7.5, respectively. As in

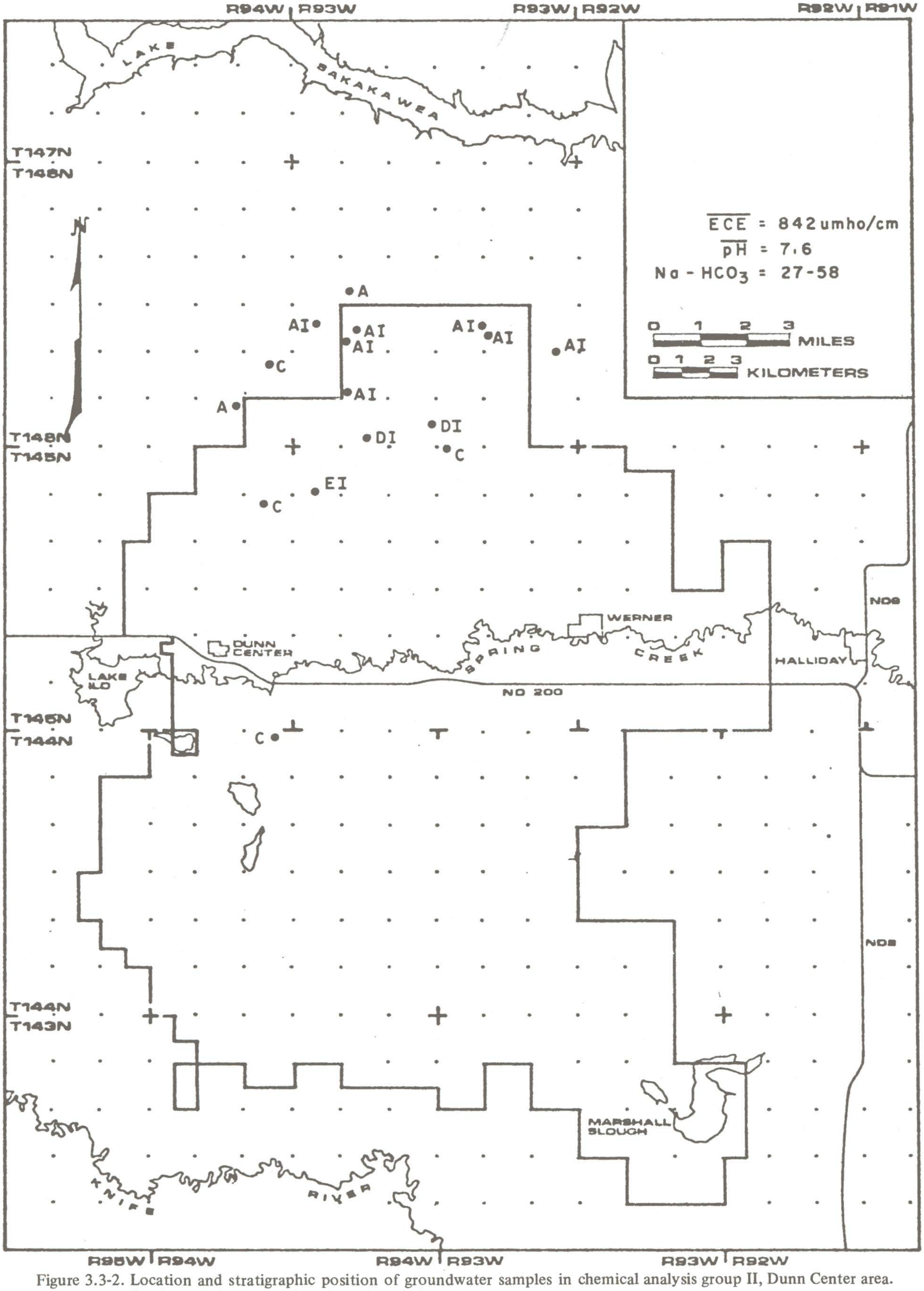

Figure 3.3-2. Location and stratigraphic position of groundwater samples in chemical analysis group II, Dunn Center area. See figure 3.3-1 for explanation of symbols.

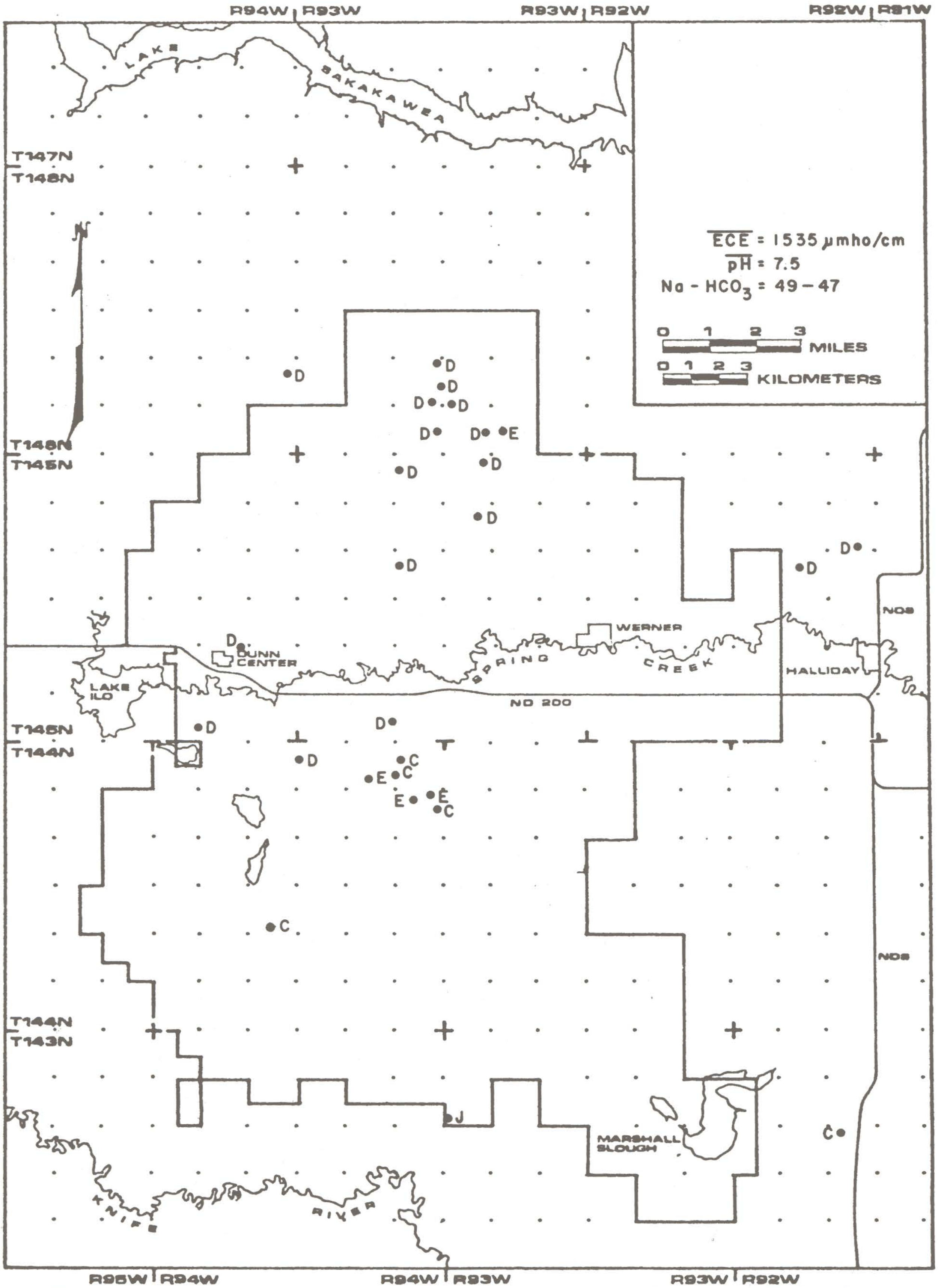

Figure 3.3-3. Location and stratigraphic position of groundwater samples in chemical analysis group III, Dunn Center area. See figure 3.3-1 for explanation of symbols.

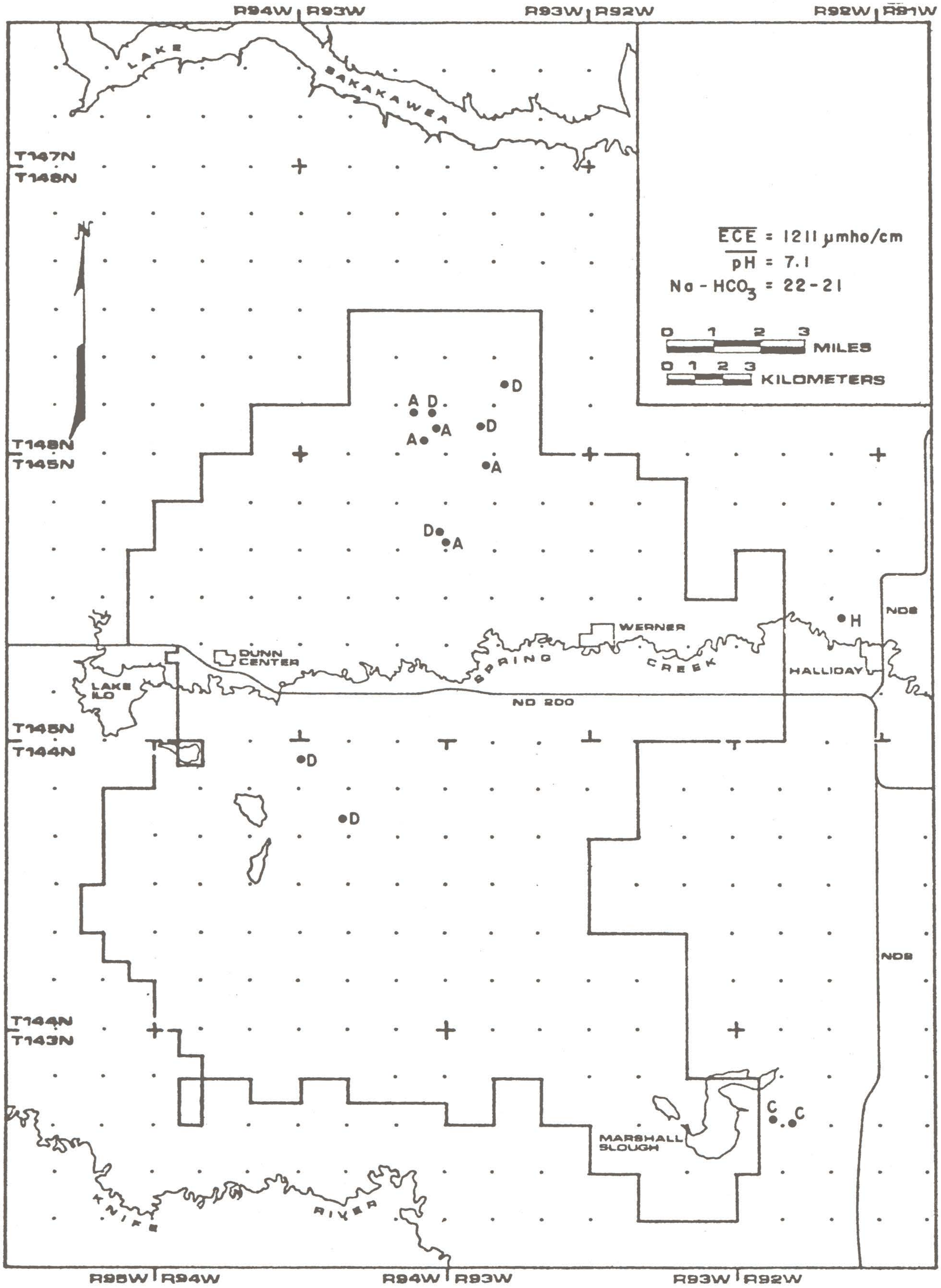

Figure 3.3-4. Location and stratigraphic position of groundwater samples in chemical analysis group V, Dunn Center area. See figure 3.3-1 for explanation of symbols.

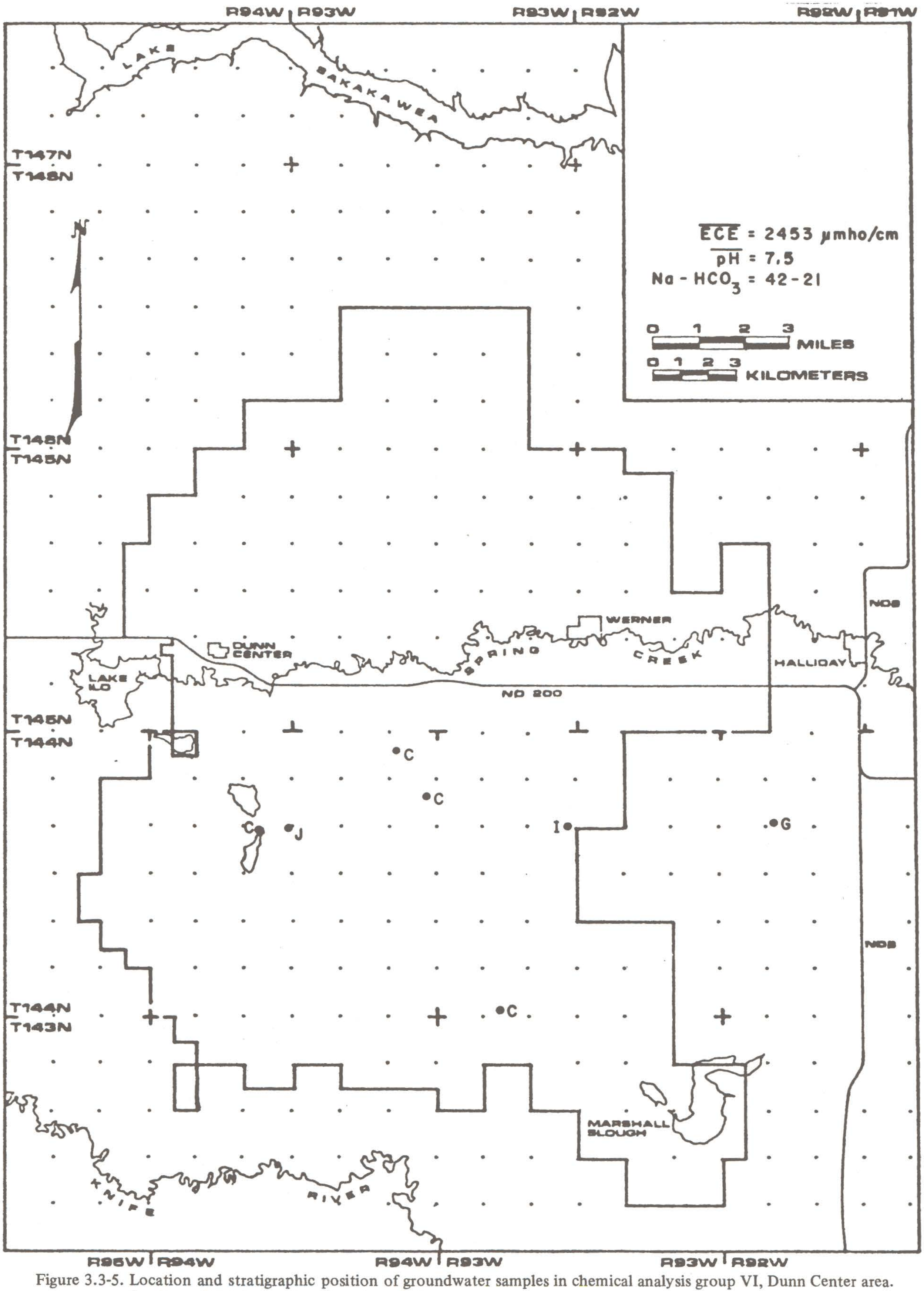

Figure 3.3-5. Location and stratigraphic position of groundwater samples in chemical analysis group VI, Dunn Center area. See figure 3.3-1 for explanation of symbols.

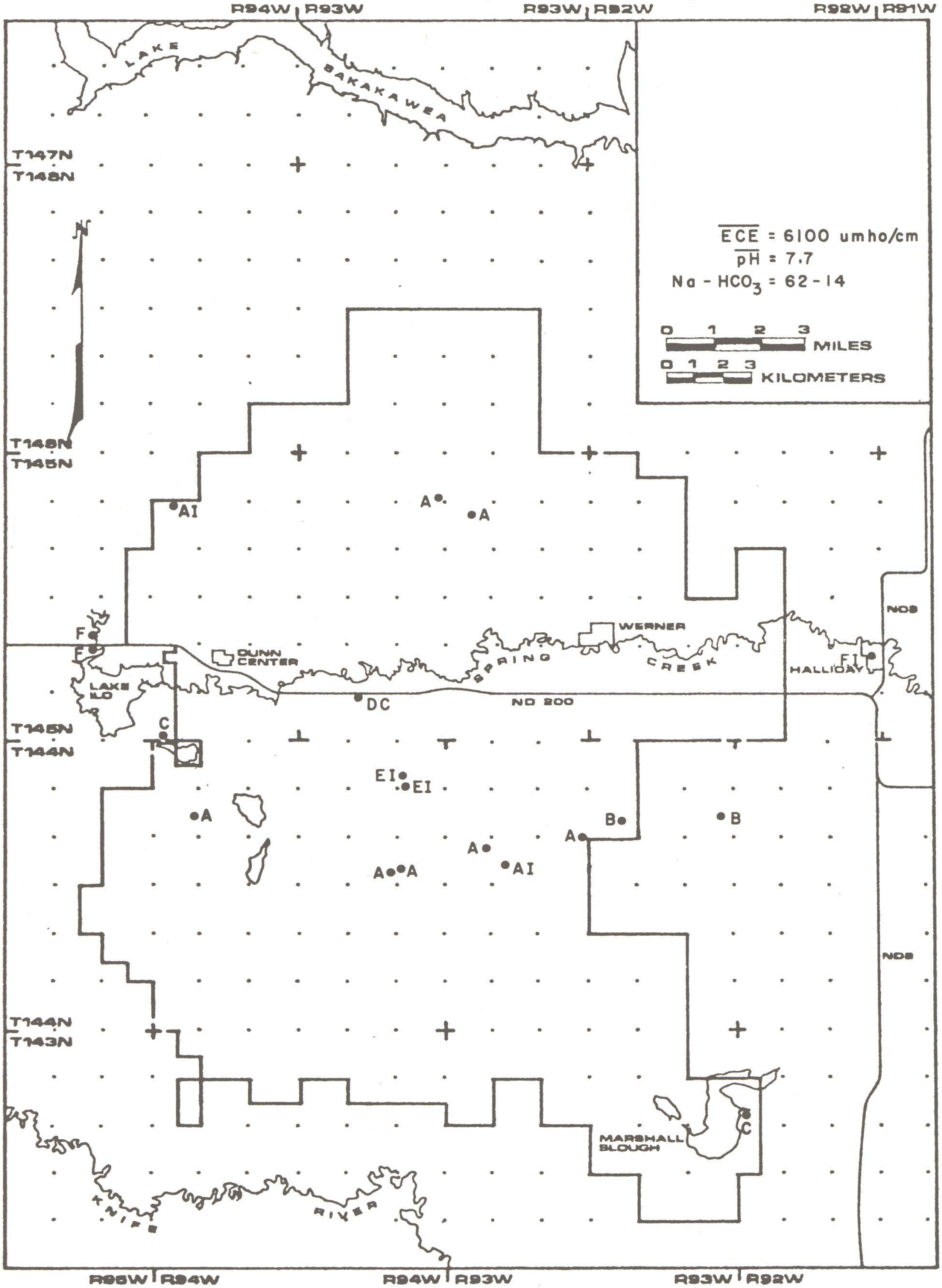

Figure 3.3-6. Location and stratigraphic position of groundwater samples in chemical analysis group VII, Dunn Center area. See figure 3.3-1 for explanation of symbols.

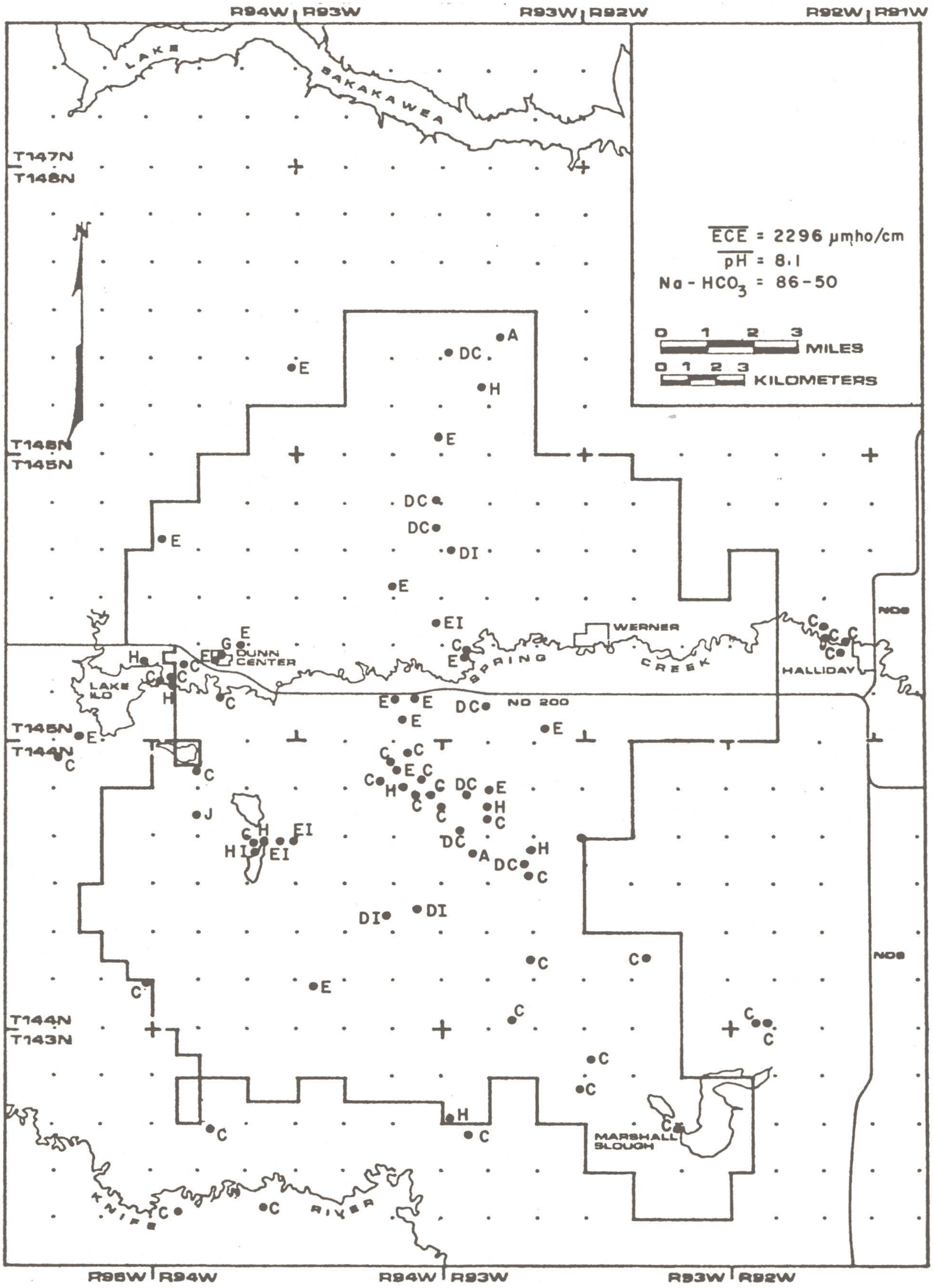

Figure 3.3-7. Location and stratigraphic position of groundwater samples in chemical analysis group IX, Dunn Center area. See figure 3.3-1 for explanation of symbols.

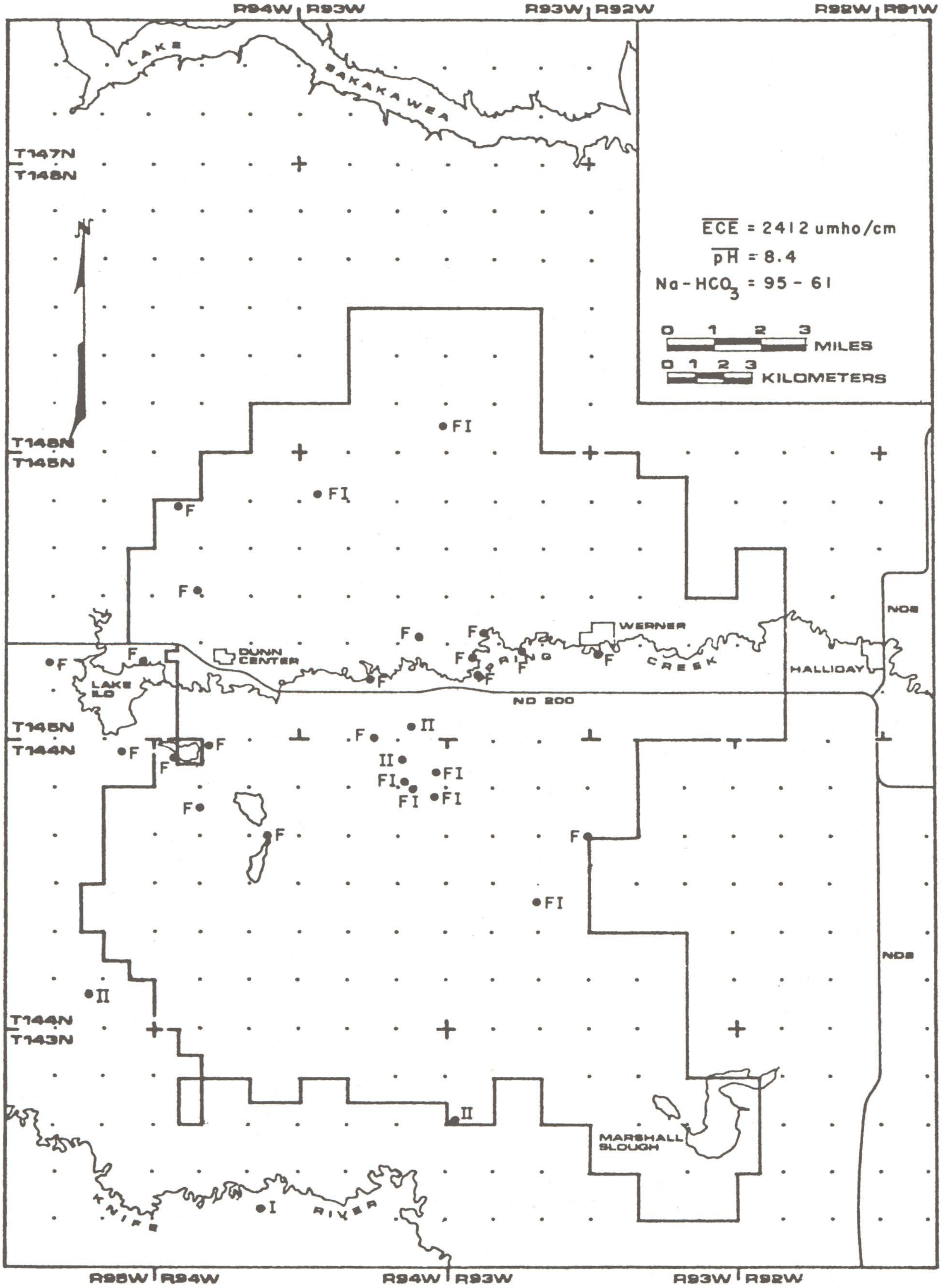

Figure 3.3-8. Location and stratigraphic position of groundwater samples in chemical analysis group X, Dunn Center area. See figure 3.3-1 for explanation of symbols.

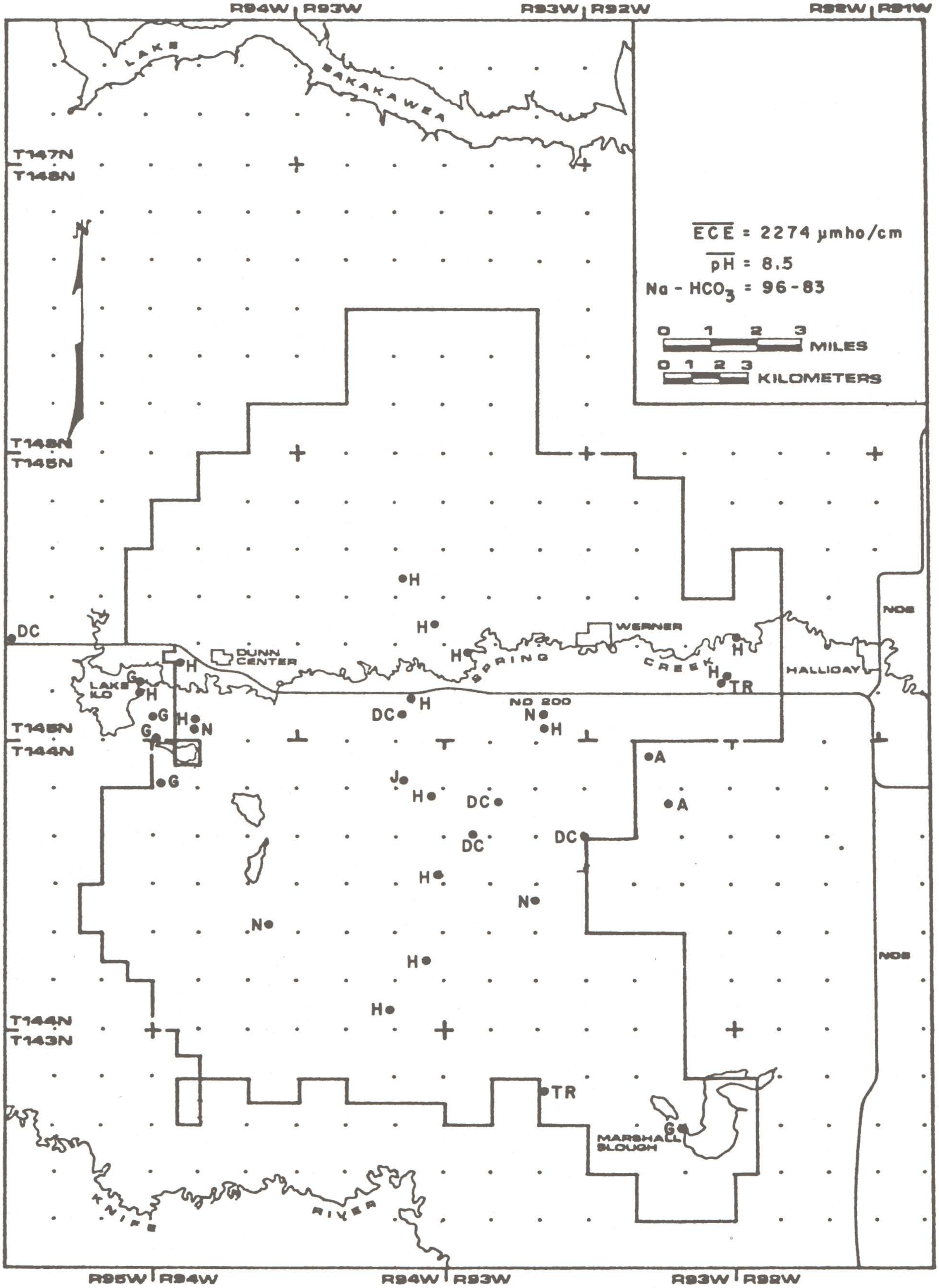

Figure 3.3-9. Location and stratigraphic position of groundwater samples in chemical analysis group XI, Dunn Center area. See figure 3.3-1 for explanation of symbols.

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 two 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. 3.3-3). 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 two analyses each from the F- and G-intervals. The mean relative $Na-HCO_3$ composition is 0.72-0.38 making the water an $Na(SO_4HCO_3)$ type. The conductivity ranges from 1616 to 2039 with a mean of 1828 µmhos/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 four stratigraphic units, Coleharbor Formation, A-lignite, Dunn Center bed, and H-lignite. The mean relative $Na-HCO_3$ composition of the group is 0.22-0.21, but individual values range from a mean of 0.10-0.16 for two samples from the Coleharbor Formation to a mean of 0.33-0.21 for six 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 one 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. 3.3-4). 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 stratigraphic position than those in group III in the same area (figs. 3.3-3 and -4). On the basis of these observations, the analyses from group V appear to represent water with 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 nine 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 relative $Na-HCO_3$ composition of 0.42-0.31, mean electrical conductivity of 2453 µmhos/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 µmhos/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. 3.3-5). 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 µmhos/cm, and a medium pH of 7.7. The group ranges from a composition of $CaSO_4$, a relative Na-HCO_3 content of 0.19-0.02, for one sample from the C-lignite to $NaSO_4$, a mean relative Na-HCO_3 content of 0.87-0.16, for two samples from the E-interval. The mean relative Na-HCO_3 content of the group is 0.62-0.14, 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. 3.3-6). 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 (Moran and others, 1976, secs. 8.3.9, 8.3.10, and 8.6). A number of analyses are from the A-lignite near its outcrop south and southeast of the proposed plant site (fig. 3.3-6). It is not known whether these analyses reflect an increase in salinity near a groundwater discharge area or recharge of saline surface water for areas of temporary ponding in side-slope positions.

Set IV consists of a small group of six 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 μmhos/cm, and high pH of 8.2. The mean relative Na-HCO_3 composition of this group of $Na(SO_4HCO_3)$ type water samples is 0.91-0.45. 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 three groups (fig. 3.3-1). The set is characterized by medium salinity, mean electrical conductivity of 2315 μmhos/cm, and a high pH of 8.2. The mean relative Na-HCO_3 composition of the set is 0.90-0.60. Composition of waters in the set ranges from $Na(HCO_3SO_4)$, a mean relative Na-HCO_3 composition of 0.86-0.50 from group IX, to $NaHCO_3$, a mean relative Na-HCO_3 composition of 0.96-0.83 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 relative Na-HCO_3 content of the $Na(HCO_3SO_4)$ type water making up this set is 0.86-0.50. The electrical conductivity has a mean value of 2296 μmhos/cm and the mean pH is 8.1.

Samples in this group are spread throughout the project area (fig. 3.3-7). 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 relative Na-HCO_3 content of these analyses is 0.95-0.61. The mean electrical conductivity is 2412 μmhos/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. 3.3-8). 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. 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 relative $Na-HCO_3$ composition of 0.96-0.83, from the A-lignite, Dunn Center bed, G-interval, H-lignite, J-lignite, and H-interval and lignite. The mean conductivity was 2274 μmhos/cm and the mean pH was 8.5.

These analyses are distributed, more or less uniformly throughout the project area (fig. 3.3-9). 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.

3.4 Center Site

Very little analytical data exists for wells in the area of the Center site. The analyses from six wells in the vicinity of the Center Mine are shown in table 3.4-1. These data are from Croft, 1973. Three of the wells are in sand and gravel of the Coleharbor Formation. The other three wells are in the Sentinel Butte Formation. Two are in sand and the other is in the Hagel bed.

The analyses indicate that sodium is the principal cation in the sand and lignite of the Sentinel Butte Formation. Sodium values range from 98 to 250 ppm. The second most common cation is calcium, ranging from 10 to 66 ppm. The principal anion in all three wells in the Sentinel Butte Formation is bicarbonate. Bicarbonate values range from 483 to 796 ppm. Sulfate ranges from 44 to 65 ppm. The pH values in the wells in the Sentinel Butte Formation range from 7.8 to 8.1.

Sodium is the prominent cation in two of the wells in the Coleharbor Formation. Calcium is the principal cation in the third well. Sodium values range from 51 to 143 ppm; calcium ranges from 68 to 101 ppm. Bicarbonate is the principal anion in all the wells in the Coleharbor Formation, ranging from 334 to 472 ppm. Sulfate ranges from 55 to 359 ppm. The pH values range from 7.9 to 8.0.

4. HYDROGEOCHEMICAL EVOLUTION OF SOIL WATER AND GROUNDWATER

In sections 2 and 3 of this report information of the geochemical nature of the overburden and groundwater in the five study areas has been described. The purpose of this section is to develop an interpretive hydrogeochemical framework that is suitable for use in studies of mine-land reclamation in North Dakota.

For the framework to be useful it must account for the characteristic chemical features of the groundwater in Quaternary and Tertiary deposits in the five study areas. Samples of soil water (i.e., water samples from overburden at locations *above* the water table) were not obtained because of the great difficulty of such a task within the framework of this preliminary investigation. Conclusions on soil-water chemistry were obtained, however, by interpretation of the saturated extract, carbonate, and cation exchange data described in section 2.

The ultimate objective in the development of an interpretive hydrogeochemical framework is to provide a basis for prediction of the chemistry of subsurface water that will develop in reclaimed-mine land. The most desirable path would be to develop a framework and then test (or verify) it by comparison of predictions based on its use with data from actual field situations. Since adequate geochemical data from reclaimed land has not yet been acquired, it was not feasible for us to follow this approach. We have proceeded, however, with the reasonable assumption that an interpretive framework that adequately accounts for the observed water chemistry in the natural overburden will have some applicability in the analysis

Table 3.4-1. *Chemical Analyses of Groundwater—Center Area.*

Location	Well No.	Depth (ft)	pH	Cond.(1)	TDS(2)	Hardness(2)	Ca(2)	Mg(2)	Na(2)	K(2)	HCO_3(2)	Cl(2)	SO_4(2)
						Coleharbor Formation							
142-082-05 DAA 02	NDSWC 3648	50	7.9	1290	911	440	101	46	143	4.7	472	4.3	359
142-084-08 AAB	NDSWC 3732	124	8.0	806	527	206	53	18	107	3.5	416	1.2	104
142-084-08 ABB	NDSWC 3733	81	8.0	595	374	214	68	11	51	2.8	334	1.8	55
						Sentinel Butte Formation							
142-084-14 BC	Center	130	8.0	1100	695	77	21	6.0	253	3.6	699	3.0	54
142-084-14 CB	Center	118	8.1	1270	806	39	10	3.4	317	3.4	796	3.3	65
142-084-15 DA	Center	139	7.8	778	479	219	66	13	98	3.7	483	2.3	44

(1)Micromhos
(2)Mg/l

of salt generation and accumulation in reclaimed land.

In this report the framework has been used to develop some concepts for simple field tests for geochemical factors that are important in reclamation design. These tests are described in section 7.

For the interpretive hydrogeochemical framework to be valid it must account for the predominant ions in the subsurface water and the pH of the water. More specifically it must account for the fact that most groundwater in the five study areas is characterized by dominant concentrations of Na^+, HCO_3^-, and SO_4^{2-}. It must also account for the less widespread but significant number of groundwater zones that have Ca^{2+} or Mg^{2+} as the dominant cations with HCO_3^- and SO_4^{2-} as the dominant anions. The model also must explain the variation in total dissolved solids of the groundwater, the general absence of dissolved oxygen at detectable concentrations, the general lack of detectable H_2S, the generally low concentrations of Cl^- and K^+, and the partial pressure of dissolved carbon dioxide in the water. Development of a hydrogeochemical model that will accomplish these tasks requires the use of constraints or boundary conditions that are based on geologic, hydrologic, and geochemical factors. It must also account for the changes in water chemistry that occur as the water moves from the ground surface, where it originates as rain or snowmelt through the solum and the underlying unsaturated zone into the groundwater zone where it moves towards its eventual zone of exfiltration.

Figure 4-1 is a schematic indication of the geochemical processes that we consider to be most important in the chemical evolution of subsurface water in western North Dakota. Most rainfall or snowmelt events cause infiltration of water below ground surface but not to depths below the root zone. Acidity is produced by CO_2 production and pyrite oxidation. Evaporation and transpiration causes concentration of salts in the soil water and as a consequence precipitation of calcite and gypsum in or near the root zone. In this manner gypsum and possibly other soluble salts are generated above the water table in geologic materials near the land surface that initially, at the time of deglaciation, were probably devoid of gypsum. Exceptional rainfall or snowmelt events can cause infiltration below the root zone and as a result can produce groundwater recharge. When this occurs, CO_2 production, pyrite oxidation, calcite (and in some areas dolomite) dissolution, gypsum dissolution, and cation exchange are the processes that control the chemical evolution of the infiltration water. It is this water, which acquires its characteristic chemical features in the root zone, that supplies the groundwater zone. The

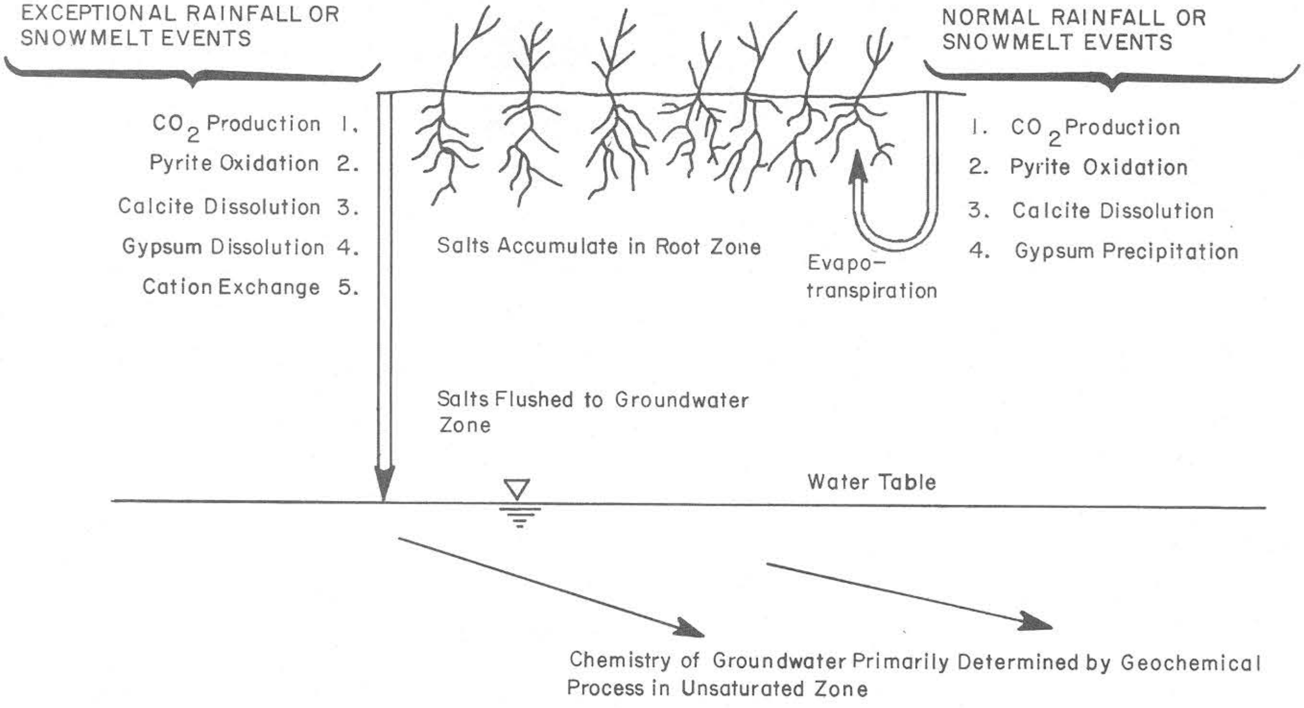

Figure 4-1. Schematic diagram of chemical processes and salt movement in much of the plains regions.

individual components of the geochemical framework summarized in figure 4-1 are described in detail below.

The first major step in the chemical evolution of subsurface water occurs when rain or snowmelt infiltrates into the organic-rich horizons of the solum. In this zone the water acquires hydrogen ions (H^+). These ions are supplied from a variety of sources. In western North Dakota the two main sources occur as a result of (1) CO_2 production during biochemical decay or organic matter in the soil zone and (2) oxidation of iron sulfide (FeS_2 as pyrite or marcasite). Organic-matter oxidation is believed to be the dominant H^+ source in most subsurface hydrogeochemical systems. Oxidation of iron sulfide is rarely considered to be an important source. In western North Dakota, and, therefore, presumably in the entire Ft. Union region, however, this H^+ source plays a key role in the geochemical evolution of soil water and groundwater.

Numerous studies have shown that the partial pressure of $CO_2(P_{CO_2})$ in the organic-rich horizons of soil is typically much above the P_{CO_2} in the earth's atmosphere, which is approximately $10^{-3.5}$ atmospheres. We have not actually measured the P_{CO_2} in soil horizons in the study areas. The occurrence of elevated CO_2 pressures in soil is so well established that there is no need for corroboration of its existence in these specific study areas.

The partial pressure of CO_2 in soil water is important because dissolution of CO_2 in water is a process that produces acidity. In this context the term acidity is used to refer to the hydrogen-ion concentration (H^+) in the water. De-ionized water in contact with the earth's atmosphere ($P_{CO_2}=10^{-3.5}$) will have an equilibrium pH of approximately 5.7. If this water is brought in contact with a gas phase with a higher P_{CO_2} the pH will decrease to a lower equilibrium value. At a P_{CO_2} of 10^{-2} atm, for example, the equilibrium pH is approximately 5.0. At a P_{CO_2} of 10^{-1} atm it is 4.2.

Values of P_{CO_2} reported in the literature for soils in a wide variety of terrain settings are typically in the range of 10^{-3} to 10^{-1} atm. The values vary with depth in the soil profile. If rain and snowmelt infiltrates into soil, its pH will drop to the range of about 5.5 to 4.2, providing that reactions with mineral matter or organic matter in the soil do not buffer the pH. In western North Dakota and in other regions where soil cover is relatively continuous, it is reasonable to expect that the process of CO_2 generation in the soil zone causes a significant production of acidity in infiltrating water as it passes through the uppermost horizons of the soil.

As the infiltrating water passes through the organic-rich soil horizons into the mineral-rich horizons lower in the soil profile and below the soil, it comes into contact with minerals with which it reacts. The most important types of reactions that occur are: oxidation of sulfide minerals; dissolution and precipitation of carbonate minerals; precipitation of gypsum; cation exchange. These four chemical processes exert a dominant control on the chemistry of subsurface water that infiltrates through the soil. Although these processes probably occur simultaneously in many subsurface zones their nature and influence will be described separately before considering the effect of simultaneous interactions. In some surface depressions where mineral particles accumulate as a result of erosion of bare rock or sediment slopes, some of these processes occur before the water infiltrates more than a few centimeters below ground surface.

The soil horizons below the uppermost organic-rich layer and the parent geologic materials below the soil are composed of a wide variety of mineralogical constituents. Of these, only a very small number exert a significant influence on the development of major-ion chemistry of water that passes through the deposits. Foremost in this category of hydrogeochemically significant mineralogical constituents are the carbonate minerals (calcite and dolomite), gypsum, iron sulfide minerals (pyrite and marcasite), and clay minerals. Minerals such as quartz, micas, and other primary alumino-silicate minerals are relatively unimportant as geochemical controls in the prairie environment of North America. Most of the overburden in the Tertiary sediments of North Dakota contain significant amounts of one or more of the hydrogeochemically significant mineral types listed above. We will now examine how water can interact with these minerals in a variety of hydrogeologic situations.

In addition to dissolved CO_2, water that infiltrates into the soil zone contains dissolved oxygen, nitrogen, and other gases. Of these, dissolved oxygen and carbon dioxide are the only ones that have geochemical significance. Dissolved oxygen is important because it provides a strong capability for oxidation of mineral matter and organic matter. Oxidation of organic matter and root respiration is the mechanism by which CO_2 is produced in the soil zones. The main mineralogical constituent in the overburden of western North Dakota that undergoes significant oxidation is iron sulfide. Iron sulfide (FeS_2) occurs as pyrite and marcasite. Henceforth in this discussion we will refer to iron sulfide simply as pyrite. The process of pyrite oxidation is expressed by the following reaction,

$$\begin{aligned}&4FeS_2+15O_2+14H_2O \rightarrow \\ &4Fe(OH)_3+16H^++8SO_4^{2-}\end{aligned} \qquad (4.1)$$

This relation indicates that reaction of oxygen, water, and pyrite produces iron hydroxide (a yellowish solid), sulfate ions, and hydrogen ions. This reaction is one of the strongest acid-producing reactions known to occur in natural geological systems. It is the cause of the acid mine-drainage problem that has been so environmentally damaging in the Appalachian region of the United States and in other mining regions of the world.

If water with this dissolved oxygen concentration moves into geologic materials that contain pyrite *and* if the water content is at 100 percent saturation (i.e., the pore spaces are filled with water and contain no free air), the dissolved oxygen would be sufficient to oxidize a maximum amount of pyrite for production of 1.7×10^{-4} moles/liter (16 mg/l) of SO_4^{2-} and 3.3×10^{-4} moles/liter of H^+. This concentration of H^+ represents a pH of approximately 3.5. The water would therefore be quite acidic. This pH is lower than the pH produced in water at the upper limit of the CO_2 partial pressure range for soil air indicated above. The example of pyrite oxidation calculated above represents a closed system with respect to dissolved oxygen.

If dissolved oxygen is supplied to the water as pyrite dissolves, more pyrite will be oxidized and as a result more SO_4^{2-} and H^+ will enter the water. For purpose of illustrative calculations it will be assumed that both atmospheric air and water containing 10 mg/l of dissolved oxygen enter a porous geological material that contains pyrite. As pyrite is oxidized by reaction with dissolved oxygen in the water, oxygen from the air in the pore spaces will go into solution in the water as a result of the disequilibrium between the concentrations of oxygen in the air and in the water caused by the consumption of oxygen in the oxidation reaction. As part of the consumed dissolved oxygen is replenished, the continuation of the pyrite oxidation process produces increased concentrations of SO_4^{2-} and a decline in pH. If the air in the pore space of the porous medium is not replenished and if the reactions proceed to equilibrium, the equilibrium SO_4^{2-} and pH values will depend on the percent saturation of water in the medium. This is illustrated in figure 4-2, which indicates that the pH can decline to a minimum value near 2. The SO_4^{2-} concentration rises to about 450 mg/l. In this analysis it has been assumed that the oxidation of FeS_2 is the only mineral-water reaction that occurs in the system. The effect of buffering reactions are considered in a later discussion.

Figure 4-2 represents the case in which the air in the porous geologic material is not replenished. If air replenishment occurs, and if the pyrite content remains significant, pyrite oxidation will continue. As a result the pH will continue to decline and the SO_4^{2-} concentration will continue to increase. Extremely acidic, high SO_4^{2-} water will therefore evolve. If minerals are present that result in reactions that consume H^+, the pH will not decline as much as indicated in the above discussion. Dissolution of calcite or dolomite have this effect on the aqueous system.

This leads us to a discussion of the next major geochemical process, that of carbonate mineral dissolution and pH control.

The carbonate minerals, calcite and dolomite, occur in most, but not all of the overburden materials in western North Dakota. These minerals are moderately soluble in water. It is well established that when water comes in contact with them, dissolution to saturation occurs within a matter of hours or days, depending on the surface area of mineral-water contact and providing that the water is not flowing rapidly in comparison to the reaction rate (Ranch and White, 1977). The dissolution reaction for calcite and dolomite can be expressed as follows,

$$CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^- \qquad (4.2)$$

$$CaMg(CO_3)_2 + 2H^+ \rightarrow Ca^{2+} + Mg^{2+} + 2HCO_3^- \qquad (4.3)$$

It is apparent from these expressions that dissolution of these minerals results in H^+ consumption. In other words, some of the H^+ in solution combines with CO_3^- ions from the carbonate minerals to form HCO_3^-. As a result of calcite and/or dolomite dissolution the pH and the HCO_3^- concentrations in the water increase. The pH and HCO_3^- concentrations will rise until the water is saturated with respect to calcite and/or dolomite. Saturation will occur when the following equilibrium relations are attained:

$$\frac{[Ca^{2+}]\,[HCO_3^-]}{H^+} = K_{eq.cal} = 10^{2.15} \qquad (4.4)$$

$$\frac{[Ca^{2+}]\,[Mg^{2+}]\,[HCO_3]}{H^+} = K_{eq.dol} = 10^{-6.14} \qquad (4.5)$$

where the square bracketed terms represent ionic activities and $K_{eq.cal}$ and $K_{eq.dol}$ denote the equilibrium constants for calcite and dolomite obtained from equations 4.2 and 4.3 using the law of mass action.

Ionic activities are the chemically effective solution concentrations. In dilute solutions they are approximately equal to the concentrations in solutions determined by standard methods of chemical analysis (expressed in molality). For a detailed discussion of the relation between activities and concentrations the reader is referred to Garrels and Christ (1965). Saturation levels

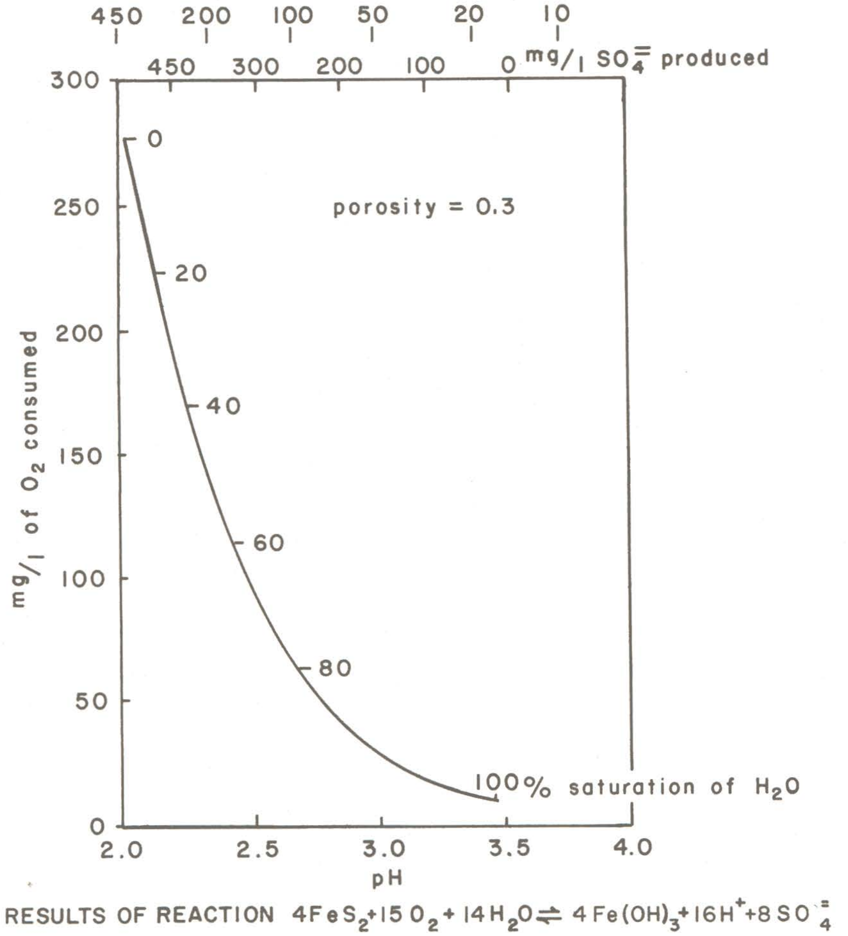

Figure 4-2. pH and SO_4^{2-} concentrations in water as a result of oxidation of pyrite. The air-water system is assumed to be closed with respect to air replenishment. The amount of O_2 available for oxidation of pyrite depends on the percent saturation and porosity of the porous medium.

in the water are reached when the product of the bracketed terms on the left side of each of these equations equals the equilibrium constants. When saturation is attained, further dissolution of calcite and dolomite will not occur unless one or more of the bracket constituents decrease in value. In other words, if Ca^{2+} is removed from solution, more calcite and dolomite will dissolve if this mineral exists in the system. As will be described below, cation exchange is a major process by which Ca^{2+} removal occurs in many subsurface zones in western North Dakota. At 8°C, which is a temperature typical of much of the groundwater in the overburden in western North Dakota, $K_{eq.cal}$ and $K_{eq.dol}$ have values of $10^{+2.15}$ and $10^{-6.14}$, respectively. The equilibrium constants used here and elsewhere in this report were obtained from Langmuir (1971).

Dissolution of calcite and dolomite is the main mechanism by which HCO_3^- is acquired by groundwater in most sedimentary regions. The normal concentration range for HCO_3^- in groundwater in overburden or rocks that contain calcite or dolomite is approximately 200 to 500 mg/l. Groundwater in Tertiary deposits in western North Dakota, however, commonly has HCO_3^- values in the range of 500 to 1500 mg/l. The unusually high HCO_3^- concentration is one of the main distinguishing features of this water.

It is evident from equations 4.4 and 4.5 that high HCO_3^- concentrations can be achieved if the concentration of Ca^{2+} or Mg^{2+} is low and/or if the concentration of H^+ is large. In the high HCO_3^- waters of

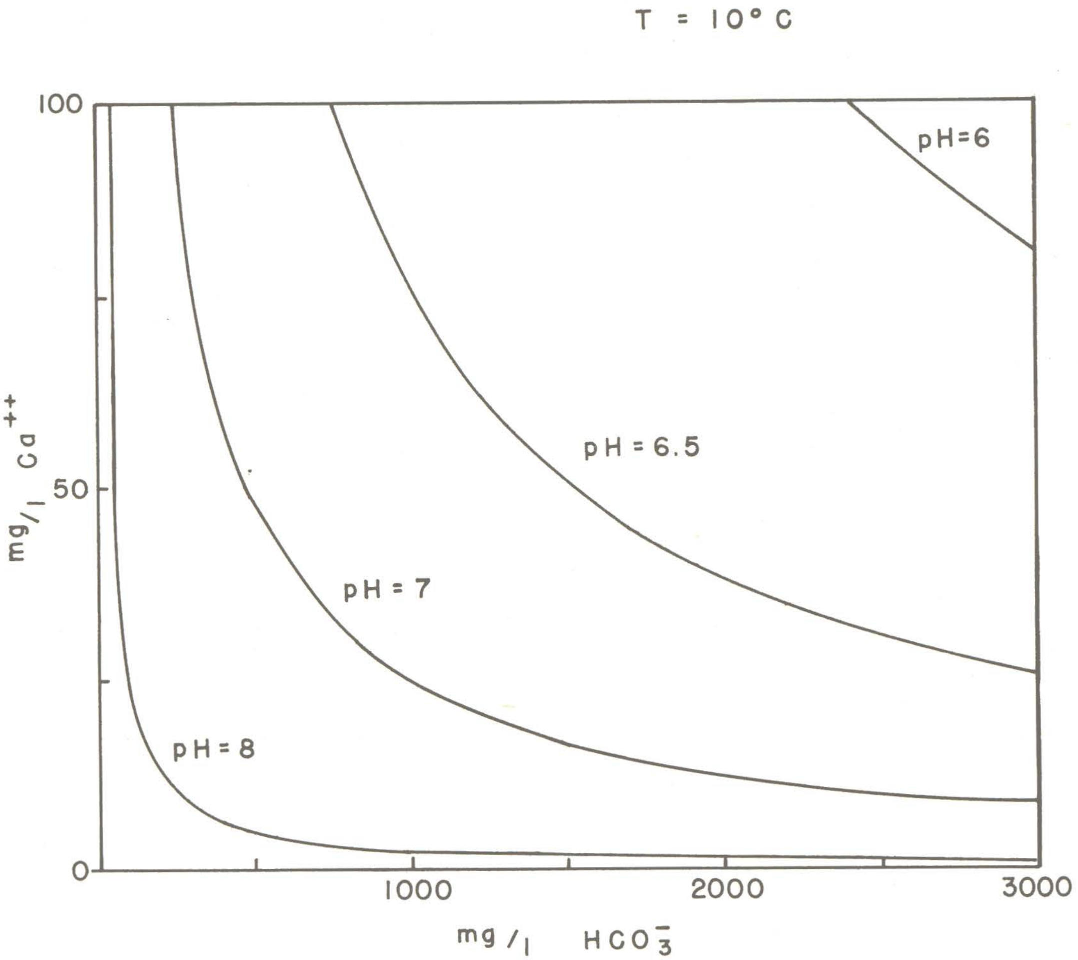

Figure 4-3. Relations between pH, HCO_3^-, and Ca^{2+} in water at equilibrium with respect to calcite with specified Ca^{2+} concentrations. The effect of activity coefficients is neglected.

western North Dakota both of these factors have an important influence. High HCO_3^- waters in this region have relatively low concentrations of Ca^{2+} and Mg^{2+} and high concentrations of Na^+. This situation is a result of exchange reactions with clay minerals. This topic is discussed in detail below. Our purpose here is to consider the source and influence of H^+ on the origin of HCO_3^- in the water.

If calcite and dolomite dissolve to equilibrium and if the concentrations of Ca^{2+} and Mg^{2+} are fixed at specified values as a means of illustrating the effect of cation exchange, the equilibrium concentrations and pH can be computed using equations 4.2 and 4.4. Results of these computations are shown graphically in figure 4-3. These graphs indicate that for the Ca^{2+} and Mg^{2+} values typical of high HCO_3^- groundwater in western North Dakota (i.e., about 5 to 80 mg/l) equilibrium HCO_3^- values in the range of 500 to 1500 mg/l can occur if the pH values are in the range of 7.8 to 6.8. When pH measurements are made in the field on samples collected by piston pumping or bailing, this is the range in which the pH values typically occur (pH values obtained from samples collected by air lift pumping are not suitable for use in geochemical studies because of the effect of degassing during pumping; pH values obtained in this manner should be disregarded in interpretation of the geochemical evolution of groundwater).

It was indicated above that the two potential sources of major H^+ concentrations are the oxidation of organic matter and the oxidation of pyrite. The reason that acidic groundwater is not commonly observed in western North

Dakota is that dissolution of calcite and dolomite consumes nearly all of the H^+ generated by these two processes. Carbonate mineral dissolution is normally considered in terms of two systems, open-system dissolution and closed-system dissolution. For calculation purposes the partial pressure of CO_2 in air in contact with the aqueous system is normally used as a control variable. Open-system dissolution occurs when the partial pressure of CO_2 in the gas phase (i.e., in the soil air) is maintained at a constant value as a result of contact of the water with a relatively large volume of gaseous CO_2 in the soil. If the dissolution occurs in partially saturated (i.e., pores contain both air and water) soil in which CO_2 in the soil air replenishes the dissolved CO_2 in the water that is converted to HCO_3^- as dissolution occurs, the system is regarded as being "open." In this context it is illustrative to express the dissolution reactions as follows:

$$CaCO_3+H_2CO_3 \rightarrow Ca^{2+}+2HCO_3^- \tag{4.6}$$

$$\begin{aligned} &CaMg(CO_3)_2+2H_2CO_3 \rightarrow \\ &\quad Ca^{2+}+Mg^{2+}+4HCO_3^- \end{aligned} \tag{4.7}$$

The relations indicate that dissolution of one mole of calcite or dolomite results in production of two moles of HCO_3^-. In an open system H_2CO_3 is replenished as it is converted to HCO_3^- in the dissolution process, CO

$$CO_2(g) \rightarrow CO_2(g)+H_2O \rightarrow H_2CO_3 \tag{4.8}$$

The equilibria for the aqueous species in the system are as follows:

$$K_{CO_2}=\frac{[H_2CO_3]}{P_{CO_2}} \tag{4.9}$$

$$K_{H_2CO_3}=\frac{[H^+]\,[HCO_3]}{[H_2CO_3]} \tag{4.10}$$

$$K_{HCO_3^-}=\frac{[H^+]\,[CO_3^{2-}]}{[HCO_3^-]} \tag{4.11}$$

$$K_{H_2O}=[H^+]\,[OH^-] \tag{4.12}$$

where K represents the equilibrium constant and P_{CO_2} is the partial pressure of CO_2 in atmospheres. In an open system P_{CO_2} is a constant, and therefore H_2CO_3 is constant. As dissolution of calcite or dolomite occurs, H^+ decreases and HCO_3^- increases, as can be surmised from equation 4.10. The solubility of calcite in water as a function of fixed P_{CO_2} and Ca^{2+} concentration is shown in figure 4-3. The initial pH and pH of the water after dissolution to equilibrium is also indicated on this diagram. It is assumed that prior to dissolution H^+ is the only cation species in the water. Specification of the P_{CO_2} also determines the initial pH. The calculation procedures used in the preparation of this figure were adapted from Garrels and Christ (1965). Ca^{2+} concentrations from 5 to 80 mg/l were used because these values represent a range typical of high HCO_3^- water of western North Dakota.

Figure 4-4 indicates that under open-system dissolution conditions P_{CO_2} of $6x10^{-1}$ to $3x10^{-3}$ atm would be necessary to produce the HCO_3^- values in the range of 500 to 1500 mg/l in water with Ca^{2+} concentrations in the range specified above. Soil zone CO_2 values reported in the literature are generally between 10^{-3} and $10^{-1.5}$ atm. Values larger than 10^{-1} have not, to our knowledge, been observed in natural soil horizons. Figure 4-3 indicates that if open-system dissolution is a common occurrence in soils of western North Dakota, the partial pressure of CO_2 in the soil would be anomalously high in at least some areas. This figure indicates that P_{CO_2} values well above 10^{-1} atm would be necessary under open-system conditions to cause very high HCO_3^- concentrations when the Ca^{2+} concentrations are on the order of a few tens of milligrams per liter. For example, figure 4-3 indicates that water with a HCO_3^- concentration of 1000 and Ca^{2+} concentration of 40 mg/l, values commonly observed in the study area, would require initial P_{CO_2} of 10^{+2} in order to originate from open-system dissolution of calcite with Ca^{2+} content controlled by ion exchange. Exceptionally high P_{CO_2} values could develop as a result of the combined effect of CO_2 generation from organic matter, root respiration, and H^+ production from oxidation of pyrite. At lower pH values a larger percent of the inorganic carbon in the system occurs as H_2CO_3. Therefore, as indicated by equation 4.9, the equilibrium P_{CO_2} would be higher than would be the case if CO_2 generation were the only control on H^+.

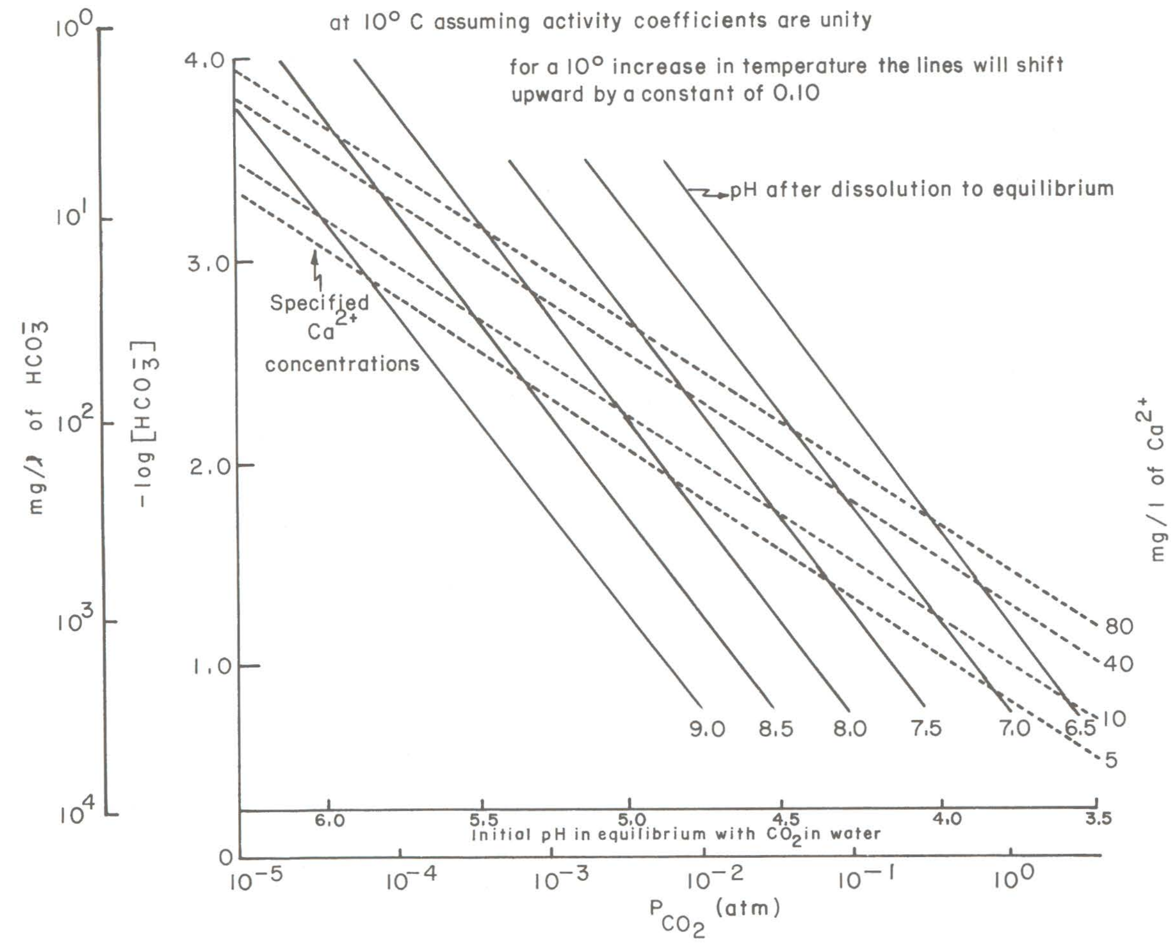

Figure 4-4. Relations between pH, P_{CO_2}, HCO_3^-, and Ca^{2+} for open-system dissolution of calcite at specified Ca^{2+} values. The pH of the water after dissolution proceeds to equilibrium is indicated. The initial pH represents the pH of the water prior to dissolution under the specific P_{CO_2}.

Partial pressures of CO_2 have never been measured in soils of western North Dakota. Whether or not exceptionally high pressures do in fact occur should be determined by direct field measurements. Our purpose here is to indicate that the interpretation of Ca^{2+} and HCO_3^- data is compatible with the production of H^+ by pyrite oxidation. If much lower P_{CO_2} values would adequately account for the HCO_3^- data, pyrite oxidation could possibly be viewed as an unnecessary appendage to the sequence of geochemical processes that are used to explain the high concentrations of HCO_3^- that typify much of the subsurface water in the region.

If calcite or dolomite dissolution occurs under closed-system conditions, CO_2 is *not* supplied to the water from soil air as dissolution proceeds. As H^+ is consumed it is not replenished. The P_{CO_2} declines as dissolution proceeds. The capability of the water to dissolve calcite or dolomite therefore depends on the initial P_{CO_2}, or on the initial pH. Specification of the initial P_{CO_2} determines the initial pH, or, alternatively, for calculation purposes the initial pH can be specified and the initial P_{CO_2} be computed. Figure 4-5 indicates the solubility of calcite for specified Ca^{2+} concentrations and initial pH or P_{CO_2}. The pH of the water after equilibrium is achieved is also indicated. Figure 4-5 indicates that under closed-system dissolution the typically observed range of pH values in groundwater can only be produced if the initial pH of the water is very low.

The analysis using open-system conditions indicated that H^+ production

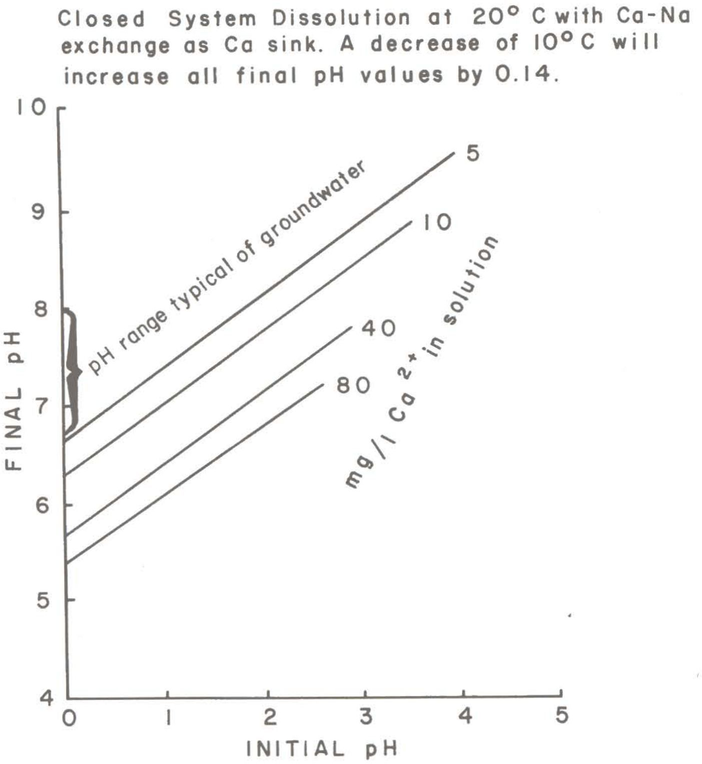

Figure 4-5. Relations between initial pH, final pH, and HCO_3^- for calcite dissolution to equilibrium with Ca^{2+} specified Ca^{2+} contents. Closed-system dissolution is assumed.

from pyrite oxidation is a necessary factor to account for the extremely high HCO_3^- concentrations in many of the samples. The analysis of closed-system conditions indicates that pyrite oxidation is a necessary factor to account for the HCO_3^- values of nearly all samples. Although there is no way of knowing based on existing data the extent of open- versus closed-system dissolution that occurs in the soils of western North Dakota, the above conceptual analysis is strong evidence in support of the hypothesis that the anomalously high HCO_3^- values in groundwater of the region occurs because of abundant H^+ supply from pyrite oxidation as well as the effect of cation exchange as a mechanism that maintains Ca^{2+} and Mg^{2+} at low concentrations. Additional evidence indicating the common occurrence of pyrite oxidation is obtained from the occurrence of SO_4^{2-} in the groundwater. This is discussed below.

Another soluble mineral that is commonly observed in shallow zones in overburden in western North Dakota is gypsum. Gypsum dissolves readily in water to produce Ca^{2+} and SO_4^{2-} ions,

$$CaSO_4 \cdot 2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \quad (4.13)$$

If gypsum is dissolved in de-ionized water at 8°C the equilibrium concentrations of Ca^{2+} and SO_4^{2-} will be 520 and 1240 mg/l, respectively (Cherry, 1968). It is evident, therefore, that if water travelling through subsurface systems encounters gypsum it can acquire relatively high concentrations of Ca^{2+} and HCO_3^-. If Ca^{2+} is removed by processes such as ion exchange, the equilibrium concentrations of SO_4^{2-} will be much higher. This is represented by the graphs in figure 4-6 which were computed using the equilibrium relation,

$$[Ca^{2+}][SO_4^{2-}] = K_{eq.gyp} \quad (4.14)$$

where $K_{eq.gyp} = 2.17 \times 10^{-5}$ at 8°C (Cherry, 1968). If calcite or dolomite dissolves in water prior to gypsum dissolution the solubility of gypsum will be reduced as a result of the common-ion effect. If the Ca^{2+} concentration is limited by cation exchange, the solubility will be increased. This condition is represented by the solubility line on figure 4-5 that has Ca^{2+} values specified at levels below the free

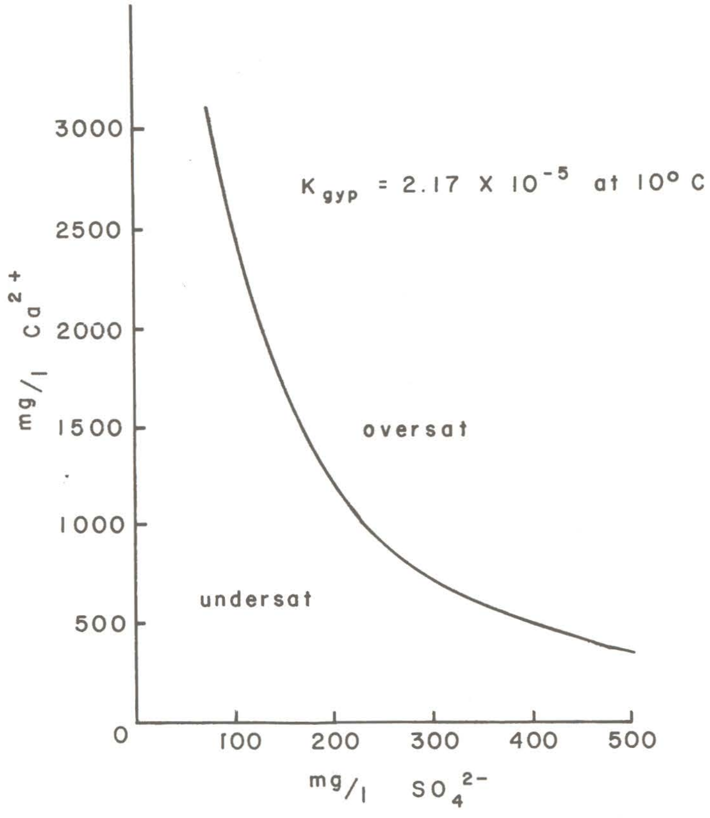

Figure 4-6. Relations between Ca^{2+} and SO_4^{2-} under conditions of gypsum saturation at 10°C.

solubility line represented by gypsum dissolution in water in which there are no other controls on Ca^{2+} and SO_4^{2-} concentrations.

In the preceding discussion the interaction between gypsum and water has been considered only in terms of gypsum dissolution. When the origin of gypsum in shallow overburden in western North Dakota is considered, gypsum precipitation is also an important process. When the reaction represented by equation 4.13 proceeds in the reverse direction to that indicated, precipitation occurs. If the product $[Ca^{2+}][SO_4^{2-}]$ exceeds the value of $K_{eq.gyp}$ at the temperature of the system, gypsum will precipitate. Laboratory studies indicate that this precipitation reaction proceeds quickly relative to the rate at which water moves in most subsurface systems.

Water in which the initial concentrations of Ca^{2+} and SO_4^{2-} are below those required for equilibrium will produce precipitated gypsum if the water is concentrated by evaporation or transpiration. If Ca^{2+} enters solution as a result of calcite or dolomite dissolution and if SO_4^{2-} enters solution as a result of pyrite oxidation and if the water is concentrated to a level at which gypsum supersaturation occurs, gypsum will precipitate from solution. There is considerable evidence to indicate that this mechanism of gypsum production occurs in shallow zones in overburden in much of western North Dakota. This evidence will be reviewed in detail later in this discussion.

Clay minerals typically occur in colloidal size and have significant amounts of adsorbed cations on their surfaces. At any given time the concentration of adsorbed cations is in equilibrium with the concentrations of cations in water in contact with the adsorption surfaces. If new water with different cation concentrations comes into contact with the clay mineral surfaces, cations in the water will exchange with cations on the adsorption sites until equilibrium is reestablished. Cation exchange reactions proceed very quickly. As water flows through porous clayey geologic materials, the exchange reactions undergo continual readjustment in order to maintain exchange equilibrium. When new water enters a pore space and the water that previously occupied the space moves further along its flow path, the equilibria will adjust accordingly.

The cation exchange reactions that are most important in the chemical evolution of subsurface water in western North Dakota can be represented as follows:

$$Ca^{2+}+2NaX=2Na^{+}+CaX_2 \qquad (4.15)$$

$$Ca^{2+}+MgX=Mg^{2+}+CaX \qquad (4.16)$$

$$Mg^{2+}+2NaX=2Na^{+}+MgX_2 \qquad (4.17)$$

where the quantities NaX, CaX, and MgX represent cations in the adsorbed state and Na^+, Ca^{2+}, and Mg^{2+} denotes these elements in an ionic state in solution. Equilibrium relations based on these reactions can be expressed as follows:

$$K'_{Na\text{-}Ca}=\frac{[Na^{+}]^{2}\,N_{CaX}}{[Ca^{2+}]\,N_{NaX}} \qquad (4.18)$$

$$K'_{Mg\text{-}Ca}=\frac{[Mg^{2+}]\,N_{CaX}}{[Ca^{2+}]\,N_{MgX}} \qquad (4.19)$$

$$K'_{Na\text{-}Mg}=\frac{[Na^{+}]^{2}\,N_{MgX}}{[Mg^{2+}]\,N_{NaX}} \qquad (4.20)$$

where K' represents an empirical equilibrium coefficient referred to as a selectivity coefficient and N represents the mole fraction of the adsorbed cation. Numerous laboratory experiments reported in the literature indicate that the selectivity coefficients for these reactions involving clay minerals are such that Ca^{2+} is selected to the exchange sites in strong preference to both Na^+ and Mg^{2+}. Mg^{2+} is adsorbed in preference to Na^+. Another way of expressing this is to state that the reactions represented by equations 4.15, 4.16, and 4.17 proceed to the right in order to achieve equilibrium in situations where the concentrations of cations in solution are initially equal and the concentrations of adsorbed cations are initially equal. At concentrations in the range that occur in fresh or brackish groundwaters the total quantity of cations adsorbed on the exchange sites of clay minerals in clayey materials with appreciable cation exchange capacity is very large in comparison to the total quantity in solution in a unit volume of water saturated material. In other words, on the microscopic scale adsorption sites on the clay minerals represent a large storage zone for adsorbed cations relative to cations in the pore solution. If the exchange sites on the clay minerals are initially occupied with a large percentage of Na^+, for example, it will be necessary for numerous pore volumes of Ca-rich water to pass through the materials in order for the percent of adsorbed Na^+ relative to Ca^{2+} to decline significantly. Each pore volume of Ca^{2+}-rich water that passes through the material will result in a transfer of Ca^{2+} to the exchange sites in the clays and a release of Na^+ to the pore water. Exchange equilibrium between the pore fluid and the exchange sites on the clays will be maintained because the reactions are fast relative to normal rates of subsurface water flow. The actual position of the equilibrium (i.e., the cation ratios) will change as the ratio of adsorbed ions changes in response to repeated passage of new fluid through the pores.

The dominant clay minerals in the overburden in western North Dakota are montmorillonitic (smectite) type. This has been established by the studies of Jacob (1973), Royse (1967), and Sandoval and others (1973). Montmorillonitic clays have relatively large cation exchange capacities. Values in the range of 20 to 80 milliequivalents per 100 grams of dry weight soil are representative. This means that one gram of montmorillonitic clay would contain on the order of 1.5×10^{20} adsorbed cations. If the clay has a porosity of 30 percent and is saturated with water and if the water has a cation concentration of 100 mg/l (expressed as Ca^{2+}) the pore water in a one-gram mass of the clay would contain 7.5×10^{-3} moles, which is a quantity two orders of magnitude smaller than that adsorbed on the clay. This illustrates the fact that in materials with an appreciable cation-exchange capacity, the cations contained on the exchange sites represent an extremely large cation source relative to the cation concentration in the pore waters.

The montmorillonitic clays in the overburden of most areas in western North Dakota are identified as

Na-montmorillonites. This means that the exchange sites are loaded with Na^+ relative to Ca^{2+}, Mg^{2+}, K^+ and other cations. From a viewpoint of soil and groundwater geochemistry and soil behavior, this is an important factor. It means that if water with appreciable concentrations of Ca^{2+} and/or Mg^{2+} comes into contact with materials that contain Na-montmorillonite, the water will acquire Na^+ as the dominant cation. As the Ca^{2+} and Mg^{2+}-rich input continues to enter the system, the exchange reactions will continue to transform the water to a Na^+-rich composition until eventually the available Na^+ on the exchange sites is depleted. When this occurs cation exchange is no longer effective in modifying the cation composition of the water even though the cation-exchange capacity of the material has not been altered.

We will now describe how the geochemical processes outlined above can combine to control the chemical evolution of subsurface waters in western North Dakota. The most common subsurface water composition, which has dominant concentrations of Na^+, HCO_3^+, and SO_4^{2-} will be considered first. When rain or snowmelt infiltrates below ground surface it becomes charged with CO_2 in the organic-rich horizons of the upper part of the soil profile. As it moves deeper in the soil and comes into contact with mineral matter, mineral dissolution occurs. If carbonate minerals are present, they will dissolve, with calcite dissolution much more rapid than dolomite dissolution. If dissolution to equilibrium occurs under CO_2 pressures in the range common in soils, the HCO_3^- concentration will rise to several hundred milligrams per liter and the Ca^{2+} concentration will rise as high as 200 to 300 milligrams per liter. The pH will rise to the range of about 7.5 to 8.5. If dolomite is present but dissolves more slowly than calcite, the Mg^{2+} concentration will rise to several tens of milligrams per liter. If there are no other major modifying influences, the soil water will therefore be characterized by dominant concentrations of Ca^{2+} and HCO_3^-.

If the soil and/or its parent material contain appreciable Na-montmorillonite the Ca^{2+} concentration in the soil water will be maintained at low values as a result of Ca^{2+}-Na^+ exchange. As calcite dissolution occurs, much of the Ca^{2+} will be exchanged for Na^+. This will permit calcite to continue to dissolve as Ca^{2+} continues to be adsorbed on the exchange sites on the clay particles. As dissolution continues the HCO_3^-, Na^+, and pH will rise progressively. If Mg^{2+} is contributed to the water from dolomite dissolution it also may be maintained at low concentrations as a result of cation exchange. It is therefore not possible to deduce from water chemistry data the extent to which dolomite dissolution influences the systems. The concentrations attained at equilibrium will depend on the initial pH of the water and on the concentration at which Ca^{2+} is maintained by the exchange reaction. The water will be characterized by dominant concentrations of Na^+ and HCO_3^- with minor amounts of Ca^{2+} and Mg^{2+}. Except for the lack of SO_4^{2-} this water has some similarity to groundwaters commonly observed in Tertiary overburden in western North Dakota.

The influence of pyrite dissolution will now be added to those of calcite-dolomite dissolution and cation exchange. It will be assumed that the infiltrating water oxidizes pyrite. In the process, dissolved oxygen is consumed. As indicated in figure 4-2 under conditions of water saturation, SO_4^{2-} concentration will rise to about 8 mg/l and abundant H^+ will be released. This SO_4^{2-} content is insignificant in comparison to the many hundreds of milligrams per liter that occur in much of the groundwater of the region. The H^+ that is released, however, permits the calcite (or dolomite) dissolution reaction to proceed much further than would otherwise be the case. Concentrations of HCO_3^- could therefore rise towards the upper limit of the range observed in the groundwater. If water that is subjected to this combination of geochemical processes infiltrates to the water table, the resulting groundwater will be characterized by very high concentrations of Na^+ and HCO_3^-. Higher Na^+ values will correlate with high HCO_3^-

values.

There is a possibility that oxidation of pyrite would occur when the soil is not saturated with water. In some situations oxygen could be replenished as consumption by pyrite oxidation takes place. This would require active movement of soil air in and below the soil profile as infiltration occurs. In order for the SO_4^{2-} concentration to rise to the very high levels that are observed (i.e., many hundreds of milligrams per liter), O_2 replenishment would have to be very active. The H^+ concentration released would permit calcite dissolution to produce HCO_3^- values well above the values observed in the groundwater. Although it is likely that O_2 replenishment causes a significant increase in SO_4^{2-} values we doubt that this mechanism directly generates all of the SO_4^2 in high SO_4^{2-} concentration waters.

The remaining key ingredient to be added in the development of our conceptual geochemical evolution sequence is gypsum. Dissolution of gypsum will produce abundant SO_4^{2-} and increased concentrations of Na^+ if the Ca^{2+} released from the gypsum is exchanged for Na^+ as a result of reactions with clay minerals. With gypsum added to the evolution sequence, the dominant ions in the water are Na^+, HCO_3^-, and SO_4^{2-}, with minor concentrations of Ca^{2+} and Mg^{2+}. Small amounts of Cl^- may be derived from atmospheric fallout (rain or dust) or from minor impurities in the geological materials.

Three of the four main minerals involved in this geochemical model, calcite, pyrite, and Na-montmorillonite are all commonly observed in overburden materials of the region. Gypsum is observed much less commonly and its mode of origin is not readily apparent. Because the SO_4^{2-} concentrations in Tertiary deposits in the study areas show no discernible general increase with depth and because the groundwaters are almost invariably undersaturated with respect to gypsum, it can be concluded that gypsum is contributed to the hydrogeochemical system at shallow depths or at ground surface and that it is *not* a significant constituent of the unweathered Tertiary deposits. The evidence and reasoning upon which this conclusion is based are discussed further by Moran et al (1976).

To account for the occurrence of sufficient amounts of gypsum near ground surface and thereby produce the observed SO_4^{2-} concentrations in the water, Moran, et al (1976) have proposed that the gypsum results from precipitation from surface or near-surface water that becomes concentrated because of evaporation or transpiration. It is well known that very little of the rainfall or snowmelt that occurs in western North Dakota penetrates far enough below ground surface to produce groundwater recharge. Nearly all of the rainfall and snowmelt infiltrates a short distance into the soil and then returns to the atmosphere as a result of evapotranspiration or the water moves as overland flow into topographic depressions and then evaporates. During exceptional infiltration events, sufficient water may penetrate the ground to cause recharge at the water table. These hydrologic concepts are illustrated schematically in figure 4-7.

If water acquires SO_4^{2-} by pyrite oxidation and acquires Ca^{2+} by calcite dissolution prior to evaporation or evapotranspiration, a small amount of gypsum will precipitate if the concentrations of the ions are increased greatly as a result of these processes. Repeated rainfall and snowmelt events will cause an accumulation of gypsum. When exceptional rainfall or snowmelt occurs, this gypsum will dissolve and the Ca^{2+} and SO_4^{2-} will be carried to the water table as recharge occurs. Some of the Ca^{2+} may be exchanged for Na^+ as infiltration occurs. The shallow groundwater thus acquires its high SO_4^{2-} concentrations. Because gypsum is generally not present in the geologic materials below the water table, this initial SO_4^{2-} concentration is the content that persists without increase in the water as the water moves along its flow paths, regardless of whether they are short or long.

For illustrative purposes in this discussion we have considered in sequence the effects of (1) hydrogen-ion generation by CO_2 production in the upper part of the soil and by pyrite oxidation in the soil or

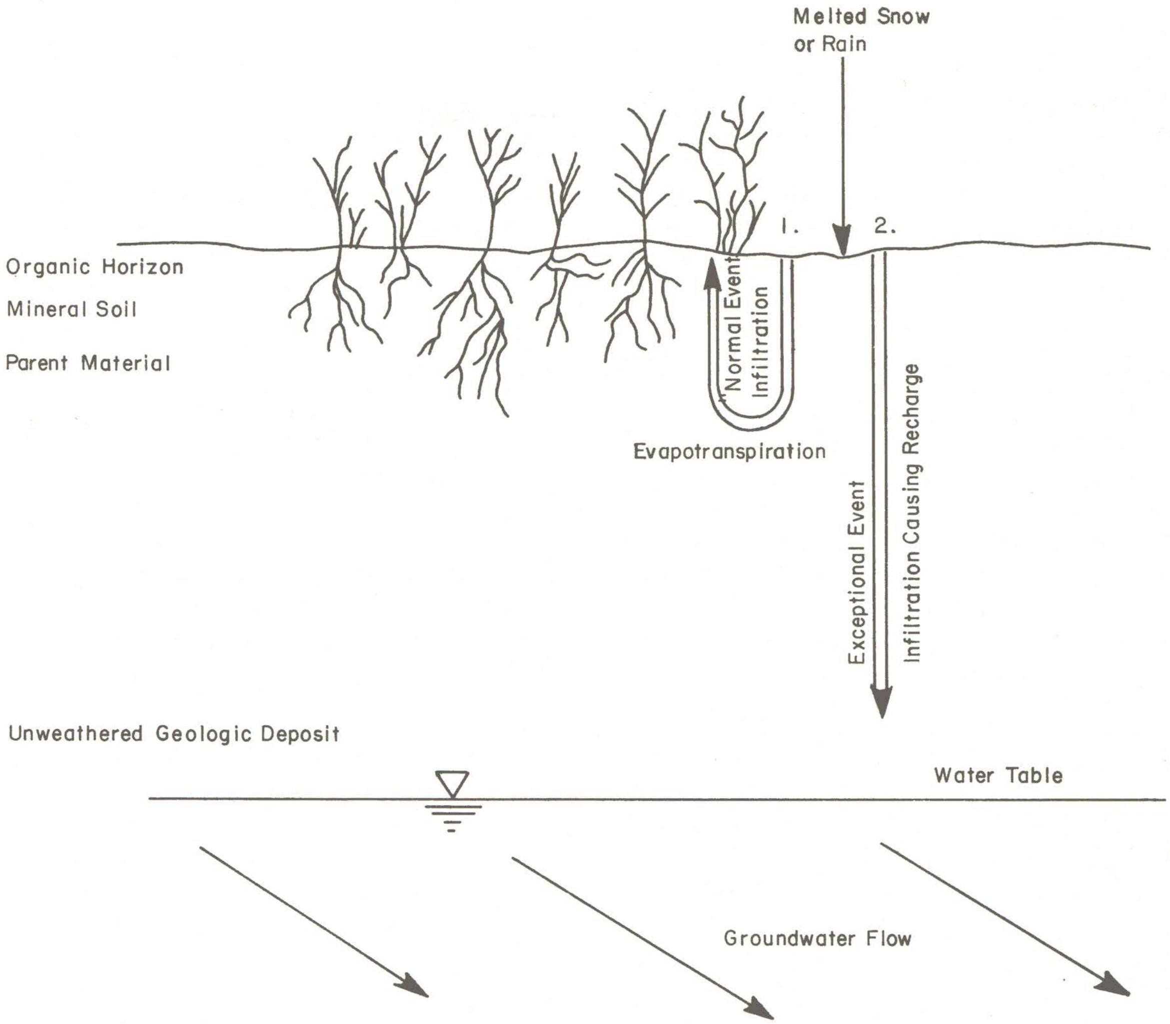

Figure 4-7. Schematic diagram of subsurface water movement in much of the plains region. 1. Annual potential evapotranspiration greatly exceeds annual precipitation, therefore infiltration caused by most rainfall and snowmelt is lost by evapotranspiration. 2. Very exceptional events cause recharge.

subsoil; (2) calcite and dolomite dissolution; (3) exchange of Ca^{2+} for Na^{+} on clay particles; and (4) gypsum dissolution. In the field these processes occur simultaneously in some situations and in sequence in other situations. The sequence can be different than the one indicated above. For example, gypsum may dissolve at or very near ground surface prior to any influence by cation exchange or calcite dissolution. If this occurs, the infiltrating water will have abundant Ca^{2+} and SO_4^{2-} as it moves deeper into the soil profile. If the water then comes into contact with Na-montmorillonite, the composition will be altered to a Na^{2+}-SO_4^{2-} solution. If the water has passed through organic-rich soil horizons it will be charged with CO_2 and therefore will be aggressive with respect to calcite and dolomite. This aggressiveness will be maintained until such time as the water encounters carbonate minerals. When this occurs, the water will acquire HCO_3^- and a higher pH. If Na-montmorillonite is not present, the Ca^{2+} content of the water will rise as calcite is dissolved. The water will then have major concentrations of Na^{+}, Ca^{2+}, SO_4^{2-}, and HCO_3^-. The Na^{+}/Ca^{2+} and HCO_3^-/SO_4^{2-} ratios will depend on the amount of gypsum that dissolved earlier, on the extent of Ca^{2+}-Na^{+} exchange that occurred earlier, and on the initial pH or CO_2 partial pressure of the water during calcite dissolution. If some pyrite is oxidized prior to or during calcite dissolution, the supply of H^+ released by this reaction will increase the amount of calcite that can be dissolved. If the H^+ supply is extremely large, it will make little difference whether dissolution occurs above the water table (open-system conditions) or below the water table (closed-system conditions). If H^+ is derived only from CO_2 production and if the CO_2 partial pressure is not high, closed-system dissolution will severely limit the amount of calcite that can dissolve.

The most common groundwater composition in Tertiary deposits in western North Dakota (water with dominant concentrations of Na^+, HCO_3^-, and SO_4^{2-}) can be generated by various sequences of the four geochemical processes indicated above. It should be noted that the infiltration need not pass through an organic-rich soil horizon in order for the evolution sequence to proceed as indicated. Water that passes directly into the geologic parent material in areas where the soil has been eroded or removed by man will acquire the same water chemistry, provided that sufficient H^+ is generated by pyrite dissolution. Consumption of only several milligrams per liter of dissolved O_2 in the water produces abundant H^+. The water may infiltrate rapidly past the solum by way of root holes, cracks, or animal burrows and not acquire soil-produced CO_2 and yet still acquire H^+ as pyrite dissolution occurs below the solum, either above or below the water table.

The Na^+ in the water is derived by ion exchange from Na-montmorillonite. In order for the Na^+ concentration in the water to increase, Ca^{2+} must become available for exchange. If rainwater moves through materials rich in Na-montmorillonite but devoid of carbonate minerals or gypsum, the water will only acquire a very small Na^+ concentration. If the water moves through materials that contain both Na-montmorillonite and calcite or dolomite without acquiring increased H^+ ion concentration as a result of CO_2 production or pyrite oxidation, the Na^+ concentration will rise to only a few tens of milligrams per liter because of the limited solubility of the carbonate minerals. Greater calcite solubility will result in high Na^+ concentration in the water. If gypsum is present the Na^+ concentration in the water will undergo a much greater increase. Na-montmorillonite can be regarded as a large reservoir of Na^+ that requires calcite (or dolomite) and/or gypsum dissolution for it to be released from the adsorption sites to the pore water. Thus, in cast-overburden the release, transport, and accumulation of Na^+ will depend on the occurrence of calcite and gypsum in the overburden. The occurrence of gypsum will depend primarily on the occurrence of pyrite and the rate and frequency at which water containing dissolved oxygen contacts it and then evaporates or is transpired.

Under the present conditions in western North Dakota, it appears that gypsum is generated by pyrite oxidation and calcite dissolution (SO_4^{2-} from pyrite and Ca^{2+} from calcite) in the shallow subsurface zones of recharge areas and in surface depressions where particulate calcite and pyrite are carried as a result of surface run-off and erosion. The surface environment is the most highly oxidizing when water is present. After rainfall or snowmelt run-off, surface waters commonly evaporate, leaving precipitate residues in the depressions that contain water only ephemerally. It is these depressions that are sites where groundwater recharge can occur more frequently than in knoll or side slope areas because ponded water can act as a feed to infiltration. We view many of the upland depressions in southwestern North Dakota as zones where surface run-off frequently causes perched water table conditions. Recharge to the main water table zone occurs as water from the ephemeral ponds moves downward. Some upland depressions contain ponded water much of the time. At these sites the saturated zone may in some cases extend continuously downward from ground surface. These remarks on recharge mechanisms are somewhat speculative because of the lack of field documentation from microhydrogeological studies of specific sites. A more detailed discussion of the field evidence supporting these

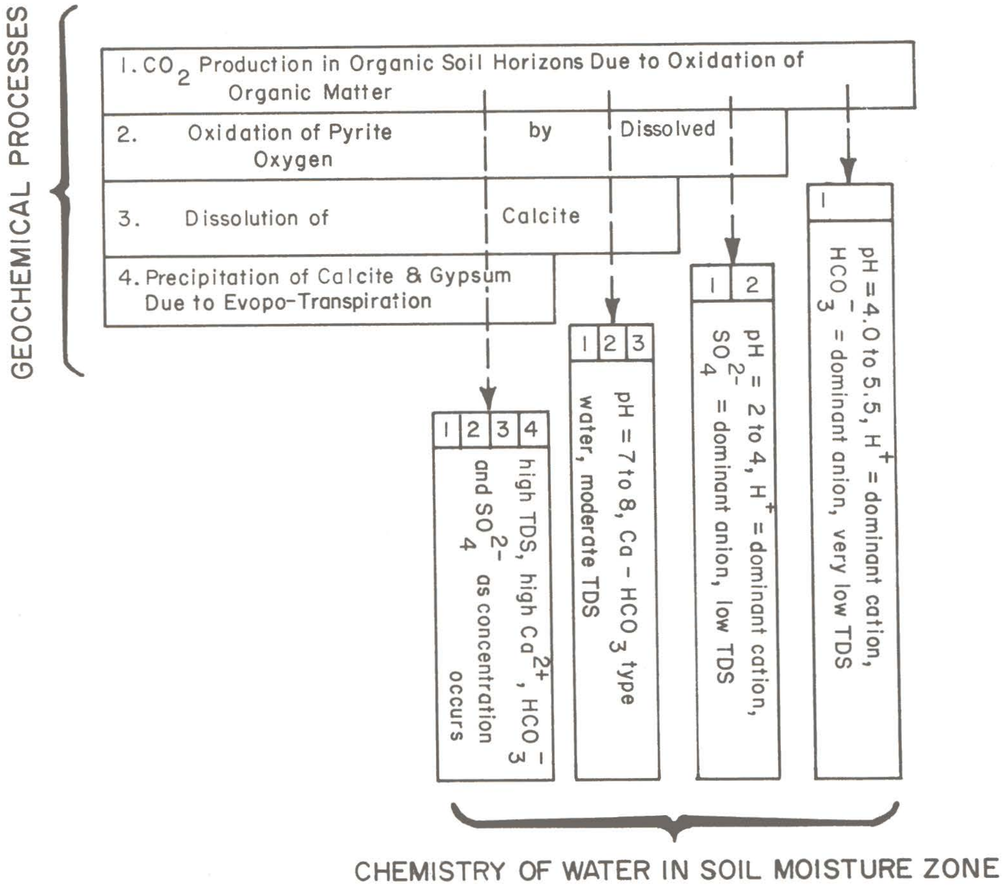

Figure 4-8. Diagram illustrating relations between major geochemical processes and water chemistry resulting from infiltration that does not pass below the root zone.

conclusions is provided by Moran and others (1976). The important point to note here is that the interpretation of the geochemical evolution of subsurface waters in the Tertiary deposits of western North Dakota cannot be separated from conceptual models of the occurrence of infiltration, groundwater recharge, and regional flow-system behavior. Predictions regarding the hydrogeochemical behavior of water in cast-overburden and the origin and accumulation of salts will require adaptation of the interpretive geochemical framework developed for the natural system to the new types of flow regimes that will occur in the cast-overburden.

Figures 4-8 and 4-9 summarize the geochemical processes and their role in the genesis of subsurface water chemistry. Figure 4-8 represents conditions associated with infiltration events that do not cause flow below the root zone. In figure 4-9, hydrogeochemical conditions that develop during groundwater recharge events are represented. These diagrams indicate the hydrogeochemical characteristics that result from various combinations of geochemical processes. If the water received little or no CO_2 from organic matter oxidation in the uppermost part of the solum, the water chemistry will nevertheless evolve as illustrated in these diagrams, providing that pyrite oxidation is an active process. If any of the other geochemical processes illustrated in the hydrogeochemical evolution sequences (figs. 4-8 and 4-9) are not active, the chemistry of the soil water will deviate markedly from that represented in the diagrams. Locally in western North Dakota, deviations can be expected to occur, but in general the available subsurface data

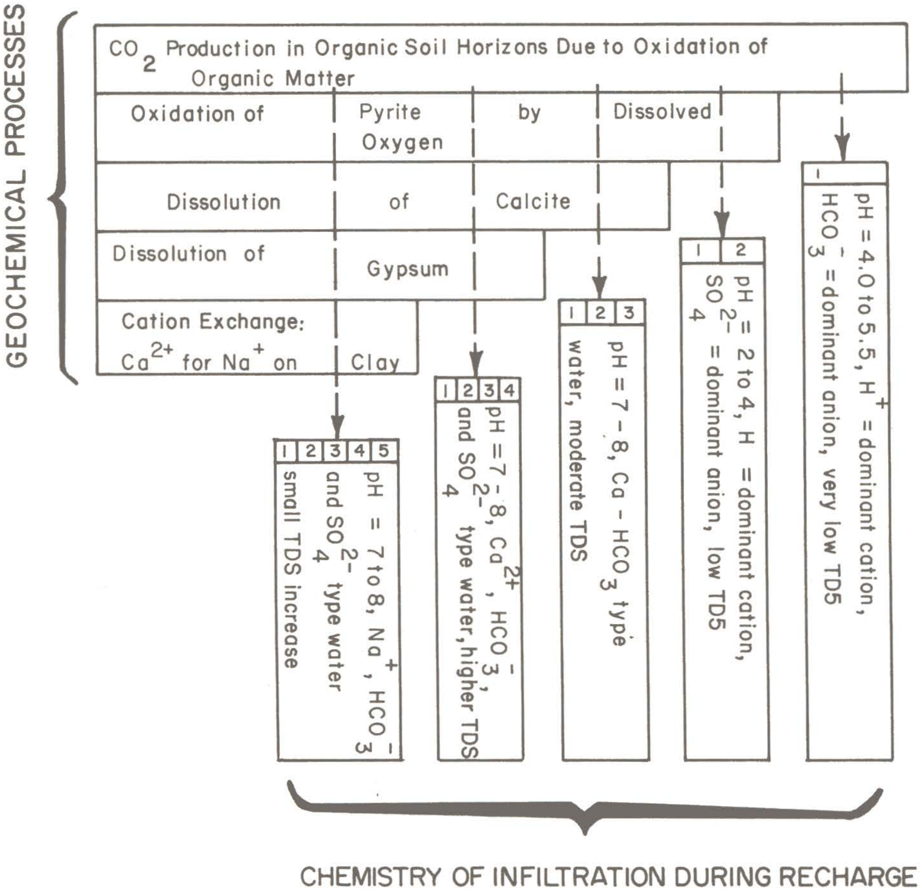

Figure 4-9. Diagram illustrating relations between major geochemical processes and water chemistry resulting from infiltration that penetrates below the root zone.

indicate the interpretive framework summarized in figures 4-8 and 4-9 is reasonable.

As a concluding statement for this section, we wish to draw attention to the fact that all of the important geochemical processes that determine the chemistry of groundwater in the study areas are primarily operative above the water table. That is, water below the water table in local, intermediate or regional-scale flow systems acquires its characteristic features (i.e., salinity, alkalinity, and pH) in shallow zones above the water table. The chemistry of the water table, regardless of the age and distance that the water has traveled, is determined by the geochemical processes that occurred during recharge. This conclusion has important implications with respect to mine-land reclamation, as is indicated in later discussion.

5. GEOLOGIC AND HYDROLOGIC CONTROLS ON SUBSURFACE WATER CHEMISTRY

The chemical composition of groundwater and of saturation extracts in the study area is, as discussed in the preceding section, a function of three gross factors: (1) the presence of calcite (and dolomite), sodium clays, and pyrite in the sediment; (2) the extensive oxidation of pyrite at or near the land surface; and (3) the degree of sluggishness or flushing of the system. We now proceed to translate these general regional factors into specific variables that can be used to develop a model for evaluating the characteristics of overburden between sampling points and predicting the long-term reclamation potential of the material.

5.1 Nature of Materials

The first of the three factors affecting the chemical characteristics of groundwater and saturation extract samples is the presence of calcite, sodium clays, gypsum, and pyrite in the sediment. This includes not only the material, which is in contact with the water at the time and place it is sampled, but also the material through which the water has moved to reach the position from which it is sampled.

The material in which the water is located is especially important in interpreting and generalizing saturation extract chemical data. The lithology can be determined by descriptions of cutting and core samples and interpretation of geochemical logs. The important lithologic factors include texture, mineralogy, and the presence of nodules and precipitates of calcite, gypsum, and pyrite. The texture of the sediment gives a first approximation of mineralogical composition. Silty and clayey sediment generally contains abundant clay minerals, which in the study area, generally contain exchangeable sodium. This is even more strongly so where the sediment is unoxidized. Sandy sediment tends to contain less clay, and, therefore, less sodium, but this is not strictly true because many of the sand bodies in the Sentinel Butte Formation contain considerable clay, both interstitially and in interbedded silt and clay beds. The presence of organic material in the sediment is, in many cases, indicative of the presence of pyrite. The presence of calcite can be determined by its reaction with dilute acid. However, from a geochemical standpoint the level of detection of this test, about 0.5 percent to 0.05 percent by weight, is very high. Therefore, absence of a visible or audible indication of carbonate cannot be taken as evidence of the absence of the mineral. By the same token, the presence of visible pyrite or gypsum can be taken as a sure indication of the presence of these minerals in the disseminated, microscopic quantities that are geochemically active; but absence of visible crystals cannot be construed as evidence for the absence of the minerals.

The second aspect of material, the material through which the water has passed to reach the point of sampling is more complex than the first. It is probably more important for coarse-grained materials and less important for samples from fine-grained materials. This aspect of available materials can be best estimated by initially determining the stratigraphy of the area around the sampling site in considerable detail. Then the groundwater-flow system is determined by making observations of depths to the water table and the potentiometric level in the appropriate aquifers as well as a variety of chemical analyses. Because of the complexity of natural groundwater-flow systems it is probably never possible to develop a specific knowledge of the path followed by a particular volume of groundwater. It is possible, however, to develop in general terms, an idea of whether water in a particular place in the flow system has passed primarily through clay or primarily through sand. This knowledge of the general pattern of groundwater movement in an area combined with the specific knowledge of the characteristics of the sediment in that area, as described above, can provide, at least, a qualitative estimate of the effects of the material through which the water has passed.

5.2 Availability of Materials—Weathering

The second major factor to be considered is the availability of the material that is present to the groundwater or pore water. The only major constituent that appears to be affected by this concern is sulfate, but minor sources of many soluble ions may also be involved. As was indicated above, sulfur occurs in the study area in two major forms, as the largely insoluble sulfide of iron, pyrite, or marcasite, and as the much more soluble sulfate of calcium, gypsum. Gypsum does not appear to be present as a primary mineralogical component of the sediment but rather as an alteration product of pyrite. Thus, the state of oxidation of the sediment is an important factor in determining the sulfate content of the saturation extract. Although probably not a significant source of dissolved material, weathered silicate minerals may contribute minor amounts of metals such as Fe, Mg, and Ca.

The availability of material for solution can be evaluated in terms of the depth of the sample below the land surface, the setting of the boring, the state of oxidation of the sample, and the presence of secondary precipitates of gypsum. The surest observations are the latter two. Secondary precipitates of gypsum indicate that sulfate will be an abundant constituent of the saturation extract. A sample, which is brown colored indicative of oxidation, suggests a greater probability of the presence of sulfate than an unoxidized sample. Whether sulfate is present or not depends, of course, on whether pyrite was present in the sample initially and whether salts have been flushed into or out of the sample. The depth of oxidation at a given site is a complex resultant of a number of variables including texture of material, presence of oxidizable iron-bearing minerals, and the micro-topographic setting of the site. In the absence of specific observation of the depth of oxidation throughout an area, it can be estimated on the basis of the lithology and topographic setting if a few observations have been made to develop a calibration for that particular area.

We have here touched on one of the principal questions relating to the saturation extract test as an estimator of the behavior of sediment as subsoil material, the oxidation of pyrite to produce sulfate. This question is discussed at some length below.

5.3 Water Movement

The third major factor to be evaluated is the direction and rate of water movement through the sediment. This factor is especially important in the near-surface regime where sulfate can be generated by oxidation of pyrite and where water that is undersaturated with respect to calcite is entering the system. If this water moves readily through the material and down into the groundwater-flow system, the salinity and SAR can be kept at low levels by the repeated leaching and flushing of the material. In the second case, water moves either laterally or from below into the domain of interest, bringing with it dissolved constituents, and is lost by evapotranspiration. The dissolved constituents are precipitated and accumulate in the domain of interest. This can result in the build-up of very high salinity and, in some cases, SAR, in saturation extract analyses. The third situation, which in much of the study area appears to be the case, is non-movement of water. In this case, the materials in the pore walls are weathered but simply remain where they are. In actual fact, there may be some movement of water into these domains from above, but it is very small; and the water either stays there or is lost by evapotranspiration.

The evaluation of water movement is complex and requires a thorough understanding of the groundwater-flow system. A knowledge of the groundwater-surface water interactions of the system, the recharge-discharge relations in the system, is especially important in this regard. This requires a thorough knowledge of the stratigraphy because of its control on the distribution of permeability. A knowledge of the water table configuration and of the potentiometric-head distribution throughout the flow system is necessary. Chemical data that are useful in interpreting the groundwater-flow systems include major-ion analyses and the stable and radioactive isotopes ^{18}O, $D(^{2}H)$, $T(^{3}H)$, ^{13}C, and ^{14}C. The identification of groundwater recharge and discharge areas is essential. Hydrologic data in the form of potentiometric-head readings at multiple-well piezometer nests and springs can be used to provide part of the picture. In addition, observation of surface features such as salt crusts, seepage scarps, persistent or very ephemeral surface water bodies, and certain types of vegetation such as salt tolerant species or phreatophytes can provide valuable tools in the interpretation of the details of near-surface water movement. The relation of these surface features to the underlying stratigraphy is very important in interpreting the significance of these features. Detailed soil mapping, at the series level, is an invaluable aid in determining surface water–groundwater interactions.

6. LANDSCAPE MODEL FOR OVERBURDEN CHARACTERIZATION

In this section, we rationalize the observed variations in geochemical characteristics of the overburden, which were described in section 2, in terms of the geochemical, geological, and hydrological information presented in the preceding two chapters. A brief explanation of the hydrologic setting of each class of geochemical profile was included in the discussion of the class in section 2.

Class I sites are characterized by elevated salinity and low to intermediate pH in the upper 20 to 40 feet. The SAR is characterized by a more or less steady increase from low values (about 1 to 15) at 2 to 3 feet to high values (about 10 to 25) at 20 to 30 feet. At some class I sites, the SAR remains at about 10 below 30 feet whereas, at other sites, the values continue to increase to more than 40. Lithologically, class I sites are dominantly silt and clay, although sand is a significant constituent in the upper part of one site at Dunn Center.

The highly saline, low pH upper part of the profile in class I sites results from oxidation of pyrite and solution of gypsum. The dominant anion in these highly saline materials is SO_4^{2-}; oxidation of pyrite is the only process that seems capable of producing the low pH values. The low landscape position and depressional nature of the sites preclude erosion of weathered sediment and promote accumulation of both chemical and physical weathering products from elsewhere in the landscape. The downward hydraulic gradient that characterizes all these sites causes salts that are concentrated in the surface to be carried downward into the substrate. The presence of permeable lignite and sand beds in the upper 20 to 30 feet that correspond to abrupt increases in SAR and pH and decreases in ECE, combined with the clayey nature of the sediment, indicate that the downward penetration of infiltrating water is limited to the upper part of the profile. The persistence of high values of SAR near the surface further indicates that the rate of infiltration is so slow that Na^+ has been flushed from the clay minerals only in the very shallow part of the profile.

Class II sites are like class I sites except that the low pH values found in the latter do not occur in the upper part of the profile in class II sites. Like class I sites, silt and clay are the dominant lithology in class II sites. Class II sites occur higher in the landscape than those in class I. They are located at the lower part of the mid-slope surface (fig. 2.2.1-1) and the middle to upper part of the side slopes of the glacial meltwater channels.

Class II profiles appear to represent sloping sites on fine-grained materials. Surface water runs off without ponding and there is no surface accumulation of salt. The high salinity of the upper part of the profile results from in place weathering of the rock and sediment. The persistence of the highly saline interval and the presence of elevated SAR values within a few feet to a few tens of feet of the surface is indicative of the lack of appreciable infiltration and the slow velocity of subsurface water that results from the fine-grained material. The absence of a low pH interval in the weathered zone results either from the absence of surface ponding and accompanying accumulation of pyrite grains or more likely from the absence of pyrite in the sediment.

Class III profiles are characterized by low salinity and intermediate to high values of pH throughout. SAR values are well below 10 except in a few places from 60 to 100 feet beneath the surface. These profiles occur in the same landscape setting as those of class II. They differ from class II profiles by containing dominantly sand rather than clay. Where clay beds do occur beneath sand in the upper part of the weathered zone, a thin interval of salt build-up does occur. This variation, class IIIa, is typical of class III profiles except for the thin saline interval. A second variation, class IIIb, is typical of class III profiles except that the materials are glacial till. Class IIIb profiles are common at the Falkirk and Center sites.

Although the sediment that characterizes the upper part of class III and IIIa profiles is permeable and would permit rapid infiltration where ponding could occur, the generally sloping nature of these sites tends to promote run-off rather than infiltration. Due to the fine-grained nature of the materials run-off would also be common on class IIIb sites. The low salinity and moderate pH probably reflect the absence of weatherable material rather than flushing of the sites. The low SAR of the material probably reflects a general absence of Na^+ clays in the material. Clay and silt beds within these sites are characterized by generally lower salinity, pH, and SAR than class II sites, so it is also possible that flushing is an important process in these sites. Where flushing is occurring, sufficient water containing Ca^{2+} ions has passed through the material to replace the Na^+ ions adsorbed on the clays. Salts would be kept flushed from the upper part of the profiles where this process has occurred.

It is difficult to generalize about class IV sites since only one testhole is represented. It occurs in the same setting as class II and III sites and the reason for the differences is not understood. The class IV profile is characterized by elevated salinity and depressed pH to considerable depth. The site contains both sand and clay in the upper part of the profile. The close proximity of the site to an abnormally steep slope, combined with considerable thickness of sand in the profile, are believed to be responsible for the characteristics of the profile. The unsaturated zone extends to about 90 feet at this site so that considerable thickness of unsaturated sand is present beneath steep slopes from which surface water surely must run off. Thus, there can be no flushing of weathering products by infiltrating water and any salt liberated by weathering remains. The salt content may be augmented by periodic lateral flow beneath the site from the east through the sand beds bringing salts flushed from the higher terrain to the east and southeast. The depressed pH of samples at depths from 40 to 75 feet can come only from in place oxidation of pyrite so the properties of the class IV profile may be a result of local abundance of pyrite combined with permeable sediment that is only occasionally saturated but is usually above the water table.

Class V profiles are characterized by conductivity values less than 20 except between 5 and 15 to 50 feet where values between 20 and 40 occur. Low pH values sometimes occur above 15 feet; below 20 feet, the pH is in excess of 80. SAR is greater than 10 below about 25 feet. The class V profile occurs at the lower edge of the upland surface in a position similar to that of classes II, III, and IV but higher in the landscape (fig. 2.2.1-1).

The presence of elevated SAR values close to the surface and the fine-grained material of the site indicate that infiltration is slow and has not penetrated far below the surface. The relatively steep slopes and absence of ponding in these sites suggests that surface water generally runs off. The relatively low salinity of the upper part of the profile may result from the balance between weathering and erosion, with the rate of physical removal of material keeping pace with the rate of weathering. In this way, there would be no accumulation of weathering products in the upper part of the profile. Another possibility for the low salinity is that pyrite, which, on the basis of the low pH values, is present, is available only in sufficiently limited quantities that weathering does not produce elevated salinity.

Class VI profiles differ from class V by having low SAR values to considerable depth. In addition, the materials consist of glacial till or till overlying bedrock as opposed to bedrock silt and clay which is typical of class V profiles. In all other aspects class V and VI profiles are identical. Class VI profiles are common at the Falkirk and Center sites.

The low SAR values are apparently due to the lack of sodic clays in the glacial materials. At sites characterized by till overlying bedrock silt and clay, the SAR values generally increase below the till/bedrock interface.

Class VII profiles are represented by only two testholes, one at the Center site and one at the Falkirk site. Class VII profiles are characterized by high conductivity values to about 15 feet. Conductivity values generally decrease below 15 feet. pH values are generally moderate to high. SAR values are high near the surface and decrease below 10 to 15 feet. Class VII sites occur in low landscape settings. The materials are generally fine-grained. Both class VII profiles occurred at local groundwater discharge sites. The high near-surface conductivity and SAR values are apparently the result of accumulation of salts and not by evaporation of groundwater at the surface. The moderate to high pH values are apparently due to the lack of weatherable pyrite at the site.

On the basis of the preceding discussion, we believe that the variations in the geochemical characteristics of the overburden in the five study sites can be explained in terms of the model of geochemical evolution of subsurface water chemistry that was developed in previous sections. We conclude that an understanding of the run-off-infiltration relationships within the landscape combined with a knowledge of the distribution of near-surface permeability and certain mineralogical constituents, especially pyrite and clay minerals with Na^+ adsorbed on the exchange sites, provides an adequate basis to evaluate the ECE and SAR of the overburden. In order to project the long-range success of reclamation, however, it is necessary to have a more thorough understanding of the overburden composition. On the basis of the geochemical evolution model, it is necessary to know the amount of calcite, pyrite, and exchangeable sodium present in the material as well as its texture. In order to predict how the material will behave in a reconstructed landscape, it is necessary to know where in the landscape each type of material will be placed and what the configuration of that landscape will be. In this way, the subsurface hydrologic regime can be projected and the resulting liberation of available ionic constituents by weathering and transport or nontransport of these constituents can be estimated. In the next section, we discuss the techniques and procedures to develop an overburden inventory adequate to permit use of this model of overburden characterization. In the section following that, we explore, through a series of simple scenarios, various material placement alternatives and the resulting evolution of subsurface water chemistry.

7. APPLICATIONS OF THE LANDSCAPE MODEL TO RECLAMATION DESIGN

The landscape model developed above can be used in three different ways in planning reclamation of surface coal mines. (1) The model can be used to design a sampling program to assess the chemical properties of overburden material. (2) It can be used to evaluate the results of analyses collected from the sampling program. (3) It can be used to generalize the conclusions of the sampling and analysis program throughout the area to be mined.

7.1 Design of Sampling Program

The first step in assessing the problems that might be encountered and the potential benefits that might be gained in reclaiming an area that is proposed for surface mining is to obtain information on the chemical and physical characteristics of the overburden. The most desirable method for collecting this information is to collect all the necessary data with a minimum of repetitive sampling. A sampling scheme based on a deterministic model of the distribution of geochemical conditions assures that all of the different geochemical environments within the overburden are sampled efficiently with a minimum of unnecessary duplication. The model developed above is a first approximation of such a model. It must be refined through use to assure that it is complete and sensitive enough to cover all the geochemical environments in the overburden.

Application of the landscape model to planning an overburden sampling program requires the collection of geological, hydrological, and pedological information.

This pre-sampling data collection can be subdivided into four phases: (1) stratigraphic data phase; (2) surface mapping phase; (3) subsurface hydrologic phase; and (4) preliminary overburden characterization phase. Although these four phases are discussed sequentially, in application several would be taking place simultaneously.

7.1.1 Stratigraphic Data Phase

The development of a surface mine involves several drilling programs beginning with a regional exploration program in which hole spacing is on the order of 6 to 15 miles. In areas where the exploration program indicates the potential for minable lignite being present, more detailed spacing patterns are then drilled. This process of acquiring more and more detailed drilling data continues until spacings of 1000 feet, or in some cases less, are used in actual mine design. Until very recently, data on material other than the coal itself has not been collected on most projects until the final, most detailed phase of drilling.

By running a complete suite of geophysical logs and collecting data on the texture, mineralogy, and oxidation state of the clastic sediment lying above and between lignites at an earlier stage in the development of a prospective mine, the stratigraphy of the site can be developed. All that is required is that the site geologist log the cutting samples while each hole is being drilled. Each change in lithology should be noted, and samples should be collected and described at five-foot intervals as well as at each change in lithology. If the driller keeps an independent log of his observations during the drilling it often provides a valuable cross check of lithology, sample position, and position of thin conspicuous beds such as concretions and lignites. There is no need to save all samples early in the program, but it will prove beneficial if some sample sets are saved, especially in areas that appear to have promise for eventual mining. These samples can then be examined using a binocular microscope for pyrite and gypsum crystals as well as be used for preliminary analytical work when the area is further developed. When cores are cut to evaluate the characteristics of the coal, any sections of overburden and underclay that are recovered, either inadvertently or intentionally to assure recovery of the entire thickness of coal, should be described in detail and preserved for future analysis. In addition to the textural, mineralogical, and color observations made on cuttings, the presence of gypsum, pyrite, iron oxide, calcite, or other soluble species in disseminated crystals and fracture fillings, should be noted. The presence of fractures is of special interest. Particular notice should be made of evidence of water movement along fractures in the form of coatings of iron or manganese oxide or crystals of minerals such as gypsum or calcite.

The collection of stratigraphic data involves a minimal additional cost because it requires only the collection of additional data from testholes that are already drilled rather than additional drilling. Synthesis of data from sample descriptions and geophysical logs into cross sections and maps provides the stratigraphic framework of each site. Synthesis of stratigraphic data early in the exploration program, although not necessary, can add materially to the exploration effort by providing a picture of the environment of coal deposition. The synthesized stratigraphic data provide both the framework within which to understand groundwater movement throughout the site and the basis to relate materials to setting within the site that is required to utilize the landscape model of geochemical overburden characterization.

7.1.2 Surface Mapping Phase

Once it has been demonstrated that a site contains sufficient coal to be a viable mining prospect and development plans move ahead, the synthesis of stratigraphic data collected earlier in the exploration program should be completed. Additional stratigraphic test drilling can be designed at this stage to accompany coal evaluation drilling. Also early in this stage of project development, an extensive program of surface mapping should be undertaken. This surface mapping program involves a detailed soil survey, which should be coordinated with the mapping of the surface geology The surface mapping program is directed first at identifying other resources in the overburden such as gravel and ceramic clay, in addition to the agricultural soil, which, if identified early enough and present in sufficient quantities, can be economically utilized or preserved. Secondly, it is directed at relating the soil parent material to the materials framework developed by the stratigraphic test-drilling program. Thirdly, the surface mapping program is directed at identifying evidence of surface water-groundwater interactions and near-surface water movement.

In order to accomplish this third objective, the mapping program must be concerned with mapping surface morphology and hydrology in addition to mapping material. Salt accumulations and salt crusts, salt tolerant vegetation and phreatophytes, variation in vegetation types, conditions and abundance, the occurrence and persistence of ponded-surface water, the nature of slopes, and the presence of springs, are just a few of the types of information that should be recorded by the surface mapper.

The final surface map or maps should indicate materials, nature of surface water-groundwater interaction and the type of near-surface water movement. Probably the best way to construct such a map is to construct a series of basic data maps including maps of surface geology, soils, surface morphology, groundwater recharge, discharge, and throughflow, and surface-water ponding, accumulation, and run-off. These maps can then be combined to generate a single map on which individual units are characterized by a distinctive lithology and near-surface hydrologic regime.

7.1.3 Subsurface Hydrologic Data Phase

Collection of data to support this phase of the preparation for use of the landscape model was begun in the other two phases. The depth of oxidation can be used as a rough approximation of the depth to the water table. The stratigraphic framework that was developed from the synthesis of geophysical logs and sample analyses provides the distribution of permeability throughout the site. The numerous observations of features related to groundwater-surface water interactions and near-surface water movement that are identified and mapped in the surface mapping phase help delineate the areas of groundwater recharge and discharge.

A rough approximation of the patterns of groundwater flow within the site can be developed from the observations collected in other parts of the study. (Although this approximation may be adequate to apply to the model, caution is necessary.) Upland areas tend to be recharge areas, especially if they are underlain by sand. In some instances, however, this is not the case. If the upland is small, with steep slopes, and is underlain by unfractured fine-grained material, as at the Indian Head Mine, it may not function as a recharge area. In some settings, groundwater may be recharged beneath a valley on one side of the upland, pass beneath the upland, and be discharged in a lower valley on the other side.

It thus becomes necessary to have a more thorough understanding of the groundwater-flow system in order to successfully apply the model. Considerable information can be obtained from existing water wells within the site. These provide excellent opportunities to obtain useful data on the groundwater chemistry if the stratigraphic position of the intake zone can be determined. Since most wells are sealed, current data on water level in wells cannot generally be determined. However, water level data at the time the well was completed is often available. This type of information is useful to delineate the overall patterns of groundwater flow, especially in areas of high local relief where the elevation head component of the total head overshadows the pressure head component.

Additional data on groundwater-flow patterns can be easily and economically obtained by the installation of standpipe potentiometric observation wells in selected testholes that were drilled for stratigraphic data or coal evaluations. The procedures that were used during this study to install such wells are outlined in appendix A. In many areas, where th groundwater-flow system is reasonably straightforward, only a few properly located observation wells should be required to verify the flow-system interpretations based on the evidence of the other data already collected. In other more complex areas, more instrumentations will be required.

It should be borne in mind that information on the groundwater-flow system is needed in several phases of the development of surface mines. Such data are required for environmental assessment and impact prediction, for mine-dewatering planning, and for highwall design and slope stability studies. Because of the role of groundwater in determining slope stability, an understanding of the subsurface hydrological regime can, in some cases, play a major role in determining the type of equipment to be used for overburden removal and hence in determining the overall mine plan. Such a situation exists at two of the sites included in this study. Because of the need for data on groundwater hydrology in all facets of mine planning, the collection of such data should be a coordinated effort among all the various branches of the mining company including mining and coal extraction, reclamation, and environmental sections.

7.1.4 Preliminary Overburden Characterization Phase

During each of the other three phases testholes have been drilled for various purposes and samples of overburden material have been brought to the surface. These samples can be used for chemical analyses that will provide a semi-quantitative preliminary characterization of the geochemical properties of the overburden. The purpose of this section is to outline a series of simple, relatively quick chemical procedures that can be used in the field. By providing a few simple premixed reagents and a few simple pieces of equipment to the man on the rig, it is possible to perform these tests out of the back of a pick-up truck or similar vehicle right on the drill site. We have accordingly coined the term "tail-gate tests" for these procedures.

As has been discussed in preceding sections, the principal mineralogical controls on subsurface water chemistry include calcite content, pyrite content, gypsum content, and content of clay minerals containing exchangeable sodium. The small amounts of calcite and pyrite that are required to significantly affect the chemistry of subsurface water are well below the level of detection in standard tests. Proposals for development of quantitative analytical procedures to evaluate small amounts of these constituents are discussed in a later section of this report. However, because of the effect of solution of these minerals on pH and conductivity it is possible to develop a series of simple procedures to estimate their abundance.

The equipment needed to establish a "tail-gate lab" include the following: balance (capable of weighing to 0.01 gm); stirring apparatus—magnetic stirrer or flask shaker; centrifuge—hand crank type such as is used in oil production to separate oil and water from wellhead crude; electrical conductivity meter; pH meter or series of pH test papers; titrating burette setup.

The following procedural discussion is intended to be a conceptual outline. We have not attempted to establish and test actual technique or procedures but rather to suggest a direction for further inquiry.

The first step in analyzing the overburden is to collect cuttings from the drilling fluid. Where water based mud is the circulation fluid, the cutting sample should be thoroughly washed in clean water to remove drilling mud. The sample should be examined and extraneous material from higher in the hole should be removed. If the hole is circulated clean frequently and care is taken in the drilling, the problem of contaminated samples will generally be minor. After permitting the sample to drain, the actual analyses are begun.

7.1.4.1 Carbonate Test

Several cuttings should be broken open and tested with dilute (1.2 N)HCl. Any visible or audible reaction indicates the presence of a carbonate mineral, in most cases calcite. The level of detection of this test is about 0.5 percent by weight and, as was indicated above, is quite high in geochemical terms.

If the sample does not react with acid, a standard weighed sample of 10 gm is mixed to a slurry with 50 ml of distilled water. After the conductivity and pH of the slurry is determined, 50 ml of acid ($1.2x10^{-3}$ N HCl) is added to the slurry. After the mixture has been stirred for several minutes to permit the available carbonate to react with the acid, the pH and conductivity are again measured. The mixture is stirred again for several minutes and the pH and conductivity are measured. When the pH ceases to rise, indicating that all available buffering capacity of the sample has been consumed, this process is stopped (and the carbonate content of the sample is calculated). The change in pH is assumed to result from solution of calcite.

The moles of $CaCO_3$ present in the sample are calculated using the following expression:

$$\text{moles } CaCO_3 = \frac{V_1(10^{-pH_i}) - V_2(10^{-pH_f})}{2}$$

where V_1=the volume of acid added to the sample slurry; V_2=volume of acid plus volume of water added to the sample; pH_i=initial pH of the acid; pH_f=final pH at the end of the test. Under the test conditions outlined above this becomes:

$$\text{moles } CaCO_3 = \frac{0.05(10^{-2.9}) - 0.1(10^{-pH_f})}{2}$$

$$\text{moles } CaCO_3 = 3.15x10^{-5} - 0.05(10^{-pH_f})$$

Using the volumes and concentrations outlined in this procedure extends the lower limit of detection for $CaCO_3$ to about $2.25x10^{-6}$ moles, approximately one order of magnitude less than the gasometric or weight loss methods (see sec 1.2.2.2 above).

7.1.4.2 The Sulfide Test

With a knowledge of the natural buffering capacity of the material, the pyrite content of a sample can be estimated by measuring the acidity produced as a result of strong oxidation. A weighed sample is placed in a container and slurried with distilled water as outlined above. After the conductivity and pH are measured, a strong oxidizing agent such as H_2O_2 is added. The mixture is agitated for a period of time sufficient to permit oxidation of any pyrite. The pH and conductivity of the sample are determined. By correcting for the amount of acidity that was consumed by the calcite in the sample, as determined in the preceding test, the total acid generation of the sample is calculated. The oxidizable sulfide content is calculated using the following expression:

$$\text{moles } FeS_2 = \frac{V_3(10^{-pH_f}) + 2(\text{moles } CaCO_3)}{4}$$

where V_3=volume of slurry plus volume of oxidizing agent and other symbols are as above.

7.1.4.3 Miscellaneous Analyses

Sulfate content of the sample can be estimated from the electrical conductivity. On the basis of the analyses collected during this study, sulfate content is related to ECE by the expression mg/l $SO_4=6.25(ECE)^{1.29}$, for values of ECE less than 2.0, and mg/l $SO_4=-14.6+17.3(ECE)$, for values of ECE greater than 2.0. The coefficient of determination of 0.87 indicates that these relationships can be used with considerable confidence to estimate the sulfate content.

Determination of pH can be done in three ways. A portable pH meter could be used although the potential for rough treatment combined with the fragileness of these instruments makes special care necessary. A second method that could be used is pH test papers. A third technique would be to back titrate to neutrality using an indicator fluid. For both of these latter two techniques, it will be necessary to centrifuge the mixture in order to obtain sediment-free clear fluid.

7.1.5 Overburden Sampling Design

With the three types of information which were outlined above available, a program to sample the overburden for geochemical analyses can be designed. A review of the composite surface map, which shows areas that are underlain by the same material and have the same near-surface hydrologic regime provides the basis for outlining the first approximation of the sampling pattern. A series of tentative sampling locations is selected to assure that each type of geochemical environment within each area of interest is sampled. These locations are then checked against the subsurface stratigraphic framework to assure that each type of material that occurs in the site is sampled in each environment in which it occurs. Additional sampling locations are added as needed. Finally, the groundwater-flow system of the site is compared with the tentative sampling pattern to determine that places where the geochemical conditions in the pores reflect conditions elsewhere in the site, rather than at the sampling location, are sampled.

The sites selected in the manner outlined above should efficiently evaluate each of the geochemical environments within the overburden. The actual number and density of sampling locations will be a function of the complexity of the site and the requirements of redundancy of both the mining company and the regulatory agencies. As experience with this type of sampling design progresses, the model will be modified and refined and confidence in its predictive capability will increase resulting in a decrease in the number of samples that need to be collected.

7.2 Evaluation of Analytical Results

Because each sampling location selected by this method constitutes a firm statement of the predicted results of the analyses of samples collected, the model provides a check of the analytical results and of the model. Each analysis can be compared with the values that the model predicts for its setting. If the model is correct, it has been properly applied, and the analysis has been properly conducted, then the results will be as predicted. If the results differ from the predictions then one of the three conditions outlined above has not been met. Which of the three conditions is responsible can be judged on the basis of the number and distribution of the analyses that do not match their predicted values. If only a few analyses that are more or less irregularly distributed do not match, the analyses themselves are suspect. If only a few analyses that are restricted to a given setting or group of settings do not match, then either the model or its application should be reevaluated. If, however, a large number of analyses do not match, a situation which we would like to believe unlikely, any of the three is possible. Because the model, in its present form, is only a first approximation, we suspect that the results of its initial applications will be to modify the model itself. We are confident, however, in the basic soundness of the concepts on which it is based, and believe that after a period of adjustment, failure to match analytical results with projected values will be traced to an error either in the application of the model or in the analysis.

7.3 Generalization of Analytical Results

Once the analyses of samples and the projected values from the model are in agreement, then the model can confidently be used to generalize the analytical results throughout the project area. If, for example, all the analyses from fine-grained, calcareous, unoxidized sediment that contains pyrite and occurs deep below the surface beneath zones of run-off and non-filtration possess characteristics that fall within the range of values projected by the model, then one can conclude that the same is true of all areas within the site in which these conditions are met.

7.4 Summary

We have discussed the need for three types of data in order to apply the geochemical model. These include: (1) information on the stratigraphic framework of the site; (2) an integrated surface map that incorporates data on surface geology, morphology, hydrology, and soils; and (3) data on the subsurface hydrological regime. With these data in hand the geochemical model can be used: (1) to design a sampling program to evaluate the chemical characteristics of a proposed surface mine site; (2) to evaluate the results of analyses of those samples; and (3) to generalize the results of those analyses throughout the site.

8. ILLUSTRATION OF THE ENGINEERED-CAST-OVERBURDEN CONCEPT OF RECLAMATION

In order to reclaim a landscape that is to be disrupted by surface mining so that it continues to be productive on a long-term basis, it is necessary to design the placement of material and the configuration of the land surface so that subsurface-water movement does not cause a progressive negative modification of the original chemical profile. In some instances it may even be possible to design the landscape so that the movement of subsurface water will improve growing conditions over an extended period of time. In order to accomplish these objectives, the landscape must be designed for salt management, especially sodium management, and therefore for water management. The first step in this process is to identify the distribution of physical and chemical conditions in the overburden as outlined in previous sections. The second step is to selectively remove and replace the overburden during mining so that materials having desirable properties are at the surface and those with undesirable properties are deeply buried. As a consequence of this process, the distribution of hydraulic conductivity and surface form, which will dictate water movement in the post-mining landscape, are established.

In this section we explore, using simple examples, some of the types of landscape design options that might be used to achieve specific reclamation goals. Because of the great complexity of the system being modelled here and the obvious need for simplicity in addressing it at this stage, the following discussion will inevitably appear simple-minded and naive. This section is intended to communicate an idea, a conceptual approach to reclamation design, not a working design for present reclamation. It is our belief that this approach to landscape reclamation is sound and that the understanding of landscapes and hydrology that is needed to implement such an approach will be obtained, even though much of the necessary knowledge is not currently at hand.

If the following line of reasoning can be taken as valid, a working conceptual design for water and salt management can be evolved. One of the principal differences between productive and non-productive soils in the states of the Old West Regional Commission is the balance between physical erosion and salt flushing and accumulation. Non-productive soils occur in two settings. They are developed either on materials that originally contained deleterious materials or on materials into which deleterious materials are transported. In the first case, the rate of flushing of sodium and other salts is slower than is the rate of physical erosion. Thus, unweathered parent material that is laden with deleterious constituents is constantly available in the soil and subsoil zones. In the second case, the rate of accumulation of salts is greater than the rate of removal of material by physical erosion. Productive soils, on the other hand, occur where flushing of deleterious constituents occurs at a rate more rapid than the rate of removal of flushed materials by physical erosion.

Additional factors which must be taken into account in considering the difference between productive and non-productive soils include organic-matter balance, availability of essential nutrients, and availability of adequate water. Since the rate of production of organic matter is a function of all the other variables, rather than an independent variable, it is not considered further in this discussion. Much of the unweathered sediment in overburden is deficient in essential nutrients, such as nitrogen and especially phosphorus (Sandoval and others, 1973). It may, therefore, be necessary to include the application of fertilizers to the reclaimed landscape, at least initially, in order to raise the level of productivity. Although a shortage of moisture may preclude the improvement of productivity in some places, modification of the soil and subsoil to make more effective use of the naturally available moisture will solve this problem in some places. Import of large volumes of high quality water is involved as an essential part of some of the coal development projects that are under consideration in the Northern Great Plains. Where this is the case, existing natural water supply may be augmented by irrigation.

On the basis of these ideas it seems reasonable that the greatest potential for optimum agricultural productivity can be obtained if water movement is downward into the ground. The rate of movement through the soil and subsoil must be slow enough that the needs of plants for water can be met yet rapid enough that undesirable salts can be carried away from the surface beyond the reach of roots of transpiring plants. There must be provision for the removal of water from within the cast-overburden mass so that the water table does not rise too high and from the surface so that erosion is not too rapid.

An example will serve to illustrate these ideas. Assume a small upland area underlain by 80 feet of sodic clay resting on 20 feet of fine-grained sand, which rests on 10 to 15 feet of coal. The small size of the upland combined with the low permeability of the clay results in very little infiltration. Nearly all the precipitation is lost to evaporation, transpiration, and run-off. As a result of the minimal flushing that occurs, the subsoil retains its sodic character. In the mining process, the stratigraphy of the overburden can be reversed. The clay is placed in the base of the pit and covered with a layer of sand. The topsoil and subsoil materials are then replaced over the layer of sand. Although the sand may initially be highly sodic, the increased infiltration that can occur because of the more permeable material beneath the soil will permit flushing of salt and sodium out of the subsoil. This process will be enhanced and accelerated if the surface configuration is such that water is retained on the landscape rather than running off. Finally, the process can be greatly accelerated if suitable water is available to permit irrigation. It should be noted here that irrigation is being used to flush salts from the subsoil, not to hasten the establishment of vegetation.

Downward drainage of this increased amount of water, which infiltrates, will ultimately be blocked by the clayey sediment, which lies approximately 20 feet beneath the surface. Initially, however, the fractured nature of the clay may permit the water to escape to the lower part of the fill. As the clayey sediment becomes compacted as a result of load and slaking in response to wetting, the cast-overburden mass will settle and the vertical permeability of the clayey sediment will decrease. As this process continues, more and more water will have to be discharged laterally through the sand. The result of this is that we have concentrated all the sodium and salinity from the entire upland into a series of springs and seeps around the upland. We have made the upland more productive at the cost of potentially lowering productivity along the side slopes of the upland. If the outlet springs are so structured that the discharging water is channeled to well defined collecting points, the areal extent of damage from these seeps can be minimized.

It is important that the lateral drainage be adequate to prevent the water table from being too close to the surface. Let us assume that the water table should be no closer than 10 feet to the surface. Let us further assume that the base of the 20-foot-thick sand bed is horizontal and that the hydraulic conductivity of the sand is in the range from about 10^{-4} to 10^{-8} M/sec. The former value was obtained by Rahn (1976) for sandy cast-overburden from Wyoming; the latter is a reasonably typical figure for undisturbed fine-grained sand of the Sentinel Butte Formation (Moran and others, 1976). If we assume that the upland is one mile across then the water level in the sand must drop from about 10 feet above the base beneath the center of the upland to about one foot above the base at the outer margin of the upland about 2500 feet away. This gives a minimum hydraulic gradient, I, of 10/2500 or 4×10^{-3}. The Darcy equation $Q=KIA$, indicates that the amount of water that can be transmitted through a section of aquifer one foot square under these conditions is:

$$Q=(10^{-4}\text{ M/sec to }10^{-8}\text{ M/sec})\text{x}\left(1.03\text{x}10^{8}\,\frac{\text{sec ft}}{\text{M year}}\right)\text{x}(4\text{x}10^{-3})\text{x}1\text{ ft}^{2}$$

$$Q=41.3\text{ ft}^{3}\text{/year to }4.13\text{x}10^{-3}\text{ ft}^{3}\text{/year}$$

The higher value of discharge will drain a recharge of 0.2 inch of water, about 1.3 percent of the precipitation in the region, from the 2500 square-foot-strip overlying the 1-foot-wide flow section.

If we slope the surface of the upland and therefore the base of the sand bed so that it drops 50 feet in the half mile, then the hydraulic gradient becomes $2.4\text{x}10^{-2}$ and the discharge is increased by a corresponding factor of 6X to 247 ft^3/yr, for the higher value of hydraulic conductivity, and $2.47\text{x}10^{-2}\text{ft}^3$/yr, for the lower value.

In order to move more water out of the landscape at the lower values of hydraulic conductivity, it is necessary for the hydraulic gradient to increase. This can occur by raising the water table beneath the upland. If the water table were to rise too much, the upland could become water-logged. Alternatively, the gradient could be increased by decreasing the lateral distance over which the head is lost. This could be accomplished by shaping the land surface into an integrated dendritic pattern of drainage ways. In this way, the areas of saline discharge are located along low areas distributed throughout the upland rather than being concentrated around the upland.

Even if the initial hydraulic conductivity of the sand layer is on the order of 10^{-4} M/sec, the upper value obtained from a pump test on sandy cast-overburden (Rahn, 1976), it seems reasonable to expect the conductivity to decrease with time. The settlement that will result from loading and slaking of wetted sand and clay will gradually produce a more densely packed mass within the cast-overburden. This will result in a decrease both in porosity and in permeability, both of which will produce higher water levels beneath the upland.

The preceding discussion dealt with the physical and hydrological aspects of landscape reclamation. In the next section, we discuss some chemical aspects of material placement and implications for reclamation. Based on the interpretive geochemical framework outlined above, emplacement of a few metres of permeable sand beneath the soil veneer would prevent the formation of appreciable amounts of SO_4^{2-} in soil and subsoil water. If SO_4^{2-} production by pyrite oxidation is relatively inactive, and if infiltration passes through the sandy subsoil zone sufficiently frequently to prevent accumulation of gypsum from the small amount of SO_4^{2-} that does occur, the pore water in the soil will be characterized by low dissolved solids. The water will have HCO_3^- as the dominant anion, and will have low contents of Na^+, Ca^{2+}, and Mg^{2+}. Flushing as a result of snowmelt and heavy rainfall will gradually remove exchangeable sodium from the sand, leaving the exchange sites on the clays loaded with Ca^{2+} generated mainly by the dissolution of carbonate materials.

If there is little production of dissolved salts in the subsurface water as it passes through the soil and sandy subsoil, there will be little tendency for extensive saline soil conditions to develop in areas of groundwater discharge. The influx of salt into surface water will also be minimal.

Because of the great abundance of Na-rich, pyritic, fine-grained deposits that will be excavated during mining in most areas, it will be necessary to emplace some of this material below the surface sand in much of the reclaimed landscape. We now examine the potential for salt generation within these materials.

Most of the water that infiltrates below the root zone in the sandy subsoil will eventually move to the base of this deposit where it will flow laterally toward discharge zones or flow into the finer-grained, lower permeability deposits below. The water that moves into the finer-grained, Na-rich, pyritic deposits will remain at low levels of dissolved solids if pyrite oxidation does not occur to a significant extent. Unless the water contains significant concentrations of dissolved oxygen, pyrite oxidation will not be an active process. If significant oxidation does occur, the pore water will acquire additional SO_4^{2-} and H^+. If the sedimentary material is calcareous, the H^+ will be consumed by dissolution of calcite and possibly dolomite. The pore water will contain increased HCO_3^-, Na^+, and possibly Mg^{2+}. The Na^+ will be contributed to the water from the Na-Ca exchange reaction between the pore fluid and the sodic clay fraction of the sediment. The concentration of SO_4^{2-} will remain very low (below 10 to 20 mg/l) because consumption, through pyrite oxidation, of all of the dissolved oxygen in oxygen saturated water (8 to 11 mg/l of dissolved oxygen) cannot yield much SO_4^{2-}. The pore water will probably contain a maximum of several hundred milligrams per litre of Na^+ and between 400 and 800 milligrams per litre of HCO_3^- and only very low concentrations of other cations and anions. Gypsum precipitates will not form because of the paucity of SO_4^{2-} and the absence of the concentration effect caused by evapotranspiration.

The above scenario in which $Na\text{-}HCO_3$ pore water at a moderate level of total dissolved solids is produced requires the presence of appreciable dissolved oxygen in the water that penetrates through the soil and sandy subsoil to the finer-grained zone below. It is unlikely that this would occur. It is more reasonable to expect that much of the dissolved oxygen would be consumed in the soil zone by oxidation of organic matter. It should be noted, however, that little is known about the occurrence of dissolved oxygen in soil moisture in sandy subsoils beneath soils that support crops or grasses. The downward flux of dissolved oxygen below the root zone will depend on the vegetation conditions, on the rate and frequency of infiltration, on the nature and distribution of soil organic matter, and on the character of the soil bacterial environment. The bacterial system is important because bacteria act as catalysts in the oxidation process.

If most of the dissolved oxygen is consumed by oxidation of organic matter above the root zone, oxidation of pyrite by the remaining oxygen will cause release of only a minor amount of H^+. The addition of HCO_3^- to the pore water from calcite will be small and the increase in Na^+ by ion exchange will also be small. The pore water will be low in total dissolved solids (a few hundred milligrams per litre), slightly alkaline (pH from 7 to 8), and will have Na^+ and HCO_3^- as the dominant ions.

The above line of reasoning draws attention to the fact that a fine-grained, sodic, pyritic sediment placed below the root zone in cast-overburden can be expected to produce minimal salinity in comparison to salinity production that would occur if this material is placed immediately below the veneer of top soil. As an oversimplification it could be stated that the salinity production capacity of these materials will not be mobilized if the material is isolated from the zone of great geochemical activity which occurs in the upper two or three metres of the landscape. It should be noted that because salts can be generated in materials that do not initially contain salt minerals, the standard tests that are used to identify saline or potentially saline soils are not useful as a measurement of the salinity production capacity of these materials.

Although the preceding discussion involves only a very simple situation and we have discussed a very limited range of the possibilities and problems associated with reclaiming this setting, the example serves to illuminate two important points. (1) It demonstrates the complex interrelations among surface form, permeability distribution, and water movement. It is not possible to accurately understand movement of subsurface water without taking into consideration both the form and the substance of the landscape. (2) The example further demonstrates the very great care that must be exercised in designing a post-mining landscape. Too much land that is too flat combined with increased infiltration without adequate allowance for drainage can produce results that are exactly the opposite of the desired result. (3) Finally, the example illustrates the distinction between the salinity and the salt generation capacity of overburden material. Material that contains pyrite but does not contain significant amounts of soluble salts and, therefore, tests as non-saline by presently accepted procedures is still capable of generating considerable salt if placed in an environment in which the pyrite can be oxidized.

9. RECOMMENDATIONS FOR FURTHER RESEARCH

Two major areas of additional research must be explored before the ECO Geochemical Model can be used as a practical tool in designing a reclamation program for surface mining. The first area is the development of analytical techniques to evaluate the amount of potentially soluble calcite and potentially oxidizable sulfide (pyrite) that is present; techniques are also required to evaluate cation exchange capability and which cations are available to be exchanged. The second major area that needs study is the model itself, which needs to be further tested, modified, and sharpened as a predictive tool.

9.1 Development of Analytical Techniques

A principal problem confronting the attempt to achieve a return to agricultural productivity following mining is to determine, prior to mining, the potential of the materials in the overburden to provide adequate topsoil and subsoil to support vegetations. On the basis of previous research, two parameters, the sodium adsorption ratio (SAR) and electrical conductivity (ECE) of the aqueous extract from samples of the overburden material, appear to correlate best with relatively short-term results of experiments in vegetation of overburden materials. These analytical tests have been developed over a period of years by agriculture workers, who were concerned with the rehabilitation of saline soils and with estimating the potential behavior of soils under irrigation. The performance of the soils following stress has then been correlated with the analytical data to build up a series of empirical relationships that appear to work reasonably well under the test conditions. A similar approach has been taken to assessing spoil materials. The existing empirical relationships between SAR and ECE and performance of material taken from, at, or very near the present land surface appear to be valid, as should be expected. The correlations between these properties and performance of unweathered materials that have been brought from deep below the surface also seems to hold, but it is not at all clear whether this will continue to be the case over an extended period of time. Current agricultural experimentation, including several of the other subprojects of this study, is directed at establishing these correlations over an extended period of time.

As has been discussed above, the saturation extract analyses only indirectly determine the actual chemical conditions in the pore spaces of the overburden sample. It is these chemical conditions in the in place material which, by and large, determine the performance of the material as a topsoil or subsoil medium. We, therefore, believe that a more direct determination of the actual chemical conditions in the pore spaces will lead to a better understanding of the potential performance of the material. As was discussed above, the three factors that most strongly influence the chemistry of groundwater-pore water in the study area are the abundance of (1) calcite (or dolomite), and (2) pyrite, and (3) the ion exchange characteristics of the material.

Accordingly, we recommend that research be undertaken to develop analyses for these parameters. The following discussions outline some of the considerations involved in developing such procedures.

9.1.1 Determination of Total Carbonate Mineral Content

It is proposed that the total mineral carbonate content of borehole or soil samples be determined from a type of leaching test.

If a selected weight of oven-dried sample is mixed with aerated distilled water (pH=5.7), the readily soluble minerals in the sample will dissolve. The extent to which the carbonate minerals (i.e., calcite and dolomite) will dissolve will depend almost entirely on the pH of the water. If the water-sediment mixture is stirred in a manner that will ensure that the sample is well aerated, the partial pressure of CO_2 in the sample water will be maintained at the earth's atmospheric value (i.e., $P_{CO_2}=10^{-3.5}$ atm). If a significant amount of calcite and/or dolomite is present in the soil sample, dissolution to equilibrium will occur. If there are only small amounts of ions derived from non-carbonate minerals in solution, and if calcite is the only carbonate mineral, the equilibrium pH will be approximately 8.4 and the concentrations of Ca^{2+} and HCO_3^- will be about 23 mg/l and 70 mg/l (Stumm and Morgan, 1970). If dolomite is the only carbonate mineral, the pH and HCO_3^- values will be the same as for the calcite case, but the Ca^{2+} and Mg^{2+} values will be about 11.5 mg/l each. If calcite *and* dolomite are present, the pH and HCO_3^- values will be similar to the calcite case, Ca^{2+} will vary from about 11.5 mg/l to 23 mg/l, and Mg^{2+} will vary up to about 11.5 mg/l. The exact values will depend on the rates at which the two minerals dissolve. In terms of total carbonate mineral content, the diagnostic parameters are pH and HCO_3^-. If the pH and the HCO_3^- values are less than the values indicated above, it can be concluded that the sample did not have sufficient total carbonate mineral content for dissolution to proceed far enough to reach equilibrium with respect to calcite or dolomite. The carbonate mineral content of the water can then be calculated. An example of the calculation procedure is as follows:

A sample with a dry weight of 10 grams (approximately 4 cm^3 dry volume) is mixed with 10 ml of aerated distilled water. If the water attains an equilibrium pH of 8.4 and Ca^{2+} and HCO_3^- concentrations of 23 mg/l and 70 mg/l, respectively, and if all of the carbonate-minerals content of the sample is consumed just as the water reaches equilibrium, it can be concluded that the 10 grams of solid material has yielded 0.58 mg of $CaCO_3$. The calcite content of the sample, expressed on a dry weight basis is therefore 0.0058 percent.

This value was obtained from the following line of reasoning: The calcite dissolution reaction can be expressed as

$$CaCO_3+H_2CO_3 \quad Ca^{2+}+2HCO_3^-.$$

From the Ca^{2+} of HCO_3^- concentrations in the water it is evident that 0.58×10^{-3} moles of calcite have dissolved. The formula weight for calcite is 100, so this equals 58 mg/l. Since the sample volume is 10 ml, the total $CaCO_3$ in solution is 0.58 mg which is the amount obtained from 10,000 mg of dry weight sample.

Of course, if the equilibrium pH, Ca^{2+}, and HCO_3^- concentrations indicated above were observed in the water, one would not know if all of the calcite in the sample were removed by dissolution. To determine whether there is more calcite in the sample, one could (1) separate the solids from the water and then mix the solids in a volume of new aerated distilled water *or* (2) add a known volume of distilled water and observe the pH and concentration changes or (3) add a known volume of acid (HCl, H_2SO_4, or HNO_3) and observe the pH and concentration changes. From this it seems that it should be feasible to develop a relatively efficient procedure that would enable the carbonate mineral content to be determined in a rapid manner.

We used calcite in the above example for simplicity of discussion. One should expect that dolomite may also be present in many samples. It is not necessary that the relative amounts of calcite and dolomite be determined. HCO_3^- and pH can therefore serve as the indicators rather than Ca^{2+} and Mg^{2+}. If the sample contains a significant percentage of clay minerals, Ca^{2+} and, to a lesser extent, Mg^{2+} may be removed by exchange with Na^+ on cation adsorption sites. In this case more calcite and/or dolomite would have to dissolve in order for the solution to obtain equilibrium. However, as long as one measures the pH and HCO_3^- concentration, the amount of inorganic carbon that has gone into solution can be calculated and related to the amount of calcite-dolomite dissolution. It would also be useful to measure the specific conductance of the solution as a means of detecting anomalous effects that may be introduced by dissolution of other minerals.

Since natural groundwater in western North Dakota typically has appreciable concentrations of HCO_3^- and Ca^{2+}, dried samples that initially have a significant water content will acquire very small amounts of calcite as a precipitate residue caused by evaporation. This residue will normally not be sufficient to produce calcite saturation when the dried sample is mixed with distilled water because the volume of water added will greatly exceed the initial water content of the sample.

Some samples will contain significant amounts of gypsum that will dissolve rapidly when the sample is mixed with distilled water. This will cause an increase in ionic strength. Specific conductance measurements will enable the ionic strength to be estimated. This should be sufficient as a means of obtaining activity coefficient values for use in the solubility calculations.

There is the possibility that the use of aerated water in the experiments will produce acidity as a result of oxidation of FeS_2. It may therefore be desirable to conduct the tests with deaerated water with addition of some acid such as HCl or HNO_3 as the hydrogen-ion control.

9.1.2 Determination of Oxidizable Sulfide Mineral Content

As was discussed above, the sulfate content of overburden material is the most important factor governing the electrical conductivity (ECE) and in the absence of calcite, the pH of saturation extract analysis. However, gypsum, the principal source of sulfate, is not present as a primary mineral in unweathered materials in the study area. Pyrite, on the other hand, is a common primary constituent and because it is readily oxidized serves as the ultimate source of sulfate. Therefore, a material that contains considerable pyrite, although not yielding high values of sulfate and ECE nor low value of pH in a saturation extract analysis, can be a potential source of very high salinity and sulfate values as well as hydrogen ions, if it is placed in an oxidizing environment. It thus becomes desirable to develop a test for the potential sulfate contribution of a material, that is, for its oxidizable pyrite content.

In any sample of overburden, sulfur may be present in two forms, either oxidized and readily soluble sulfate, primarily as gypsum, or unoxidized and essentially insoluble sulfide, primarily as pyrite. Two types of procedures suggest themselves to determine the sulfide content of the material. Both techniques begin by determining the original sulfate content of the sample. In the first case, one would then determine the total sulfur content and determine the sulfide content as the difference between the two values. In the second case, the sample would be oxidized after the initial sulfate content was determined and then the sulfate content would be again determined. As was the case in the first procedure, sulfide would be determined as the difference between the two values. One of two approaches could be utilized for both procedures. One could attempt to dissolve the sulfate and then flush the sample under nonoxidizing conditions until the sulfate was removed. The sulfur content would then be determined, or the sulfur would be oxidized on the same sample. Alternatively, the sample could be split and parallel analyses be made on the two sub-samples. In the first case one sample would be analyzed for sulfate, the other for sulfur; in the second case, one would be analyzed for sulfate, the other first subjected to oxidation, then analyzed for sulfate.

We recognize that formidable but probably not insurmountable obstacles are involved in developing a sulfide test. The necessity of having this information as a basis to understand and predict water chemistry makes it very desirable to pursue such procedure.

9.1.3 Analysis of Cation Exchange Characteristics

In order to evaluate the behavior of a material as a cation exchanger, three types of information are needed: (1) the cation-exchange capacity, (2) the composition of the exchangeable cations, and (3) selectivity coefficients for the major cations in exchange reactions. Analytical tests are available for the first two properties. However, because of the manner in which the tests are generally conducted, these results probably are not directly applicable to the problem under consideration.

The cation-exchange reaction is both concentration and pH dependent. Thus any change in the concentration of ions in solution or in the pH of the pore fluid will modify the exchange characteristics of clay minerals in contact with the pore fluid. If the fluid content of a sample is permitted to change, the concentration of dissolved species will increase and exchange reactions will alter the exchangeable cations on the clays. Such a change will result if a sample is dried before analysis. The pH of groundwater samples is generally observed to decrease by as much as two pH units between the time it is sampled in the field and analyzed at a later time in the lab. This change, which can be traced to changes in the CO_2-HCO_3^--CO_3^{2-}-calcite equilibria, results from the change in P_{CO_2} associated with removal from the ground and exposure to the atmosphere. A similar change in the pH of pore water in sediment samples is also to be expected. Such a change in pH may also alter the ion-exchange capacity of the clay.

A test of ion-exchange capacity and exchangeable cations is thus needed in which pore fluid is removed in as close to its field conditions as possible so that neither concentration of dissolved species nor pH is altered. If this could be done, the exchange sites should be left in essentially their field state.

The selectivity coefficients for ions in exchange reactions describe the equilibrium exchange reactions in terms of relative activities or concentrations of the ions in their dissolved and adsorbed states (Moran and others, 1976). These coefficients are very poorly known for the major ionic constituents of groundwater. Development of a technique to determine values for these coefficients is necessary to make conceptual analysis of the exchange reactions feasible.

9.2 Evaluation of the Geochemical Model

The geochemical model that is presented herein has been developed using data from several mine and proposed mine sites in North Dakota. Before it can be confidently used in other areas as a means of predicting overburden characteristics, it should be further evaluated using existing data on sites in that area. We believe that the model is probably applicable, more or less in its present form, in North Dakota, Montana, and Wyoming and possibly farther to the south and west. We recommend that a process of validation similar to that used in this study to develop the model be undertaken in those areas using existing data on existing mining projects.

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APPENDIX A
METHODS AND PROCEDURES

A.1 Collection of Geologic Data

Various field and laboratory techniques were utilized in the collection of geologic data. These included rotary drilling, coring, outcrop and highwall sampling, geophysical logging, surficial mapping, and geochemical analysis of overburden samples. These various techniques were integrated to maximize the amount of information available for stratigraphic interpretation of the study areas.

A.1.1 Test Drilling and Sampling

All test drilling was accomplished using forward-circulation rotary drilling rigs. In most testholes 5 1/8, 5 7/8, 6 3/4 standard drill bits were used. Concretions or boulders in some testholes necessitated the use of tri-cone roller bits. Most holes less than 200 feet in depth were drilled with air or air-water mist circulation. Difficulties in maintaining circulation in certain testholes necessitated mud circulation. Such testholes were drilled by circulating water-based drilling mud, either natural, Quick-jel, or Johnson UOP Revert.

Samples were collected at no greater than 5-foot intervals and often at considerably smaller intervals. The driller maintained a log of the materials at each site. A field log was kept by the geologist on the site. The samples were oven-dried and were described in detail before being bagged.

A.1.2 Coring

Core holes were drilled at 16 different sites within the Dunn Center project area (fig. A.1.2-1). A total of 301 feet of 4-inch diameter core was recovered by UND Engineering Experiment Station from 10 sites using a 5½-inch O.D., 10-foot-long double barrel core barrel made by Diamond Drill Contracting. An additional 400 feet of NX core was cut by the Paul Wier Co.

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 540 feet of the core was taken above the Dunn Center bed and 160 feet below the Dunn Center bed. About 10 percent of the core below the Dunn Center bed was from material immediately below the Dunn Center bed.

A.1.3 Geophysical Logging

All testholes were geophysically logged by Century Geophysical Corporation of Tulsa, Oklahoma. Resistance, Natural Gamma, and Gamma-Gamma Density logs were obtained in all testholes at each of the sites. Spontaneous Potential logs were obtained at some testholes at the Falkirk, Beulah-Hazen, Indian Head, and Dunn Center sites. In addition, Neutron logs were obtained in some testholes at the Dunn Center site.

A.1.4 Outcrop and Highwall Mapping

Exposures in the form of natural outcrops as well as strip mine highwalls were measured and mapped in detail. Outcrops in the Fort Mandan Badlands area (fig. A.1.4-1) were measured and marker beds defined as described in Hemish (1975). The marker beds, as defined in these outcrops, were then used as the stratigraphic framework for the Sentinel Butte and Bullion Creek Formations in the subsurface at the Falkirk area. Highwalls at the Indian Head Mine afforded a unique opportunity to evaluate three-dimensional cross sections of the mine area based on testhole data. The highwalls were initially sketched from the opposite side of the open pit. The highwalls were then cleaned at strategic locations with a trenching tool, and measurements were made using a steel tape. Twenty-three sections were described in this manner along about 2 miles of continuous highwall exposure. In addition, samples of the various exposed materials were collected for chemical analyses. These were collected by excavating about one foot back from the exposed face to obtain an unweathered sample, in which no build-up of salinity should have occurred as a result of evaporation of seepage water. The samples were then placed and sealed in

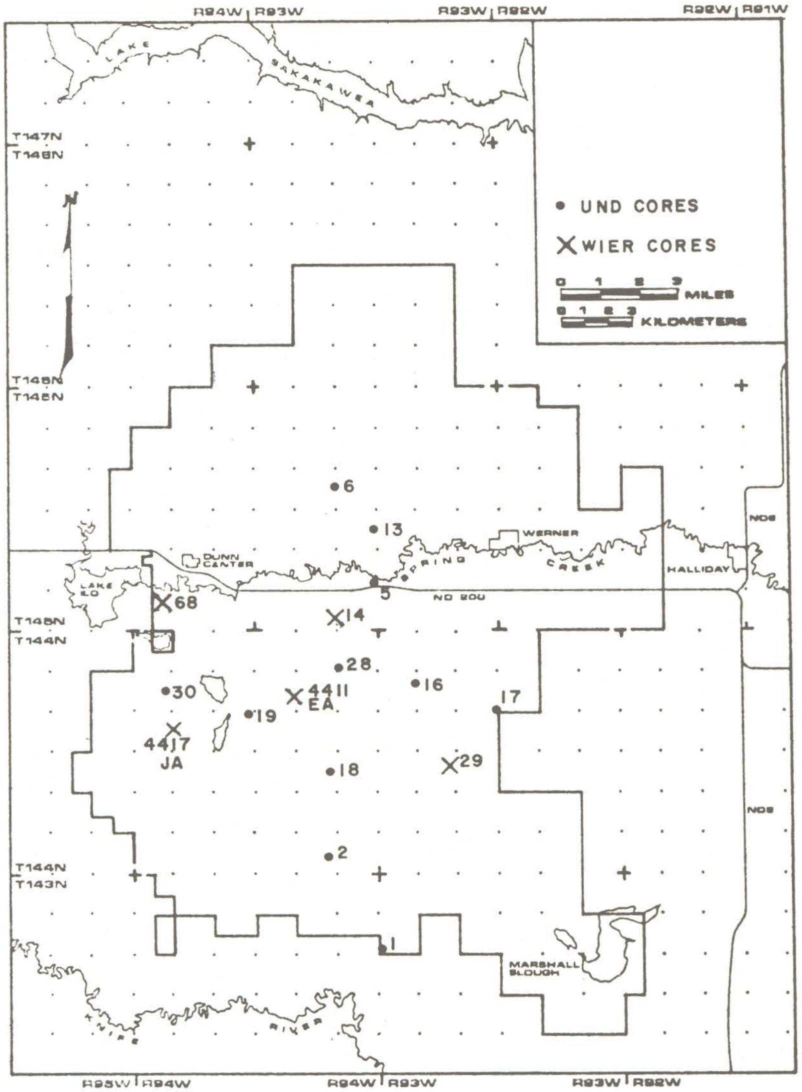


Figure A.1.2-1. Map of the location of overburden core holes in the Dunn Center area.

APPENDIX A—Continued
METHODS AND PROCEDURES

plastic bags for analysis.

A.1.5 Geochemical Sampling and Analysis

Geochemical sampling sites and intervals were selected to give a representative sampling of the lithologies in the overburden at all study sites (figs. A.1.5-1, -2, -3, -4, and A.1.2-1). The samples were obtained from rotary-drill holes at all sites except Dunn Center, where cores were taken. Attempts to obtain dry samples by circulating only air had variable success. In most cases, only the upper 20 to 40 feet could be sampled with air because below that depth air circulation was usually lost. In such situations, the remainder of the testhole was drilled using air-mist circulation.

Samples were collected at a minimum of 5-foot intervals. The samples were described in the field and then placed and sealed in plastic bags. Analyses were performed on saturation extract from each sample in the reclamation soils laboratory at North Dakota State University under the direction of Fred Schroer. Standard analytical methods were used as outlined in Agricultural Handbook No. 60 (U.S.

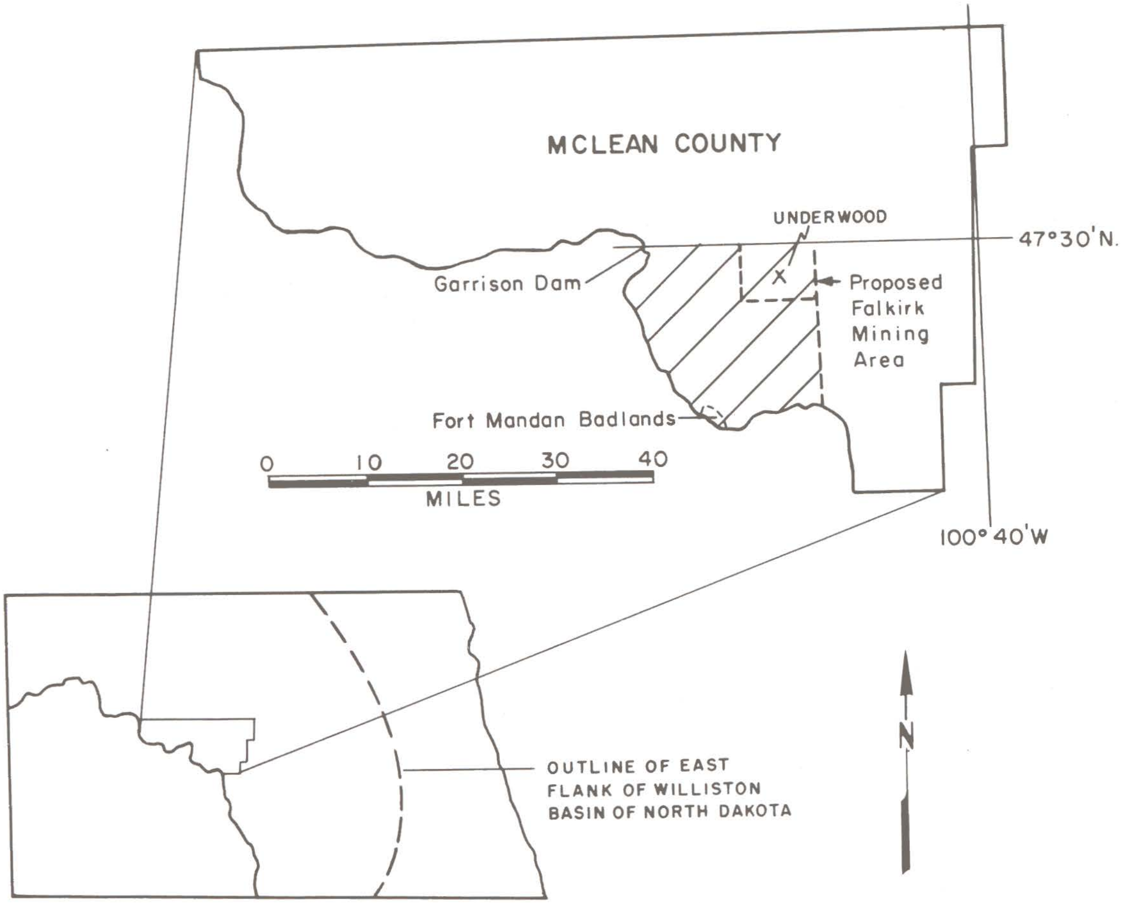


Figure A.1.4-1. Map showing location of Fort Mandan badlands.

APPENDIX A—Continued
METHODS AND PROCEDURES

Salinity Laboratory Staff, 1954). Overburden analyses are summarized in appendix D.

A.2 Development of a Three-dimensional Materials Framework

A complete knowledge of the physical and chemical properties of the overburden is essential to an understanding of the reclamation potential and problems of an area. In addition, groundwater-flow patterns and chemistry in an area are largely dependent upon the materials framework. The development of a three-dimensional materials framework thus is the initial critical step in designing reclamation procedures for a proposed mining area.

A.2.1 Interpretation of Testhole Data

Sampling and description of the materials, as previously described, resulted in a field log of each testhole as well as a more detailed final descriptive log based on dried samples. The descriptive logs were combined with the geophysical logs to construct a final interpretive log for each testhole (fig. A.2.1-1). The final interpretive logs were initially constructed at a vertical scale of 1 inch=10 ft. At this scale it was possible to conveniently define units as thin as 0.5 feet. The various descriptive units, as defined on the interpretive logs, include lignite, carbonaceous clay, silty clay and clayey

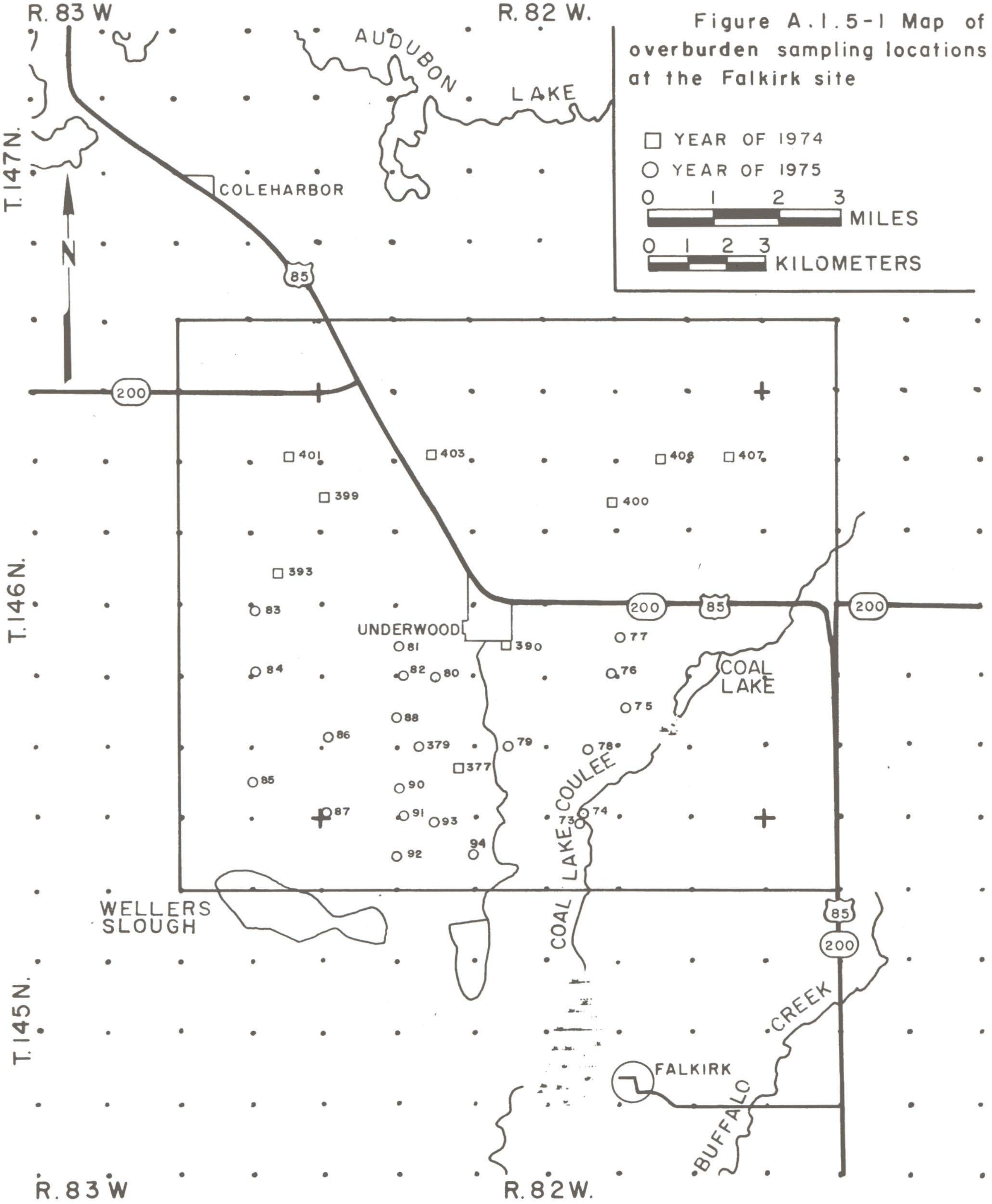


Figure A.1.5-1. Map of overburden sampling locations at the Falkirk site.

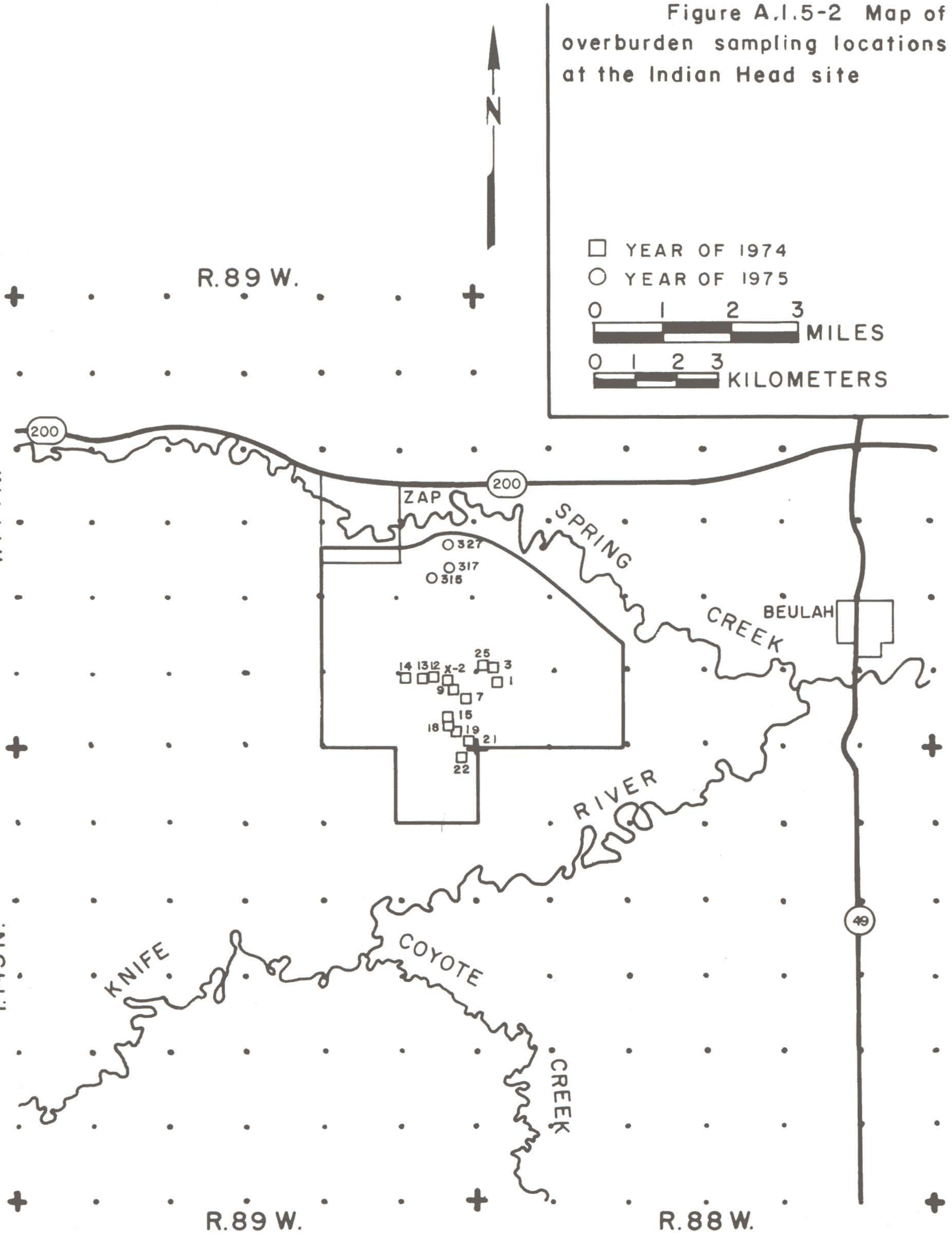


Figure A.1.5-2. Map of overburden sampling locations at the Indian Head site.

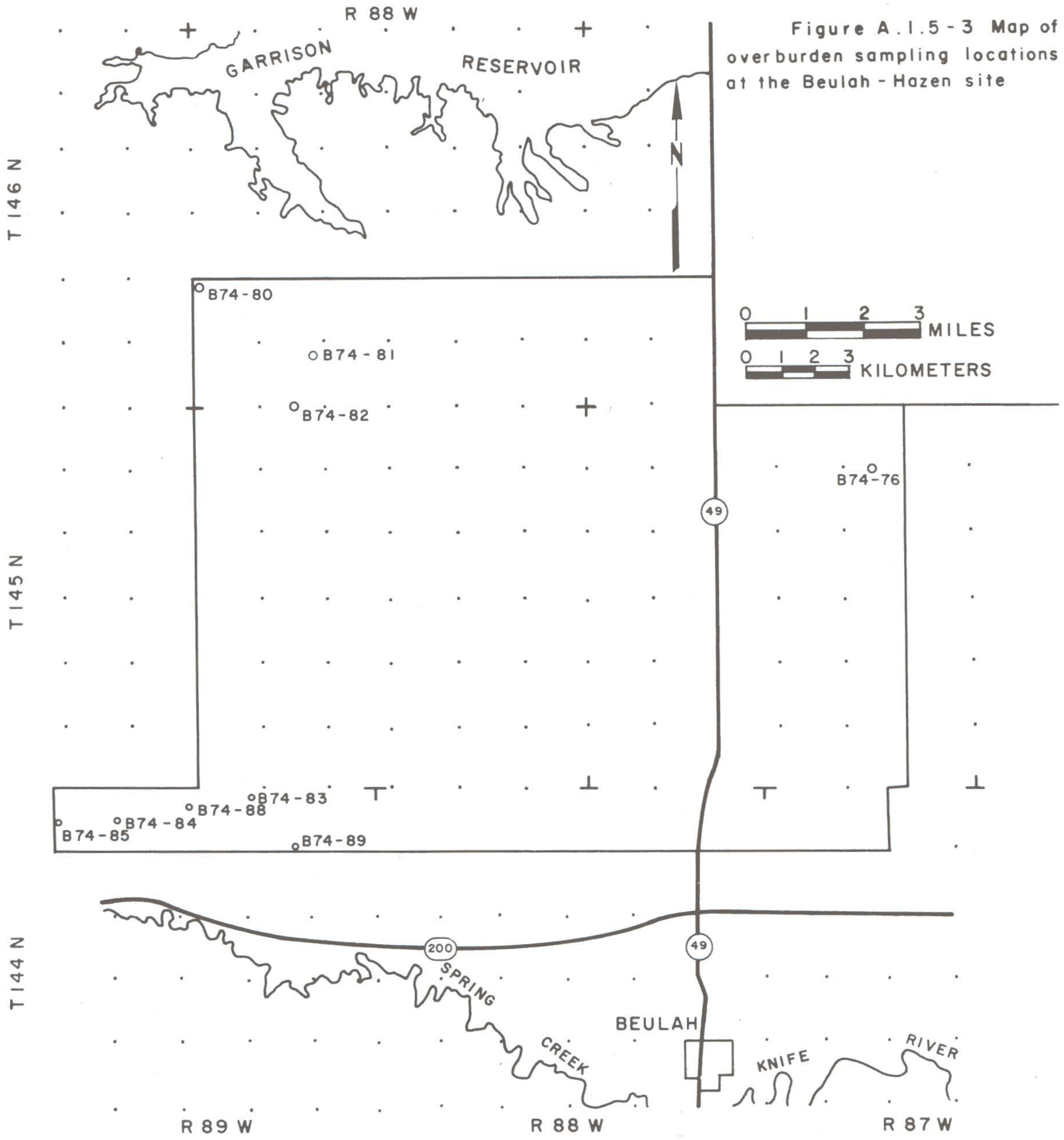


Figure A.1.5-3. Map of overburden sampling locations at the Beulah-Hazen site.

APPENDIX A—Continued
METHODS AND PROCEDURES

silt, silt, silty sand, sand, gravel, and pebble loam (till).

A.2.2 Correlation of Subsurface Data

The two lignite-bearing lithostratigraphic units of major concern in the study area were the Bullion Creek and Sentinel Butte Formations of the Fort Union Group. About 60 percent to 80 percent of the sediment making up these formations consists of interbedded silt and clay that occurs in beds ranging from tenths of inches to tens of feet in thickness. From 15 percent to 35 percent of the sediment making up these formations consists of silty, fine-grained to

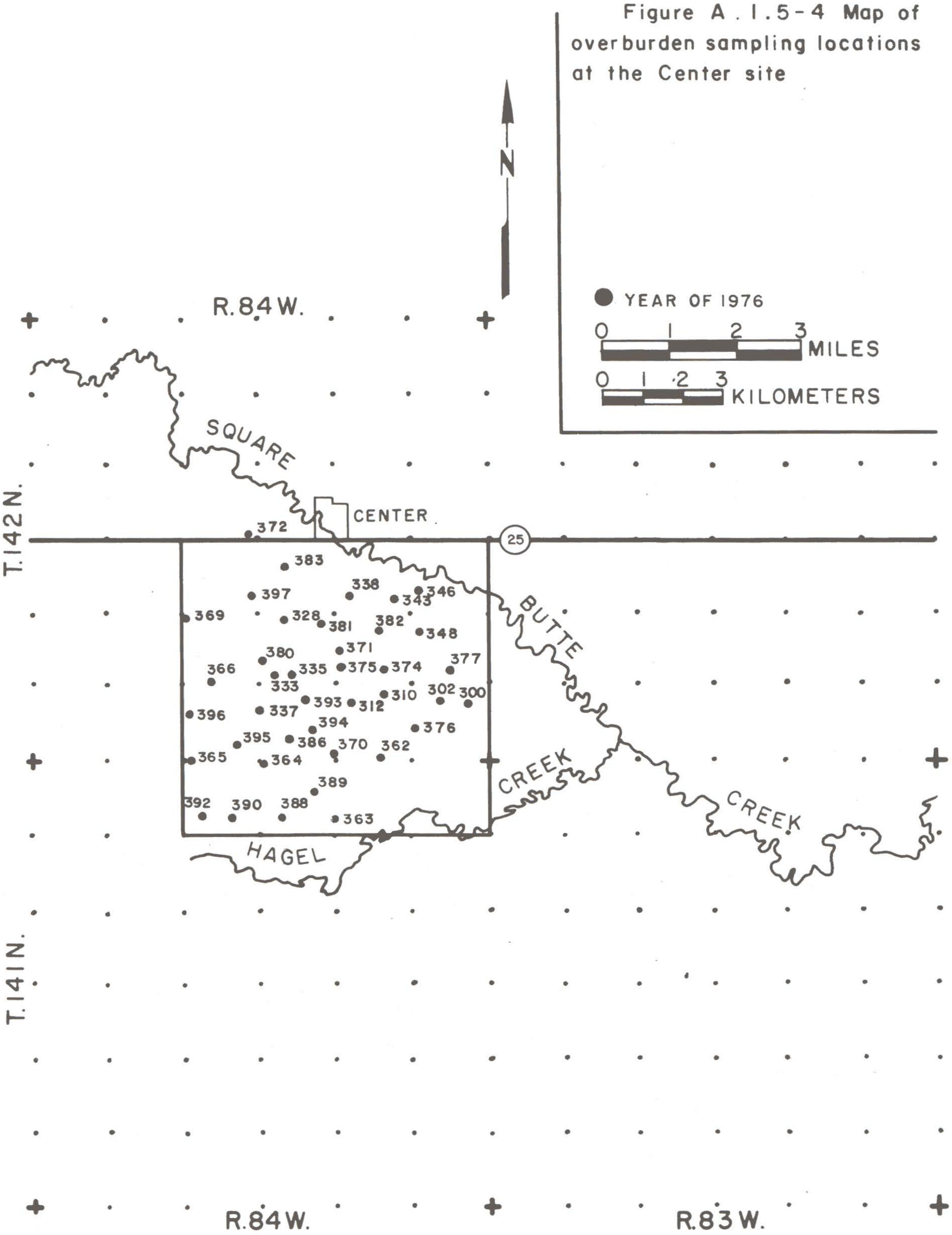


Figure A.1.5-4. Map of overburden sampling locations at the Center site.

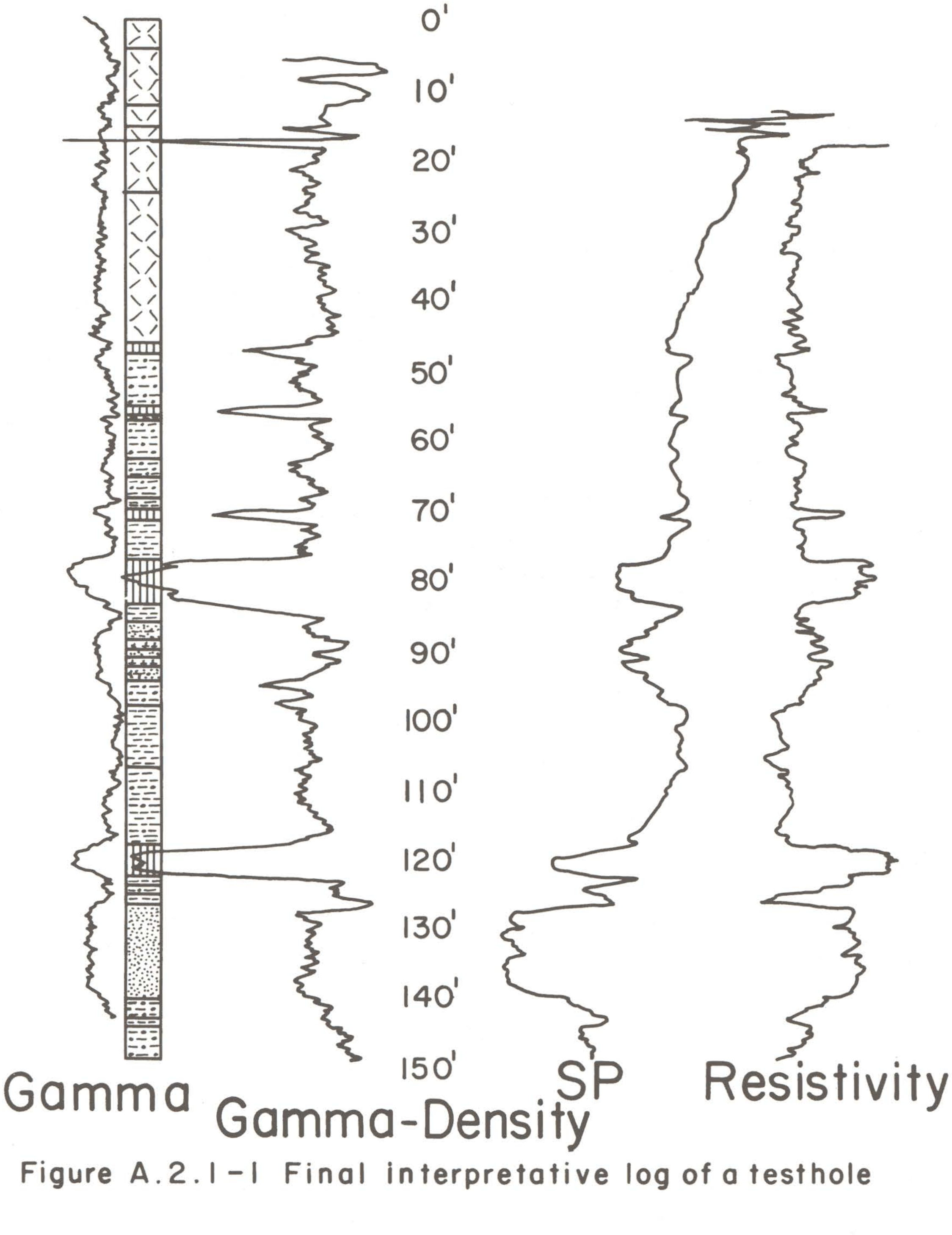


Figure A.2.1-1 Final interpretative log of a testhole

Figure A.2.1-1. Final interpretive log of a testhole.

medium-grained sand in beds that range in thickness from one foot to 100 feet. Lignite is a minor constituent occurring in beds that range in thickness from an inch to about 40 feet locally. The lignite generally comprises less than 5 percent of the total thickness of these units in North Dakota.

Plate A.2.2-1 is a cross section of part of a portion of the highwall exposed in the Indian Head Mine near Zap, North Dakota. This section was completely exposed so the stratigraphic relations shown were actually observed, not inferred. Examination of this cross section indicates that the rocks are both complex and at the same time quite simple. Although there is considerable change in lithology laterally, there is a rather simple, repetitive sequence to the section. Lignite beds are generally continuous, and separate sequences of gray silt and clay, brown silt and clay, and sand. In short, the apparent complexity consists of the repetition of simple, lignite-bounded cyclic-sequences.

Subsurface correlation of these lignite-bounded units, as defined on the final interpretive logs, is dependent, to a large degree, on the determination of the sedimentary environment in which they were formed. Determination of the sedimentary environment involves using the gross distribution of the various types of material and the small-scale sedimentary structures contained in the material. By relating the characteristics of these sediments to similar sediments that are being currently deposited, it is possible to develop a conceptual, depositional model that relates the various types of material to one another. Thus, the geometry of each body of sediment can be visualized and related to the other bodies of sediment found in the same environment. In approaching an unknown sequence of rock, the observed characteristics of the new rocks are compared with those of the various possible models. The model which seems best to fit the characteristics of the unknown rocks is then selected and used as a guide to interpret the three-dimensional relationships among the bodies of sediment within the area of interest.

This type of approach has been used successfully in North Dakota by Jacob and his associates (Chervin, 1973; Jacob, 1972, 1973; Johnson, 1973). They have studied both the Bullion Creek (formerly Tongue River) and Sentinel Butte Formations in considerable detail in several different small areas. Their findings are that the model that seems to fit these rocks in the areas studied is that of an alluvial flood plain. The sand beds and lenses represent channel fills or accretionary deposits formed by channel migration. The sandy silt to clayey silt beds that tend to weather to yellowish colors were deposited as natural levees along the channels. The gray, clayey, silt, silty clay, and clay beds were deposited in the back-basin areas of the flood plain (Jacob, 1972, 1973) (fig. A.2.2-1). This model was used for subsurface correlation at all the study areas.

The Indian Head Mine site, as previously mentioned, functioned primarily as a field laboratory. Of the various sites, Indian Head was the only one where ongoing strip mining was in progress. It was possible, therefore, to construct interpretive pre-mining cross sections from testhole data utilizing the alluvial flood plain model. As mining progressed, new pits were open in the areas where the interpretive cross sections had been constructed. The geology that was exposed in the highwalls was mapped in detail, as previously described and used as a check for the depositional model. The interpretive cross sections showed a very high degree of similarity to the highwall exposures.

A.2.3 Correlation of Geochemical Data with Material Framework

The overburden at each study site was subdivided into large stratigraphic units that are bounded by major lignites. Each of these intervals has, in turn, been further subdivided into lithologically defined units that have been mapped throughout the respective areas. These units are described

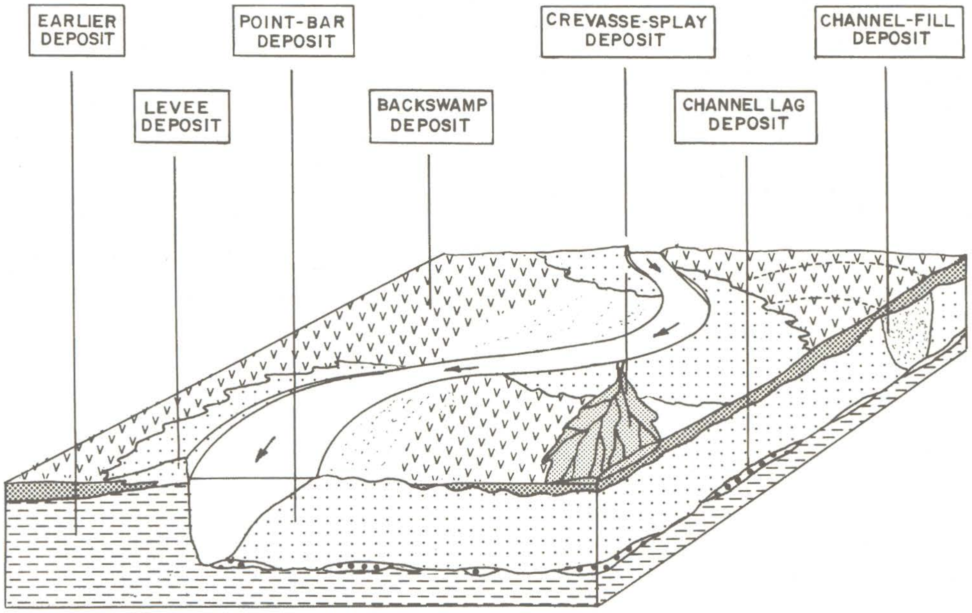


Figure A.2.2-1. Depositional model for Bullion Creek and Sentinel Butte Formations.

APPENDIX A—Continued
METHODS AND PROCEDURES

in the discussion of stratigraphy of the respective sites.

Most of the lithologic units were sampled at one or more places for geochemical analyses. The values of SAR, electrical conductivity, and pH for each sample were evaluated in terms of the depth, lithology, location in the groundwater-flow system, and direction of groundwater movement. The range of values for the unit was then generalized from these analyses and the capability of each unit to meet the requirements of "suitable plant-growth material" as defined by North Dakota law and regulation was assessed.

A.3 Collection of Hydrological Data

A.3.1 Procedures Used in the Installation of Potentiometric Observation Wells in the Dunn Center Area

Many of the observation wells at the Dunn Center site were deeper than those installed at the other sites, reaching a maximum of 750 feet in depth. As a result different procedures were evolved for these deeper wells than for the wells at the other site. This section documents in some detail the experience in methods and procedures gained during the well installation program at the Dunn Center site; a later section discusses procedures at the other site.

The well installation procedure consisted of six steps: (1) screen and pipe assemble; (2) screen and pipe insertion into the borehole; (3) circulation; (4) gravel packing; (5) grouting; (6) backfilling.

Steel pipe was used in wells deeper than about 500 feet. Steel pipe and screen was assembled in 21-foot sections as it was inserted into the borehole by the drilling crew using threaded pipe collars.

Plastic pipe was used in shallower wells. Complete assembly of the plastic pipe and screen took place before insertion into the borehole. The pipe was joined together in 20-foot sections with sleeve couplings and glue. The pipe was cut so that, with the screen at its proper depth, the top of the pipe was two to three feet below ground level. The screen was glued to the lower end of the pipe and was fitted with a washdown valve and protector. A male or female threaded adapter was glued on the upper end of the pipe. The pipe was generally allowed to sit for 30 minutes or longer to permit joints to cure. However, in some cases, individual joints were cured only a few minutes when new joints had to be made during installation and additional delay would have adversely affected the installation.

In some holes, pipe was run into the hole until buoyancy could no longer be overcome. The pipe was then cut above the ground and filled with water. After gluing a new joint and recoupling the pipe the well was run into the hole until buoyancy again became too great. The process was repeated until the entire pipe was inserted.

In other holes, the pipe was run in until buoyancy could no longer be overcome. The threaded coupling at the upper end of the pipe was connected to a hose from the mudpump of the drill rig. Water was pumped from the water truck into the pipe. In this way buoyancy was overcome and, in addition, water circulating out the bottom of the screen helped to flush away obstructions in the hole. The major difficulty of this technique was that the water-filled pipe was very heavy and unwieldy. Great care was needed to arch the pipe high enough to prevent it from breaking.

Once the pipe was inserted and the screen at its proper depth, the pipe was wired to a steel fence post that was driven adjacent to the hole to prevent it from moving, and clean water was pumped down the pipe to clear the screen and the screened interval of mud and cuttings. In most holes, water circulated up the borehole outside the pipe to ground level and circulation was continued until the effluent became relatively free of mud and cuttings.

Gravel packing was perhaps the most difficult part of the procedure to carry out. Several techniques including gravity feed, surge and probe, and circulation through a tremie pipe were used.

In the first six to ten wells installed at Dunn Center, the sand pack was installed by gravity feed. Gravity feeding of sand consisted of pouring sand down the hole in amounts calculated to cover the screen. The amount of sand needed was calculated from the drill bit diameter, the pipe diameter and length of the gravel packed interval. The well was slowly circulated during this procedure to keep the hole open. In some cases changes in circulation behavior indicate the covering of the screen by sand. We assumed all of the sand poured in at ground level reached its destination and that the hole diameter was equal to the bit diameter. Both assumptions proved shaky at best. Experience indicated that the boreholes bridged off quickly as the sand encountered obstructions and in many instances the hole diameter bore little resemblance to the bit diameter. Thus the seals in the first several installations probably did not reach their intended destination. Most of the wells that were gravel packed using this technique were destroyed by lithostatic pressure when the water level was drawn down during well development.

The surge and probe technique, an extension of the gravity feed method, was next used. Water was pumped down the well pipe as sand was poured into the hole. Water flowing up the borehole tended to keep sand from piling up in zones of restricted diameter. At regular intervals a one-inch PVC pipe (tremie pipe) was run down alongside the well pipe to probe the upper surface of the gravel pack. Circulating water and running in the tremie insured proper gravel packing; however, the hole gradually became restricted from sand clinging to the walls resulting in increased drag on the tremie and frequent sticking. Since the tremie was run in and out of the hole by hand, the effort required to gravel pack deep holes was formidable.

The tremie technique that was used

APPENDIX A—Continued
METHODS AND PROCEDURES

for most of the wells utilized a 1-inch PVC schedule 40, tremie pipe to deliver sand to the screened interval. A 12-inch funnel was attached to the tremie pipe using Kam lock quick-connect fittings. A mixture of water and sand was fed into the funnel. Once circulation was established down the tremie pipe, a small but continuous flow of water would continue to transmit sand down the pipe. A steady feed rate permitted flow rates of two to five GPM of sand. Hand feeding of sand was usually necessary to keep the feed rate steady and to prevent large pebbles from entering and plugging the tremie. Care was needed to prevent the build-up of the gravel pack above the lower end of the pipe, which resulted in a plugged tremie.

In some holes, an initial gravity flow of clean water in the tremie could not be attained because of the higher density of muddy water in the borehole. This situation was overcome by slowly feeding sand into the standing water in the tremie. The heavier sand would soon overcome the density difference and initiate downward flow and the operation could proceed. As the top of the gravel pack approached the desired level, the feed of sand was stopped. A period of time was allowed for the sand to settle, then the top of the pack was probed with the tremie. The process was repeated until the top of the sand pack reached the desired height.

Cement grout was used to seal the wells. The grout was initially mixed in a portable mixer and then later in a 55-gallon barrel or a 100-gallon stock tank. The barrel, which proved the most useful technique, was designed and built by the Russell Drilling Company, Harvey, North Dakota. The barrel uses paddles attached to a vertical shaft with a crank to mix the cement and has a hose attached to the side of the barrel at the base. About 35 gallons of water were placed in the barrel; then 4 bags of cement were added while agitating. Gradual addition of cement and agitation are necessary to prevent formation of lumps which plugged the pump or tremie. A centrifugal pump was used to mix cement in the stock tank by pumping the mixture through the pump and back into the tank several times. Thoroughly flushing the pump with clean water after pumping cement and draining at the end of each day are essential to prevent clogging of the pump.

Initially the grout seal was gravity fed by pouring concrete in the hole at ground level, but the necessity of tremiing it down soon became apparent. Since no aggregate was used in the seal, centrifugal pumps were used to pump grout to the desired depth via the tremie pipe. In early wells using both the cement mixer and the stock tank, the pump suction was placed in the cement with the grout barrel. The hose at the base of the barrel was attached to the suction of the pump and the grout was pumped down the tremie.

The holes were filled to ground level by gravity feeding concrete (with aggregate) into them from commercial ready-mix trucks. Since one truckload would fill several holes, wells that were sealed but not backfilled were accumulated until an entire truckload could be used. Although it was difficult to estimate how much concrete a hole of particular depth would require because of the variety of depths at which holes collapsed or bridged off, our experience indicated that seven yards of concrete would fill about 15 holes.

Water hauling and pumping capabilities were necessary for well installation to proceed independently of the drill rig. We used a 750-gallon tandem-wheel trailer and an 850-gallon gasoline-bulk truck to haul water. In many cases, the tank trailer was difficult to work with because it became stuck readily, was difficult to maneuver at certain well sites, and was impossible to pull up short, steep grades with the project pick-up trucks. As a result, the water truck proved more useful. Two-inch and 1½-inch gasoline-operated, self-priming, centrifugal pumps with 50-60 GPM capacity and a variety of two-inch and 1½-inch suction and pressure hoses were used to handle the water. Quick-connect O.P.W. hose connectors

APPENDIX A—Continued
METHODS AND PROCEDURES

were used on all hose joints. All connectors were two-inch size and all hoses had male fittings on both ends. Adapters to permit connection to tremie and well pipe were built up from ordinary pipe fittings.

Two pick-ups and the water truck were used to conduct well installations. The pick-ups were fitted with pipe racks and were used to haul sand, cement, pipe tools, and other supplies. One of the pick-ups was equipped for pulling the water trailer. The water truck was used for hauling sand and cement in addition to water. We found that 2-way radio communications for all vehicles were essential for efficient operations.

Schedule 40 1-inch PVC pipe with weld by threaded adapters was used as a tremie pipe to transport sand and cement to the screened interval. It, like the well pipe, was assembled to the correct length before insertion and run in to the hole. The ends of the threaded adapters used to join the pipe were beveled on a turning lathe to prevent their hanging up on the couplings of the well pipe. Although mud was cleaned from the pipe threads frequently, the threaded adapters had to be sawed off and replaced from time to time. A liquid form of teflon lubricant and a 1-inch pipe tap were found to be very helpful in prolonging thread life.

The principal difficulty that was encountered in the use of the tremie pipe was breakage of the threaded adapters. Considerable care was required to assure that a high enough arch was maintained when inserting and removing the tremie pipe, especially in cold weather. This problem was somewhat alleviated by the use of long tapered fittings supplied by the Certain-Teed plastic company.

Five types of well screens were used at the Dunn Center sites: (1) commercially produced PVC wrapped well screen (2 in. x 5 ft. 12 slot). This screen was used for nearly all the wells; (2) commercially produced PVC wrapped well screen (1¼ in. x 18 in. 12 slot); (3) commercially produced slotted steel pipe (2 in. x 10 ft.). These screens were used in the very deep wells (500 ft.); (4) commercially produced slotted PVC pipe (2 in. x 20 ft.). The 20-foot screens were sawed to the appropriate length for specific wells; (5) slotted PVC pipe, 2-inch-diameter custom made to various lengths by project personnel.

A backwash valve or one-way check valve was installed on the bottom of the 2-inch-diameter screens. The valves allow one-way flow out of the bottom of the piezometer to permit the well to be developed by backwashing. A short (1 ft.) section of pipe was attached to the bottom of the well screen to protect the valve during insertion of the pipe into the borehole.

Most of the wells were constructed of 2-inch PVC pipe, 160 psi strength. In holes deeper than 200 feet, Sch 40-strength PVC pipe was substituted for 160 psi below 200 feet. The very deep wells (500 ft.) were constructed of either 1½-inch or 2-inch Sch 40 steel pipe. In some installations two piezometers were installed in the same borehole. At these sites, 1-inch 200 psi PVC pipe was used for the second piezometer. This procedure was generally unsatisfactory because of the difficulty of assuring a seal between the two wells.

All wells except the 1-inch-diameter pipe are topped with a 2-inch-diameter steel standpipe. The five-foot-long standpipes are attached to the plastic pipe by means of threaded adapter couplings 1 to 3 feet below ground level. This resulted in 2 to 4 feet of steel pipe extending above ground level. A cement backfill effectively anchors the standpipes from livestock damage. Since the 1-inch-diameter wells are installed in boreholes along with 2-inch-diameter wells, the 1-inch plastic pipe is allowed to extend above ground level, protected by the 2-inch steel standpipe.

In some wells, rubber formation packers or shale catchers were used either with or without a gravel pack. They are attached to the well pipe above the screen and form an inverted cone that prevents passage of grout downward. Packers were used only on very deep wells to assure that the screen was isolated even if the gravel pack could not be placed at that depth.

The location of hydrologic sites at the Dunn Center site is shown in figure A.3.1-1.

A.3.2 Procedures Used in the Installation of Potentiometric Observation Wells in the Falkirk, Indian Head, and Center areas

Potentiometric observation wells installed at the Falkirk, Indian Head, Beulah-Hazen, and Center sites were generally less than 125 feet deep. The location of wells of these sites is shown in figures A.3.2-1, -2, and -3. The borehole diameter varied from 5 1/8 inches to 6 inches. The well installation procedure consisted of five steps: (1) screen and pipe assembly; (2) screen and pipe insertion into the borehole; (3) circulation; (4) gravel packing; (5) backfilling.

Plastic PVC pipe was the only type used at these sites. Some installations utilized 1-inch PVC pipe, 200 psi strength. In order to facilitate water sampling, all later installations were constructed with 2-inch PVC pipe, 160 psi strength. Commercially produced steel well screens (1¼ ft. x 18 in. x 12 slot) were used on 1-inch installations. Commercially produced slotted PVC pipe (2 in. x 20 ft.), sawed to the appropriate lengths, was used for all 2-inch installations. Complete assembly of the pipe and screen took place before insertion into the borehole. The pipe was joined together in 20-foot sections with sleeve couplings and glue. The pipe was cut so that, with the screen at its proper depth, the top of the pipe was 2 to 3 feet below ground level. The screen was glued to the lower end of the pipe. A male or female threaded adapter was glued on the upper end of the pipe. The pipe was generally allowed to sit for 30 minutes or longer to permit joints to cure. However, in some cases, individual joints were cured only a few minutes when new joints had to be made during installation, and additional delay would have adversely affected the installation.

The pipe was inserted by arching it up, sometimes over the drill rig or water truck and running it into the hole screen first. Because of the shallow testholes, buoyancy problems generally did not occur. In the few cases where buoyancy did occur, the problem was not severe enough to prevent total insertion of the pipe.

Once the pipe was inserted it was filled with water from the water truck. In most wells, the water circulated up the borehole outside the pipe and flowed out at the ground surface. This circulation was continued until the effluent became relatively free of mud and cuttings.

Gravel packing was accomplished by gravity feeding 5/16-inch-diameter pea-gravel down the hole in amounts calculated to cover the screen. The well is slowly circulated during this procedure with water from the water truck. In almost all cases changes in the circulation behavior of the well indicated the covering of the screen by the pea-gravel.

All holes were filled to ground level by gravity feeding concrete, with sand aggregate, into them from commercial ready-mix trucks. Backfilling was not carried out until an entire truckload could be utilized. Additional water was occasionally added to the ready-mix to maintain a highly fluid mixture. Calculations of the amount of ready-mix required to fill several holes invariably corresponded well with the volumes actually used. Thus, we were quite confident that this method of backfilling was very successful for shallow (less than 125 ft.) wells.

A.3.3 Comparison of Installation Techniques

As previously discussed, various types and sizes of pipe and screen were tested. It is our conclusion that two-inch-diameter pipe and screen is best suited from the standpoints of ease of handling, as well as adaptability to sampling and monitoring techniques. The type and strength of pipe, as discussed previously, varies with

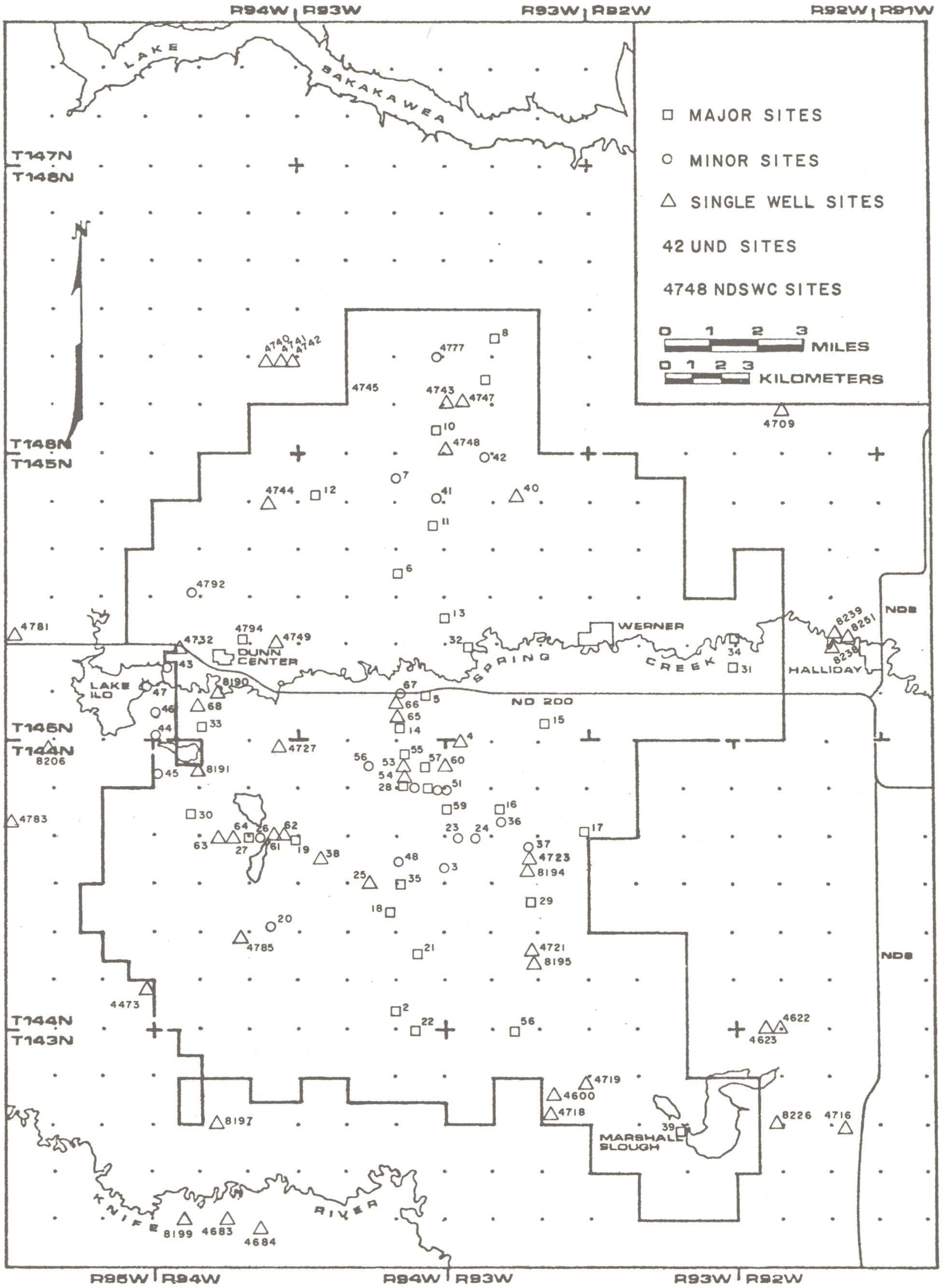


Figure A.3.1-1. Map of the location of hydrological sites in the Dunn Center area.

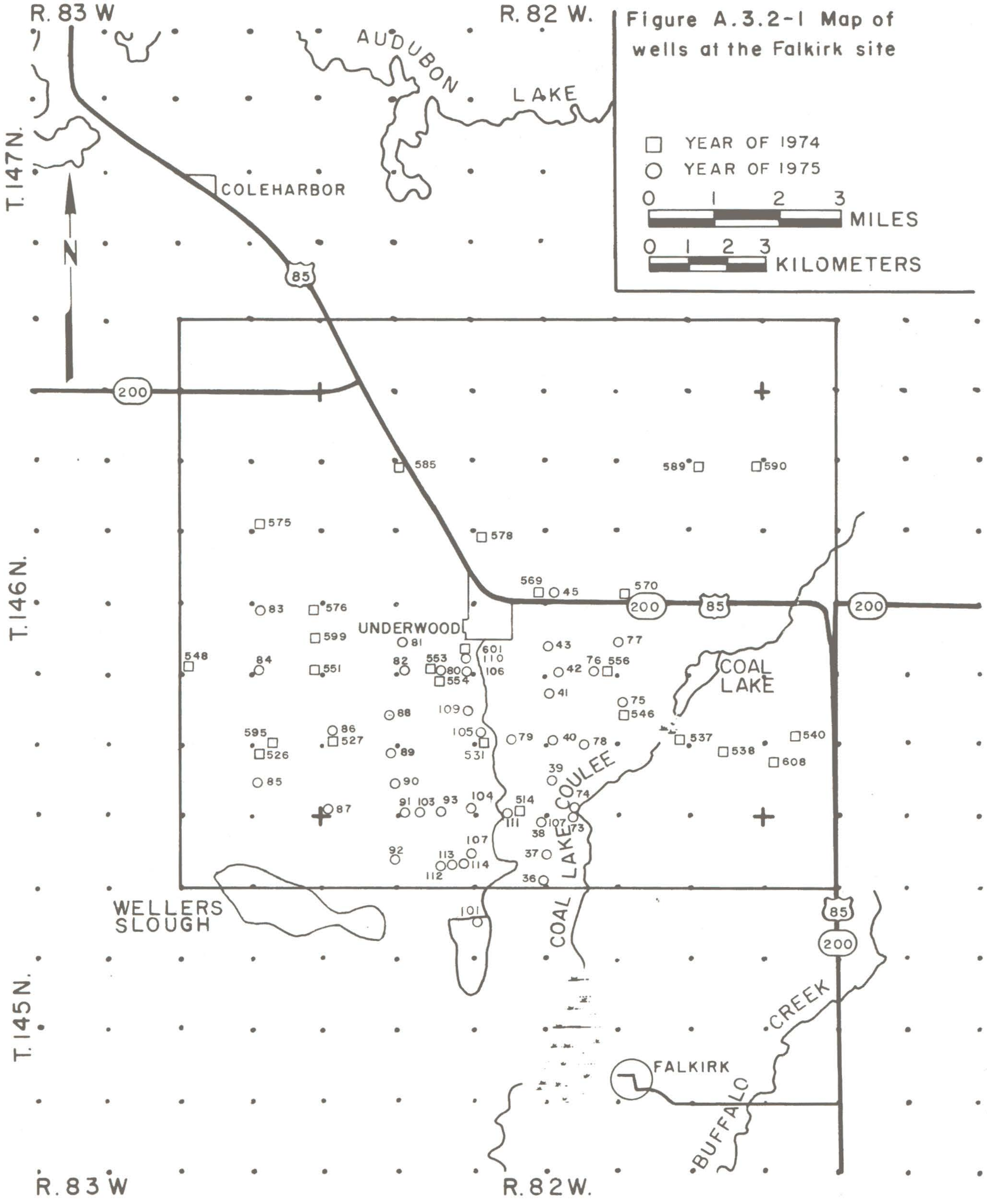


Figure A.3.2-1. Map of wells at the Falkirk site.

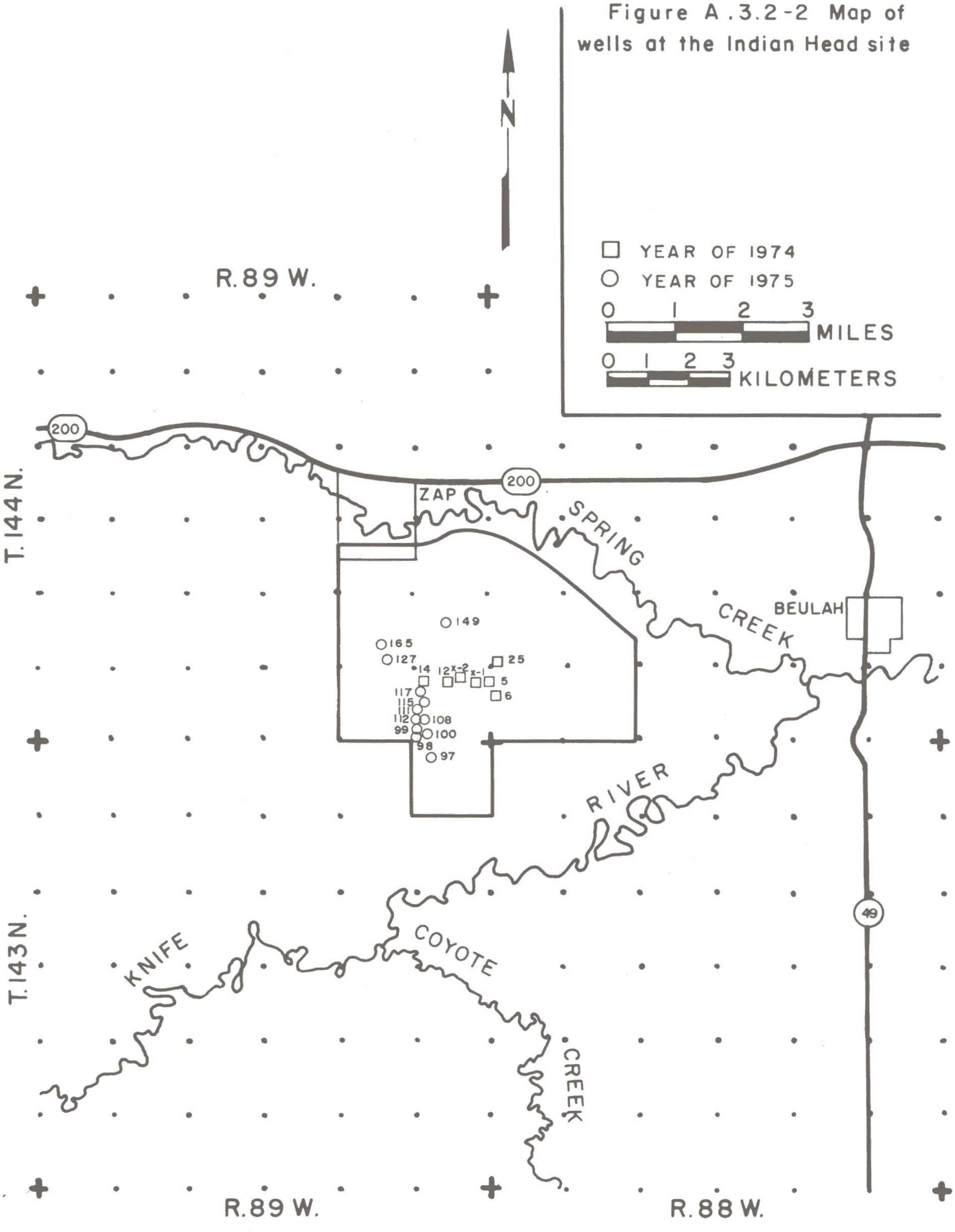


Figure A.3.2-2. Map of wells at the Indian Head site.

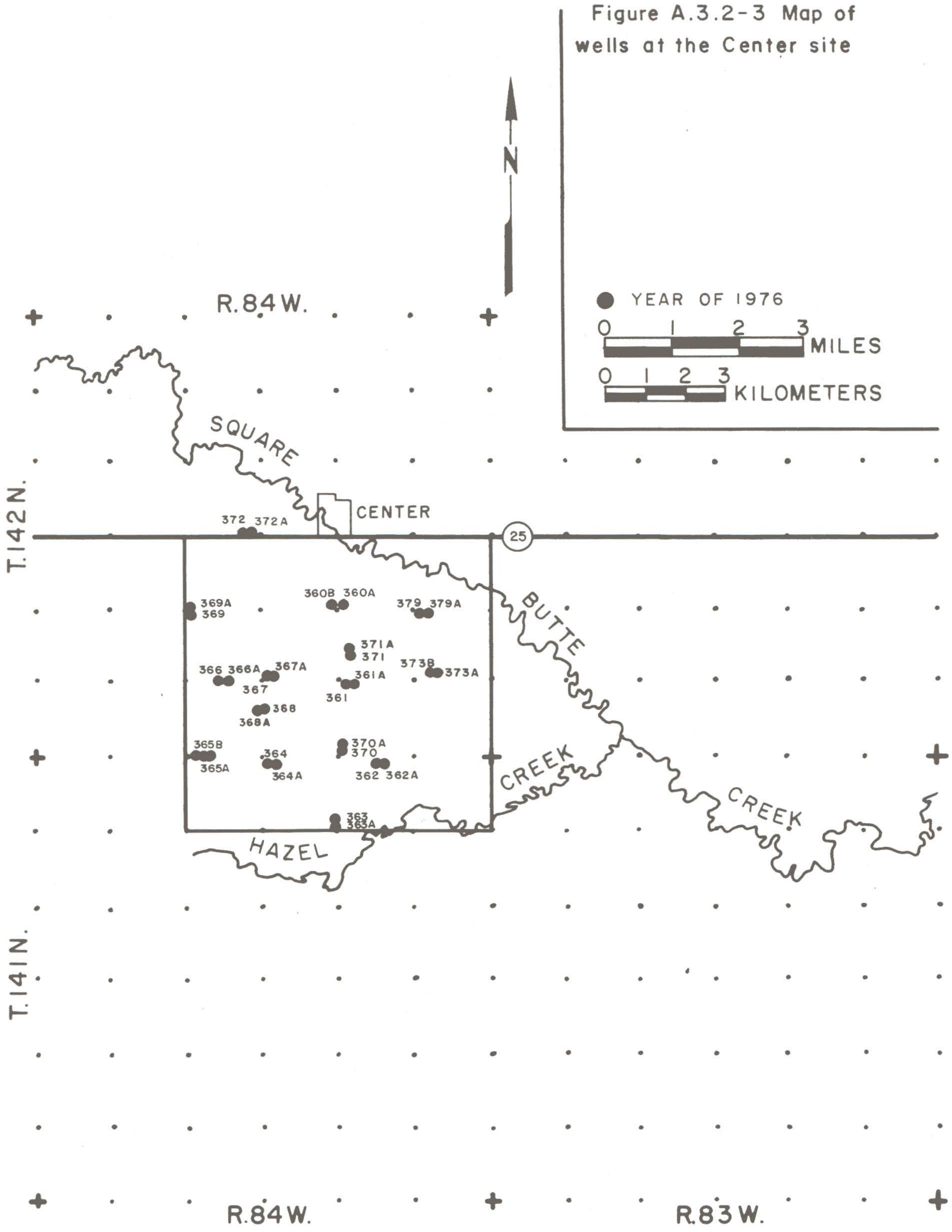


Figure A.3.2-3. Map of wells at the Center site.

APPENDIX A—Continued
METHODS AND PROCEDURES

depth—PVC, 160 psi, 0-350 feet; PVC, Sch 40, 350-500 feet; screens cut from slotted PVC, Sch 40, can be used for less than 500 feet; steel for depths greater than 500 feet.

Various methods of circulation and placement of gravel packs and grouting were also tested. It is our conclusion that depth of the installation is also the major factor affecting installation techniques. From our experiences in the various study sites, we have identified two depth categories, each requiring specific installation techniques. The first category includes installation less than 125 feet in depth; the second includes those greater than 125 feet in depth.

Gravity feeding of gravel pack, as well as grout, appears to be very efficient at depths less than 125 feet except where saturated permeable sediment occurs close to the surface. Pea-gravel (5/16 in.), rather than sand, is recommended if emplacement is by gravity. The sand tends to adhere to the walls of the borehole. Circulation of installations less than 125 feet in depth can generally be accomplished by gravity drain from a water truck.

Tremiing of both gravel pack (sand) and grouting is recommended for installations greater than 125 feet in depth. Circulation at depths greater than 125 feet requires pumping of the fluid. We recommend following procedures as described in section A.3.1.

APPENDIX B
CHARACTERISTICS OF STUDY SITES

B.1 Soils of the Study Sites

The soils in the Falkirk area are subdivided by Omodt, Schroer, and Patterson (1975) into three groups. All the soils are formed on medium-textured glacial till. The first is an Entic Haploboroll. The soil occurs on steeply to strongly sloping positions and the convex crests of knolls and hills (Omodt and others, 1975, p. 30). The soil has a dark-colored A horizon six to eight inches thick underlain by calcareous glacial till. It has 5 percent exchangeable sodium within 60 inches and is non-saline to a depth of five feet. Free lime exceeds 10 percent at six inches. This soil is generally used for grazing (Omodt and others, 1975, p. 30).

The second group of soils are Typic Haploborolls that occur on strongly sloping plane and convex slopes. The average combined thickness of the A and B horizons is 10 to 14 inches. Exchangeable sodium percentages of 5 to 12 percent generally occur within four feet. These soils are non-saline and exceed 10 percent free lime at 10 inches. They are generally used for crops on gentler slopes and for grazing on steeper slopes (Omodt and others, 1975, p. 30-33).

The third group of soils include Pachic Argiborolls and Typic Argiborolls. The combined A and B horizons are thicker than those in the first two groups. They are non-saline to 60 inches. These soils are generally low in exchangeable sodium. All exceed 10 percent free lime within 30 inches. The soils are used predominantly for cropland (Omodt and others, 1975, p. 33).

The soils of the Indian Head area are classified by Omodt, Schroer, and Patterson (1975) as Typic Usthorthents. These soils occur in areas of steeply to strongly sloping terrain. They are common on sharply convex crests of hills and knolls. They are characterized by a thin, dark-colored surface layer overlying calcareous silt beds. These soils have 5 to 12 percent exchangeable sodium within 30 inches of the surface and are generally non-saline to a depth of five feet. Free lime exceeds 10 percent within 10 inches. These soils are predominantly used for grazing (Omodt and others, 1975, p. 14).

The soils of the Beulah-Hazen site are subdivided by Omodt, Schroer, and Patterson (1975) into two major associations. The first of these groups are Typic Usthorthents. These soils are generally restricted to the immediate area of the trench, where glacial sediment is lacking.

These soils occur in areas of steeply sloping terrain and are characterized by 5 to 12 percent exchangeable sodium within 30 inches of the surface. In addition, they are generally non-saline to a depth of five feet and contain free lime in excess of 10 percent within 10 inches. These soils are predominantly used for grazing (Omodt and others, 1975, p. 14).

The second group of soils includes all those formed on glacial till. These soils include Entic Haploborolls, Typic Haploborolls, Pachic Argiborolls, and Typic Argiborolls and have characteristics that are similar to the same soils at the Falkirk site.

The soils in the Dunn Center area are subdivided by Omodt, Schroer, and Patterson (1975) into three groups. The first group of soils, which is limited to the northern and southwestern part of the area (Omodt and others, 1975, p. 16), consists of Regosols that are formed on soft, calcareous silt beds of the Sentinel Butte Formation (Omodt and others, 1975, p. 14) and on calcareous till of the Coleharbor Formation. These soils have a thin, dark-colored surface layer overlying calcareous silt. These soils are calcareous at the surface and contain more than 10 percent free lime within 10 inches. Where these soils are developed on the Sentinel Butte Formation, they contain more than 10 percent sodium within three feet of the surface. The soils in this group are generally used for grazing (Omodt and others, 1975, p. 14).

The second group of soils are Typic Haploborolls that are developed on soft sand and sandstone beds of the Sentinel

Butte Formation. These soils occur through the central part of the Dunn Center area. These soils are characterized by thicker A horizons than those in the first group. They are non-saline and low in exchangeable sodium. They are generally used for crops where slopes are less than six percent and for grazing on steeper slopes (Omodt and others, 1975, p. 24-25).

The third group of soils include Leptic Natriborolls, Typic Natriborolls, and Glossic Natriborolls that are restricted to the south-central part of the Dunn Center area. They are characterized by a sodic clay pan and an A horizon about nine to 14 inches thick. These soils are saline and have exchangeable sodium content of more than 12 percent within 48 inches of the surface. These soils are generally used for grazing although some areas are in crop where they are associated with more favorable soils (Omodt and others, 1975, p. 27).

B.2 Vegetation of the Study Sites

Approximately 81 percent of the Falkirk area is cropland, 14 percent range and pastureland, and 4 percent wetland (U.S. Dept. of the Interior, 1976, p. 35). The following discussion of the vegetation in the wetland, range, and pastureland is extracted nearly verbatim from the environmental analysis record for the Falkirk area (U.S. Dept. of the Interior, 1976, p. 17-20).

"Approximately 900 acres of wetlands were identified in September 1975 by the BLM (from 1966 vintage SCS aerial photos) overlying coal inside the Falkirk mine "take-line." This includes wetland and wetland-meadow range sites. The wetland range is characterized by poorly drained, saturated soils (often with standing water during part of the year) and a vegetative cover of sedges, rushes, marshgrasses, and hydrophytic forbs. In drier years this site may be cut for hay. The wet meadow range is typified by poorly drained soils of shallow depressions and a vegetative cover of sedges, reedgrass, cordgrass, switchgrass, bluegrass, and some hydro-mesophytic forbs.

"This region of the Coteau Slope has been identified as the Wheatgrass-Needlegrass (*Agropyron-Stipa*) physiognomic type in the grassland vegetation formation. This area has been classified as belonging to the mid-grass prairie biome, or ecosystem. The dominant species of this physiognomic type include western wheatgrass, blue grama, needle-and-thread, and green needlegrass. These species would be expected to prevail as "climax" (potential) vegetation in this area under "natural" conditions. However, McLean County, including the Underwood vicinity, is highly agricultural. Within the coal "take-line" of the Falkirk mine, 81 percent of the surface is cultivated and managed as cropland. Only 18 percent (estimate) of the surface lands over the coal "take-line" remain as undisturbed prairie lands (including wetlands). What little prairie still exists is usually found along the edges of sloughs, fencelines, and in limited areas too rough for cultivation.

No specific information is available concerning the vegetation of the Indian Head site. The study site consists predominantly of prairie communities. The remainder of the site consists largely of agricultural communities. Wetlands and forest constitute a very small portion of the biotic assemblages.

Nearly all the land suitable for cultivation has been developed. The major crops are spring wheat and oats. About 25 percent of the cropland is in summer fallow.

The following discussion of the vegetation in the vicinity of the Beulah-Hazen site is extracted nearly verbatim from the environmental impact report for the study area (Woodward-Clyde Consultants, 1975, p. 2-67—2-68).

"The study area lies within the Missouri Slope Vegetation Zone of North Dakota. Due to its location near the northeastern boundary of this zone, plant communities may be expected to reflect characteristics of the Coteau Vegetation Zone.

APPENDIX B—Continued
CHARACTERISTICS OF STUDY SITES

"Approximately 59 percent of the area under investigation consists of agricultural communities. The agricultural communities represent a widespread disturbance community created and perpetuated by man at the expense of the native prairie grasslands. Agriculture has modified the former open-country aspect of the grasslands through the establishment of shelterbelts, windbreaks, and the presence of farm-related structures. Problems for wildlife associated with agricultural activities include erosion, introduction of plant pests, and loss or degradation of wildlife habitat.

"Almost all land suitable for cultivation is developed; and, in most cases, slopes are plowed to the steepest point where machinery can operate or to a point where the depth of the topsoil (soil horizon A) is less than plow depth.

"Approximately 72 percent of the agricultural community is presently used as cropland. Major crops in 1974 were spring wheat (45 percent), oats (22 percent) and corn (5 percent). Small acreages of barley, flax, and sunflowers were present. Approximately 28 percent of the cropland acreage was in summer fallow.

"The usual stages of small grain crop culture include bare fields, sprout growth, mature grain, and stubble fields following harvest. Post-harvest grazing and/or tillage are common practices.

"Domestic haylands accounted for 26 percent of the agricultural community in 1974. Planted pastures are included in this habitat type, since the plant species sown for this pupose are similar, and sometimes both land uses are practiced on the same acreage. Hay species commonly planted include alfalfa, sweetclover, smooth brome, and crested wheatgrass. In addition, Kentucky bluegrass, another introduced species, is commonly encountered as a volunteer in planted hayfields.

"Narrow strips of weedy habitat usually border croplands, hayfields, tracts of grazed prairie, fence rows, section lines, roads and railroad rights-of-way. An association of native prairie grasses, native forbs, hay grasses, and introduced coarse weeds are common inhabitants of these disturbed sites, with the occasional occurrence of native trees or shrubs.

"Farmsteads vary in size from one to ten acres and represent a community complex of several distinct niches distributed over a relatively limited area. The farmstead complex usually includes a residence, barns, and associated structures; lawns with ornamental trees; and garden plots. Approximately one percent of the agricultural community is classified as farmsteads (abandoned farmsteads are included in this percentage).

"Approximately 40 percent of the area under investigation consists of prairie communities. The prairie community in the study area was classified into 13 range site categories based on available soil information, field inspection, and vegetation sampling. These range sites represent a wide spectrum of climax plant communities."

The thirteen range sites in the study area include: subirrigated, overflow, saline lowland, closed depression, sandy, silty, clayey, thin upland, shallow, clay pan, shallow to gravel, very shallow, and thin clay pan.

"Wetland communities occupy less than one percent of the area under consideration. Natural woody plant communities in this area can best be classified as prairie thickets. A considerable number of tree plantings also are present. Approximately 0.7 percent of the study area is occupied by woody vegetation over six feet in height."

Approximately 32 percent of the Dunn Center area is cropland, 67 percent range and pastureland, and one percent is marshland (Whitman, W. C., and others, 1974, p. 18). The following discussion of the vegetation in the range and pastureland is extracted nearly verbatim from Whitman and others (1974, p 22-23).

"The principal natural vegetation type of Dunn County is the mixed grass prairie dominated by grasses of medium height such as western wheatgrass (*Agropyron* *smithii*), needle-and-thread (*Stipa comata*), prairie Junegrass (*Koeleria cristata*), and green needle-grass (*Stipa viridula*). Associated with these species are a number of shorter grasses and sedges including particularly blue grama grass (*Bouteloua gracilis*), Sandberg bluegrass (*Poa secunda*), threadleaf sedge (*Carex filifolia*), and needleleaf sedge (*Carex eleocharis*). This type is of particular importance because it is the basic resource of the extensive range grazing enterprise of the county.

"The actual composition of the grasslands, while fairly uniform in the broad sense, is actually highly variable in relation to specific site characteristics. Species composition varies with slope, soil texture, exposure, drainage and soil moisture relations, salt influences, and a host of other factors, not the least of which is grazing itself. Where soil moisture and exposure influences are especially favorable, small developments of the tall grass prairie association may occur, even though the type is normally potential climax only in the extreme eastern part of the state.

"The woodland vegetation of the county is rather distinctive, although the area occupied by woodlands is relatively small in comparison to the extensive grasslands. The woodlands are very much site related. The principal woodland types which can be distinguished are the cottonwood forests in the larger stream valleys, the juniper—slope type associated with the steep badland slopes with northwest to easterly exposures, the so-called upland hardwood draws primarily dominated by green ash, and the sagebrush shrub type of the stream terraces. Various other shrub complexes are of some importance, of which the buffaloberry-chokecherry thickets might be considered a typical example. A rather unique oak woodland is developed on parts of the Killdeer Mountains.

"The wetland vegetation of the county as a whole is limited in extent, but is of singular importance in relation to wildlife. This is especially true where ponded areas provide some open water and the rushes, sedges, and taller marsh grasses provide wildlife cover."

B.3 Climate

Climatic data for the Falkirk area have been compiled in the environmental analysis record for the area (U.S. Dept. of the Interior, 1976, p. 8-11). The following discussion has been extracted nearly verbatim from that publication.

"Day light length in the Falkirk area ranges from nine hours in December to 16 hours in June. The sun angles are much higher in the summer than winter, producing much more solar radiation and contribution to large seasonal temperature extremes. In 1974, the average daily temperature ranged from 8.8° F in January to 73.2° F in July at Underwood (U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, NOAA). The highest temperature at Underwood that same year was 98° F on July 18, 1974. The lowest was -32° F on January 10, 1974. Temperatures of 100° F and over are not uncommon and temperatures less than -32° F are also possible at this location. The most rapid warming occurs during April. In 1974 the average daily temperature went from 25.5° F in March to 42.4° F in April. Although the average daily temperature is above freezing the frequency of freezing temperatures during this month is still high.

"The average length of frost free periods in North Dakota are from 110 days to 130 days. The topography of the area has much to do with when the first frost occurs. Cool air flows downhill and will collect in the depressions resulting in an earlier frost there than adjacent high ground. It would be expected that the area in and around Weller slough will have its first frost prior to the areas adjacent to it as a result of its lower elevation."

Soil temperature and frost penetration data in North Dakota are scarce. Specific information for the Falkirk-Underwood area is unavailable. In Bismarck, the average frost depth is 4.5 feet and the maximum is

APPENDIX B—Continued
CHARACTERISTICS OF STUDY SITES

7 feet. In Minot, the average is four feet and the maximum is 6.5 feet. Bismarck is approximately 50 miles south of the study area, and Minot is approximately 50 miles north. It can be expected that the frost depth information for the study area would be similar to that in these locations. It must be kept in mind that freezing depth of a soil depends mainly on the winter air temperature; the soil itself, including moisture content; type of soil, and presence or absence of vegetative cover; and the presence or absence, depth, and density of snow cover.

"Precipitation averages over 16 inches a year for the Bismarck area (NOAA). The annual rainfall at Underwood was 14.95 inches in 1974. More than 75 percent of this amount falls from April through September and more than 50 percent falls in May, June, and July. Most summer rainfall occurs as thunderstorms in the late afternoons and evenings. Winter precipitation is light and nearly always occurs as snow. On the average, two blizzards occur each winter.

"Mean wind speeds at Bismarck vary from 9.8 MPH in December to 12.8 MPH in April. The average daily variation is quite small. The yearly average is 10.8 MPH. The mean daily maximums run from 54 MPH in January to 72 MPH in July and August. The winds are primarily west-northwest except in the spring and summer, they then shift to south-southeast and east."

Hailstorms are estimated to occur in the Underwood area between 40 and 50 days per year. Most frequently, hailstorms appear in the afternoon and early evenings in July.

Climatic data for the Beulah-Hazen area have been compiled in the environmental impact report for the area (Woodward-Clyde Consultants, 1975). These data are also applicable to the Indian Head site. The following discussion has been extracted nearly verbatim from the publication.

"The climate in the vicinity of the study sites is semiarid-continental. The summers are generally cool with only a few hot, humid days, and the winters are quite cold and long. Blizzards and cold waves can be expected in any winter. Likewise, chinook winds (warm, dry, downsloping winds from the mountains) may also be expected on several days during the winter. Large annual and diurnal ranges of temperature are typical in the area.

"The mean annual temperature for Bismarck is 42.2° F, varying from 9.9° F in January to 71.7° F in July. The highest temperature on record at the airport (1955-1964) was 108° F and the lowest -43° F. The maximum daily temperature is greater than 100° F about once a year and below 0° F about seven days a year. Minimum temperatures are below 0° F about 53 days per year.

"Precipitation in the area is generally light, averaging 17.20 inches annually at Beulah, seven miles from the Beulah-Hazen site and five miles from the Indian Head site. Half of the annual precipitation (7.56 inches) falls during May, June, and July and results primarily from thunderstorms. Snowfall is moderate (39.1 inches annually) but has occurred in every month except July and August. Blizzard conditions occur about once a year.

"Annually the prevailing wind direction is from the west-northwest. From May to August, easterly winds occur with the greatest frequency. The annual average wind speed is 11.1 miles per hour. Fastest average wind speeds occur with northwest winds (15.2 miles per hour) and the slowest from the west-southwest (7.5 miles per hour). Winds are strongest in April with a mean speed of 13.3 miles per hour and slowest in July (9.9 miles per hour). Calms occur during 5.1 percent of the year. The greatest frequency of calms occurs in October (6.1 percent) and the least in April (3.3 percent)."

Climatic data for the Dunn Center area have been compiled by Ramirez and others (1976). The following discussion has been extracted nearly verbatim from their work.

"Air temperatures in Dunn County cover a wide range because of the typical

APPENDIX B—Continued
CHARACTERISTICS OF STUDY SITES

continental climate and the more northerly location of the area on the North American continent (47° to 48° N Latitude). The mean annual temperature across Dunn County varies from 40° to 42° F. The variation of temperature in the area is quite large with monthly normals ranging from 8.6° F in January to 68.5° F in July. The daily temperature extremes show a normal daily minimum in January of minus 2.7° F while the normal daily maximum is 82.5° F in July.

"In Dunn County, minimum daily temperatures rise above freezing in only 120 to 125 days (33 to 34%) of the year. This means that in about two-thirds of the year, minimum temperatures are at or below 32° F. In the average fall season, the first freeze is expected about September 16, while the mean date of the last freeze in the spring occurs about May 20, on the average.

"As late as the last week in May, there is about a 30 to 35 percent probability of frost in Dunn County, and as early as mid-September there is more than a 50 percent likelihood that freezing temperatures can occur in the mornings.

"Maximum daily temperatures exceed 90° F in about 22 to 24 days of the year in Dunn County. During the hottest days of the year from the last week in July through mid-August, there is at least 80 to 85 percent probability that on one day of the week the maximum temperature will be over 90° F. The highest temperature recorded at Dunn Center was 110° F in the month of August.

"Throughout the year on the average, Dunn County receives about 15 to 16 inches of precipitation mostly in the form of rain. Despite this low precipitation amount which puts the county under semi-arid climatic classification, the area's rangeland and small grain agriculture benefits from the fact that over 75 percent of the annual precipitation falls during the growing season. Precipitation in the spring is usually light and increases until late June before declining through the rest of the year.

"During the last 55 years, the annual precipitation extreme at Dunn Center includes a high of more than 20 inches in 1941, while in 1934 only about six inches was recorded.

"The probabilities of receiving no rain at any specified week of the year are almost always less than 50 percent. This means that although total amounts of rain in Dunn County are small, rain occurrences are frequent and usually come from isolated small rainstorms.

"Approximately 25 percent of the annual precipitation in Dunn County falls as snow. Over the winter, it is expected that at least six inches of snow are on the ground 30 to 40 days of the year. The first inch of accumulation may be expected around the middle of December on the average, while the last inch may occur as late as the middle of March. These dates correspond to average conditions when at least one inch of snow is still accumulated on the ground.

"In Dunn County, about 45 percent of the days are cloudy (80 to 90% cloud cover) while 25 percent of the days of the year are clear (0 to 3% cloud cover). Cloudier days occur in early fall through late spring, whereas relatively clear days are uniformly distributed in occurrence from June through October. July and August have relatively more clear days than other periods of the year.

"In the attempt to estimate the prevailing wind behavior in Dunn County over a period of years, the data from four surrounding wind stations (Bismarck, Williston, Dickinson, and Minot) were combined. The prevailing wind directions by month show that northwesterlies prevail during fall and winter from September through March. In the spring and summer, southeasterly winds prevail in Dunn County. Average wind speeds vary from 8 to 13 miles per hour (mph) with the highest speed recorded at 72 mph. Wind observations obtained during the field monitoring program in August through November, 1975, did not show significant deviations from the corresponding

APPENDIX B—Continued
CHARACTERISTICS OF STUDY SITES

interpolated averages of longer term data from Bismarck, Dickinson, Williston, and Minot.

"Most of the summer precipitation over Dunn County is associated with severe storm activity (i.e., thunderstorms). In northwest North Dakota about 20-30 thunderstorm days occur each year with peak activity in July when eight to ten days of the month have some thunderstorm activity.

"Tornadoes are rare occurrences in central-western North Dakota. During the period 1940-1970, Dunn Center reported three tornado occurrences and nearby Stark and Golden Valley Counties reported one and two occurrences, respectively, during the same 31-year period. It must be pointed out, however, that reports of severe storms such as tornadoes are a less reliable statistic, especially in sparsely populated areas where tornadoes can touch down without being observed. Nonetheless, it is proper to note that tornadoes and their associated damaging forces do occur in Dunn County.

"Blizzards occur when masses of extremely cold air from Canada move southward accompanied by gale-force winds and blowing snow. Drifting snow becomes severe and transportation may become impossible. The relatively flat terrain of North Dakota makes this area very susceptible to these storms, although they usually occur an average of only several times per year. Sub-zero temperatures commonly persist for several days after these storms pass."

APPENDIX C
DETAILED STRATIGRAPHY

Geologic data was collected at each of the five study sites using the procedures outlined in appendix A. The density of control points varied among sites as does the complexity of the geologic setting. The same sedimentological pattern was found at each site. The Sentinel Butte Formation consists of a series of sedimentary cycles each bounded above and below by laterally continuous lignites that underlie the entire site. The complexity of the overburden varies from one cycle throughout most of the Falkirk site to four cycles in parts of the Dunn Center site.

In order to describe the material making up the interval of clastic sediment that lies above each lignite, a uniform system of nomenclature was adopted. The lowest lignite to be mined at each site was designated as unit 100. The overlying major lignite was named unit 200, and so on. The clastic sediment between each major lignite was subdivided into units on the basis of lithology and rough stratigraphic position. These units were named in ascending stratigraphic order using a three-digit number related to the underlying lignite. For example, unit 110 would be a unit that rested on the lowest lignite; unit 240 would be a unit lying on other clastic sediment above the second-deepest lignite. The nomenclature for a given site is unique to that site, that is, there was no attempt to generalize the terminology among the sites.

It should be noted that the data summarized here represent additional data collected on testholes that were drilled for exploration or development of lignite. Thus, the detailed stratigraphy of the overburden, which is the essential basis for understanding the groundwater regime of a mine site and for planning acceptable, and successful reclamation practices, can be determined without considerable additional drilling and logging.

C.1 Detailed Stratigraphy of the Falkirk Area

In the Falkirk area the Sentinel Butte Formation is characterized by three major, laterally continuous, lignite beds. The sediment between these lignites are of highly variable lithologic character; any specific lithologic unit can rarely be traced for more than a few miles.

The contact between the Bullion Creek and the Sentinel Butte Formations, as identified by Hemish (1975), lies at the top of a clay of variable thickness which immediately overlies the TR bed. The lowest major lignite bed in the Sentinel Butte Formation, the C bed of Hemish (1975) is from 5 to 25 feet above the TR bed. In some places a sand bed occurs between these two beds. The B bed of Hemish (1975) is separated from the C bed by as much as 65 feet. Two or three distinct sand units occur in this interval. They are generally separated by a lignitic silt or clay. The uppermost sand unit varies in thickness from 5 to 20 feet and occurs throughout the Falkirk site. The B bed is separated from the Hagel bed by as little as 1.5 feet and as much as 59 feet (pl. C.1-1). The interval is generally about 20 feet thick. The Hagel bed is overlain by a lenticular sand body that ranges in thickness from a few feet to as much as 100 feet (pl. C.1-1). In some parts of the area, silt and clay overlying the Hagel bed is as much as 60 or 80 feet thick where the sand is thin or absent (pl. C.1-1). Two or three minor lignite beds occur in this fine-grained unit. A fourth major lignite overlies the thick lenticular sand and associated fine-grained sediments. This bed is present in a very limited area in the northeastern portion of the study area.

The intervals above the B bed have been subdivided into lithologic units using a three-digit identification system. The B bed is 100; the Hagel bed is 200. The units above either the Hagel bed or B bed are designated in ascending stratigraphic order using a three-digit number corresponding to the underlying lignite. All post-Tertiary sediment have been included within a 500's series. Plate C.1-2 is a cross section which illustrates this system.

APPENDIX C—Continued
DETAILED STRATIGRAPHY

C.2 Detailed Stratigraphy of the Indian Head Area

The only stratigraphic units of concern at the Indian Head site are the Sentinel Butte Formation and the Coleharbor Formation.

The Sentinel Butte Formation in the vicinity of the Indian Head Mine is characterized by a series of thin (20-40 ft.) cyclic intervals. Each cycle is bounded both above and below by a lignite or carbonaceous zone. The sediments between the various lignites and carbonaceous zones are of variable thickness and lithology.

Plate C.2-1 is a cross section through a portion of the Indian Head site. At the base of the section is a thick lignite, the Beulah-Zap bed. This is the bed that is presently being mined. As can be seen from the cross section, as many as four or five cyclic intervals are present in certain testholes above the Beulah-Zap bed.

One of the striking characteristics of these sediments is the traceability of even the thinnest "lignite." Although certain lignites grade laterally into carbonaceous clays in some places, they rarely drop from the sequence. Area-wide correlation indicates that the thin lignites often can be traced for tens of miles. Specific lithologic units between the lignites, with the exception of certain sand units are seldom traceable for more than a couple of miles.

The Coleharbor Formation is represented by a few patches of thin pebble loam (till) on upland areas, by scattered occurrences of wind-blown silt (loess), and by interbedded till and valley-fill sediment in partly buried valleys. The major occurrence of valley-fill sediment, as much as 40 feet thick, is in a partially filled valley that crosses section 36 from the northwest to the south. The fill in this valley is predominantly silt and sand, which overlies three to five feet of till. The till unit in places lies within five feet of the Beulah-Zap bed.

Each of the intervals above the Beulah-Zap bed has been subdivided into lithologic units following the procedure outlined above. The Beulah-Zap bed is 100, the next overlying lignite is 200, and so on. All post-Tertiary sediment has been included in a 500's series (pl.C.2-2).

C.3 Detailed Stratigraphy of the Beulah-Hazen Area

The stratigraphic units of major concern at the Beulah-Hazen site are the Sentinel Butte Formation and the Coleharbor Formation.

The exposed portion of the Sentinel Butte Formation in the study area is characterized by thin cyclic lignite-bounded intervals as described at the Indian Head site (sec. C.2). Plate C.3-1 is a cross section which runs from the Indian Head site, six miles to the south-southwest, through the Beulah-Hazen area. The target lignite in the Beulah-Hazen area is the Beulah-Zap bed.

Sediments of the Coleharbor Formation are more widespread in the Beulah-Hazen area than at the Indian Head site. Pebble loam (till), of variable thickness, covers much of the upland areas. Two or more tills are present in some localities. The tills are generally quite sandy and contain numerous pebbles of highly variable composition. Valley-fill materials within the Beulah-Hazen attain a maximum thickness of greater than 200 feet. These sediments consist of interbedded till, outwash sand and gravel, and lacustrine silt and clay. At least two loess units are present in the Beulah-Hazen area. These are of highly variable thickness ranging from 0 to 5 feet and, where both are present, are separated by a thin paleosol. The coded lithologic cross section is shown in plate C.3-2.

C.4 Detailed Stratigraphy of the Dunn Center Area

In the Dunn Center area, the Sentinel Butte Formation is subdivided into ten intervals by named lignite beds. 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 (pls. C.4-1 and -2). These units have been extended throughout the project area where feasible. The Dunn Center bed (Beulah-Zap bed) has been designated as unit 100; the A-lignite is unit 200; the B-lignite is unit 300; and the C-lignite is unit 400.

C.4.1 C-lignite Interval

The C-interval is the highest unit recognized in the Sentinel Butte Formation in the Dunn Center area. It extends from the base of the Golden Valley Formation to the base of the C-lignite (fig. C.4.1-1). The upper contact of the interval has not been seen either in exposures or drill holes. The C-lignite, and, therefore, the C-interval occurs in four places in Mine Area No. 1. The largest area occupies two to three square miles beneath the upland in the south central part of the mine area (pl. C.4.1-1). The C-lignite appears to extend southward beyond Mine Area No. 1 in the southeastern part of this upland. The second large area is about 1.5 sq. miles around Horse Nose Butte in the east-central part of Mine Area No. 1 (pl. C.4.1-1). The C-lignite probably underlies all of Horse Nose Butte to the east of the mine area. An area of about 2 sq. miles in secs 17, 18, 19, and 20, T144N, R94W is underlain by the C-lignite. The only other known occurrence of the C-interval in the Dunn Center area is an area of a few acres beneath the isolated knob between secs 11 and 14, T144N, R94W in the center of Mine Area No. 1 (pl. C.4.1-1).

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 (pl. C.4.1-1).

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, interpretation of the interval is difficult and subdivision of the interval was not attempted. Most of the preserved C-interval appears to be upper levee sediment that consists of alternating beds of sand and silt. Nearly all of the interval in the area around Horse Nose Butte appears to be composed of this facies, although channel sediment is present along the eastern edge of this area. In the western part of its occurrence in secs 11, 14, and 15, the interval contains the base of what may have been a large channel. The remainder of the interval in secs 22, 23, and 24, T144N, R94W appears to consist predominantly of silt and clay with only minor sand. This sediment is believed to be mid- to lower-levee sediment. No flood-basin sediment was definitely identified in the C-interval in the Dunn Center area.

In two places, in T144N, R93W, the C-lignite thins to a depositional edge against levee and channel sediment. North of Horse Nose Butte in secs 10, 15, and 16, a narrow-meandering channel no more than ¼ mile wide replaces the C-lignite. Sand of this channel overlies the C-lignite elsewhere in sec 10. The second area of channel sediment that is laterally equivalent to the C-lignite is in secs 19 and 20. In this area the north-south-trending channel, or meander belt, is about one mile wide (pl. C.4.1-1).

C.4.2 B-lignite Interval

The B-lignite interval extends from the base of the C-lignite to the base of the B-lignite (fig. C.4.1-1). 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) (pls. C.4.1-1, C.4-1 and -2). In most

COMPANY: UND ENGINEERING EXPERIMENT STATION
BORE HOLE: 75-17-2
LOCATION: SE ¼ SE ¼ SE ¼ SEC 9, T 144 N, R 93 W
ELEVATION: G.L. 2286.3 FEET

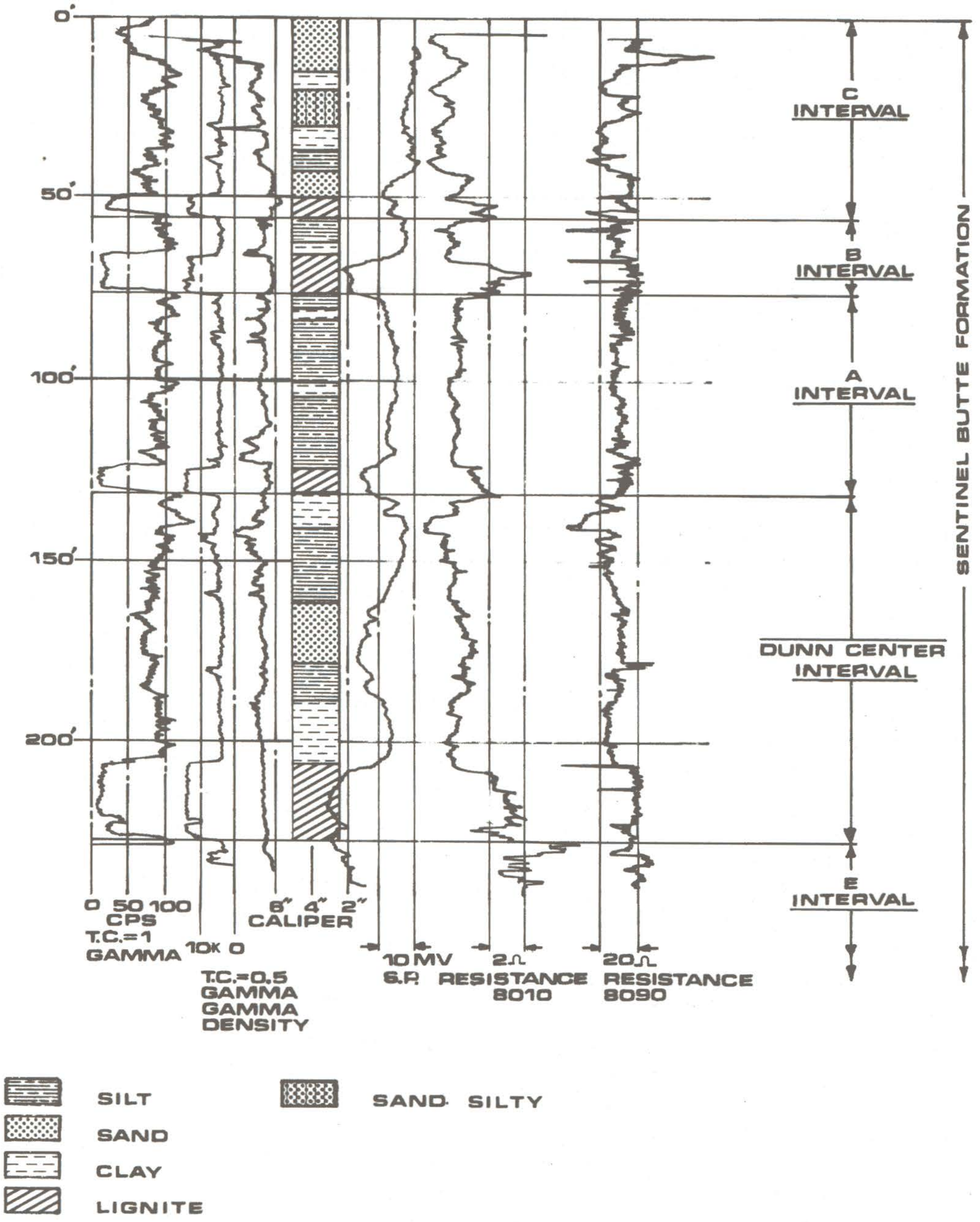


Figure C.4.1-1. Geophysical log of the upper part of the Sentinel Butte Formation.

places, the C-lignite rests on this silt, but, in some places, a second unit of sand (unit 330) overlies the silt. Along the cross sections of Plates C.4-1 and -2 the B-interval has a mean thickness of 31 feet, of which 9.4 feet is the B-lignite.

C.4.3 A-lignite Interval

The A-lignite interval extends from the base of the B-lignite to the base of the A-lignite (fig. C.4.1-1). 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 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 (pls. C.4-1 and -2).

The greatest thickness of the A-interval consists of a northwest-southeast trending channel and levee complex in the south-central part of Mine Area No. 1 (pl. C.4.1-1). A second narrow channel complex occupies the central part of sec 33, T145N, R93W, in the northern part of Mine Area No. 1. The A-lignite thins to a depositional edge against a thick sand body in the Dunn Center interval that lies along the western and southwestern edges of Mine Area No. 1.

In the Mine Area No. 1, the A-interval varies in thickness from about 40 to about 110 feet. The mean thickness is about 70 feet.

C.4.4 Dunn Center Interval

The Dunn Center interval extends from the base of the A-lignite to the base of the Dunn Center bed (fig. C.4.1-1). The uneroded thickness of the Dunn Center interval is extremely variable, ranging from about five feet to about 140 feet.

Throughout the central part of Mine Area No. 1 and from place to place along the eastern, western, and northern edges, the Dunn Center bed is overlain by a layer of clay, silty clay, and clayey silt that ranges in thickness from about five to as much as 20 feet. This layer, unit 110, consists of the fine-grained flood-basin mud that was spread over the accumulating vegetation by the bordering rivers as they advanced out into the coal swamp. It is not clear whether this change in conditions reflects lateral migration of a large meandering channel, an influx of sediment from the west, or a change in base level brought about by a rising sea level to the east. The streams that ended formation of the Dunn Center bed deposited channel sediment in the form of sand and silty sand along the western, northern, and eastern edges of Mine Area No. 1. This sediment, unit 120, which is as much as 70 feet thick, generally rests on unit 110 but, in some places, rests directly on the Dunn Center bed. Although the channel pattern has not been worked out, individual channels appear to be from ¼ to ½ mile wide. The channel sediment of unit 120 grades laterally into sandy silt of unit 123, which in turn grades into silt, silty clay, and clayey silt of unit 127. Unit 123 and part of 127 represent levee sediment along the edges of the streams. The finer grained sediment in unit 127 includes sediment of the outer levees and flood basins. A thin bed of lignite that is as much as 4 feet thick and occupies an area of about 0.5 sq. mile occurs in units 123 and 127 in the southwestern part of Mine Area No. 1. This suggests that lignite continued to form during deposition of the Dunn Center interval where conditions were favorable. Nearly everywhere a thin bed of silt and clay overlies the coarser sediment of the channel and levee facies. This bed, unit 130, represents quiet water sediment that accumulated between the cessation of stream sedimentation and the return to the coal swamp conditions that resulted in the formation of the A-lignite.

The Dunn Center bed varies in thickness from less than 10 to more than 50 feet. In the western part of the Dunn Center area, a wedge of silt, which in places is as much as 30 feet thick, splits the Dunn Center bed into two beds eight to 10 feet thick. The structure of the Dunn Center bed is complex but generally the bed dips eastward.

C.4.5 E-lignite Interval

The E-lignite interval extends from the base of the Dunn Center bed to the base of the E-lignite. 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. 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.

C.5 Detailed Stratigraphy of the Center Area

The stratigraphic units of major concern at the Center site are the Sentinel Butte Formation and the Coleharbor Formation. The main lignite, the Hagel bed is separated from a second, overlying lignite, the I bed, by 5 to 50 feet of clastic sediments (pl. C.5-1). The clastic materials between the two lignites typically grade upward from a silty sand to a clay. In some places the interburden is almost totally silty sand. The Hagel bed varies in thickness from 8 feet to 11 feet. The I bed varies from four feet to seven feet in thickness.

In some localities the I bed has been removed by erosion. The Sentinel Butte Formation overlying the I bed is predominantly sand and silt. Much of the study area is overlain by glacial till and associated sand and gravel deposits of the Coleharbor Formation. The till varies in thickness from 0 to 100 feet. As in the case of the other sites, the units have been coded according to a three-digit system (pl. C.5-2).

APPENDIX D
SATURATION EXTRACT ANALYSES

The saturation extract data from each site are grouped according to the stratigraphic units described in appendix C. The data for pebble loam (glacial till) from the Falkirk site, unit 530, have been subgrouped according to individual till units. However, the discussion of these data has treated all the tills as one unit.

D.1 Falkirk Site

D.1-1 Unit 530

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
FA-74-327	3.3- 5	17.9	8.1	0.41	1.5
	5 - 5	20.2	8.2	0.57	2.7
FA-74-379	1.9- 3	16.6	7.9	0.39	0.9
	3 - 4	18.0	8.0	0.56	1.8
FA-74-390	0 - 5	10.6	8.1	0.45	1.1
	5 - 10	11.6	7.8	3.60	1.1
FA-74-393	3 - 5	16.0	8.0	2.19	2.1
FA-74-399	2.5- 5	15.4	8.2	10.3	6.3
FA-74-401	2.3- 3.5	15.8	8.2	0.45	0.6
	5 - 10	14.8	8.0	0.40	0.7
	10 - 15	14.0	8.0	0.33	0.6
FA-74-403	3.4- 6	12.2	8.2	5.03	6.3
	5 - 10	10.7	8.0	5.15	2.8
	10 - 15	10.6	7.8	3.41	3.3
FA-75-73	0 - 6	17.8	8.0	1.40	2.9
FA-75-75	3 - 8	14.0	8.0	1.40	2.2
FA-75-76	2 - 5	23.8	8.0	1.50	1.8
FA-75-78	7 - 10	7.6	7.6	0.54	0.3
	10 - 15	13.8	7.7	0.62	0.4
	15 - 20	11.2	7.6	0.59	0.4
	20 - 24	18.4	7.7	0.62	0.4
FA-75-79	1.5- 6	13.4	8.0	0.89	0.7
FA-75-80	0 - 5	17.2	7.9	1.0	1.4
	5 - 10	17.2	7.7	5.6	1.7
FA-75-81	0 - 5	19.6	7.8	0.9	0.5
	5 - 10	21.2	8.0	0.7	0.6
	10 - 15	20.8	8.0	0.66	0.5
	15 - 20	19.2	8.0	0.55	0.6
	20 - 25	18.2	7.7	0.60	0.4
	25 - 30	16.4	7.7	0.54	0.4
FA-75-82	0 - 6	10.8	7.7	1.20	1.0
FA-75-83	2 - 5	19.2	7.8	7.0	2.5
	5 - 10	17.0	8.1	6.0	1.9
	10 - 15	13.7	7.6	5.9	1.9
	15 - 20	14.0	7.7	5.2	2.1
FA-75-84	7 - 12	11.5	7.6	0.4	0.3
	12 - 18	15.2	7.7	0.48	0.3
	18 - 25	16.4	7.4	1.55	0.4
	25 - 30	18.4	7.3	1.62	0.4
FA-75-85	2 - 5	13.6	8.1	0.60	1.3
FA-75-86	3 - 6	17.8	8.0	0.50	0.8
FA-75-87	2 - 8.5	17.2	8.1	0.55	2.0
	8.5- 10		8.0	1.72	2.6
FA-75-88	2 - 5	13.4	7.9	1.05	1.3
	5 - 10	13.8	7.6	5.0	1.6
	10 - 17	13.8	7.5	3.5	1.2
	17 - 20	14.2	7.5	4.3	1.4
	20 - 25	11.8	7.5	3.2	0.8
	25 - 33	8.8	7.3	3.3	0.6
	40 - 45	13.0	7.5	2.6	0.7
FA-75-90	2 - 5	22.6	8.2	0.54	0.4
	5 - 10	16.6	8.1	0.52	0.9
FA-75-92	2 - 4	12.4	8.0	0.53	1.5
FA-75-93	3 - 5	12.8	7.9	0.68	1.6
	5 - 10	10.4	7.6	3.6	0.7
	10 - 19	5.6	7.6	3.7	1.4
FA-75-94	3 - 6	15.4	7.8	0.33	0.2
FA-74-377	8 - 12	14.2	7.6	3.78	1.2
FA-74-379	4 - 10	13.6	7.5	4.25	1.4
	10 - 15	12.8	7.5	3.38	1.4
	15 - 19	13.6	7.4	3.58	1.2
FA-74-390	10 - 15	9.1	7.8	2.20	1.8
	15 - 20	5.0	7.8	2.60	1.2
FA-74-393	5 - 10	12.3	7.8	6.10	1.7
	10 - 15	12.2	7.6	4.95	2.1
	15 - 20	13.6	7.5	3.61	1.4

APPENDIX D—Continued
SATURATION EXTRACT ANALYSES

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
FA-74-399	5 - 10	20.0	8.2	11.2	5.0
	10 - 15	19.4	8.1	11.1	5.1
	15 - 20	17.8	8.0	7.7	4.3
	20 - 25	25.5	7.7	4.08	2.0
	25 - 30	17.8	7.6	2.24	2.0
	30 - 35	14.1	7.7	2.49	2.9
	35 - 40	18.6	7.7	2.38	2.2
	40 - 45	18.3	7.6	2.78	2.1
FA-74-401	10 - 15	13.8	7.7	2.35	1.9
	15 - 28	12.8	7.7	.93	0.9
FA-74-403	15 - 20	8.7	7.8	2.39	2.4
	20 - 25	9.2	7.6	2.80	1.5
	25 - 30	10.0	7.8	2.55	1.7
FA-74-406	0 - 5	10.3	8.2	0.41	1.5
	5 - 10	10.6	7.8	3.79	2.5
	10 - 15	13.4	7.8	4.00	3.1
	15 - 20	12.2	7.7	3.70	3.3
FA-74-407	0 - 5W	13.2	8.2	0.70	2.1
	0 - 5	15.1	8.0	0.82	1.7
	5 - 10	12.6	7.7	4.20	1.8
FA-75-73	6 - 15	8.0	7.7	1.30	1.6
FA-75-75	8 - 15	6.4	7.6	2.50	1.7
	15 - 20	9.6	7.7	1.75	1.7
FA-75-76	5 - 10	12.0	7.7	6.0	2.0
	10 - 15	12.8	7.5	5.2	1.6
	15 - 20	14.4	7.5	4.1	1.7
	20 - 25	14.6	7.5	3.6	1.4
FA-75-77	2 - 5	16.6	8.0	0.84	.8
	5 - 10	12.4	7.7	1.46	.6
FA-75-79	6 - 8.5	9.0	7.9	1.50	2.7
FA-75-80	10 - 15	11.8	7.5	3.7	1.2
	15 - 20	14.6	7.5	3.6	1.2
	20 - 25	13.0	7.6	3.0	1.1
	25 - 30	12.0	7.5	3.2	0.6
	30 - 37	12.6	7.4	3.5	0.6
FA-75-82	6 - 10	12.4	7.7	4.5	1.3
	10 - 15	12.0	7.4	3.8	1.4
	15 - 20	11.4	7.6	3.2	1.1
FA-75-83	20 - 25	10.2	7.5	4.2	1.8
	25 - 30	9.4	7.6	3.8	2.2
	30 - 35	8.0	7.6	3.6	2.4
	35 - 40	11.4	7.7	4.2	2.5
FA-75-84	30 - 35	14.2	7.6	1.2	0.4
	35 - 40	13.0	7.8	2.9	1.8
	40 - 45	15.0	7.6	1.3	0.5
FA-75-85	5 - 10	13.6	8.2	0.8	2.3
	10 - 15	13.0	7.8	2.9	1.8
	15 - 20	11.4	7.6	3.4	1.6
FA-75-86	10 - 15	9.1	7.9	0.72	0.9
	15 - 20	6.4	7.7	1.70	0.7
	20 - 25	7.2	7.5	1.45	0.7
	25 - 30	8.0	7.6	1.58	0.6
	30 - 35	8.0	7.6	1.48	0.7
	35 - 40	12.0	7.6	2.6	0.7
	40 - 45	7.6	7.6	1.95	0.8
	45 - 50	8.2	7.6	1.98	0.8
FA-75-87	10 - 15	7.0	7.6	4.5	1.3
	15 - 20	7.4	7.5	4.0	0.9
	20 - 25	8.4	7.5	4.0	0.7
	25 - 30	8.8	7.5	3.7	0.6
	30 - 35	8.0	7.6	4.0	0.7
	35 - 40	9.8	7.6	3.2	0.7
FA-75-90	10 - 15	10.2	7.8	0.7	1.6
	15 - 17	8.7	7.7	0.73	1.3
FA-75-92	4 - 8	13.4	8.4	0.72	4.1
FA-74-407	10 - 15W	10.8	7.7	3.10	1.8
	15 - 20W	9.4	7.6	3.70	1.8
	5 - 10	9.4	7.7	4.40	2.2
	10 - 15	10.2	7.8	4.20	2.4
	15 - 20	8.4	7.7	3.95	2.3
FA-75-77	10 - 15	7.4	7.4	3.2	0.3
FA-74-393	20 - 25	0	7.4	2.75	.5
	25 - 30	6.8	7.4	2.70	.3
	30 - 35	7.3	7.5	1.72	.4
FA-74-399	45 - 50	10.5	7.6	2.45	2.1
	50 - 60	9.8	7.6	2.07	2.3
	60 - 70	9.8	7.7	1.79	2.7
	70 - 80	9.4	7.7	2.05	2.6
FA-74-401	20 - 30	9.5	7.6	2.86	0.9
	30 - 40	9.1	7.6	1.70	0.9
	40 - 50	10.5	7.9	1.40	1.1
FA-74-407	20 - 25W	11.5	7.6	3.80	1.4
	25 - 30W	12.8	7.7	3.85	1.4
	30 - 35W	13.1	7.7	3.62	1.3
	20 - 25	11.7	7.7	3.90	1.9

APPENDIX D—Continued
SATURATION EXTRACT ANALYSES

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
	25 - 30	12.0	7.7	3.90	1.7
	30 - 35	11.4	7.7	3.30	1.5
	35 - 38	13.6	7.6	3.80	1.5
FA-75-76	25 - 30	11.8	7.5	3.9	1.2
	30 - 34	9.6	7.4	2.7	0.8
	36 - 41	11.6	7.5	2.8	1.0
FA-75-77	15 - 20	10.2	7.5	3.6	1.1
	20 - 25	11.6	7.5	3.8	1.2
	25 - 30	7.6	7.4	3.2	0.7
FA-75-82	20 - 25	8.6	7.4	3.2	0.7
	25 - 30	8.2	7.5	3.2	0.6
FA-75-83	60 - 62		7.5	4.7	2.0
	78 - 80		7.1	4.3	2.4
FA-74-401	90 -100	11.3	7.8	1.50	2.0
	100 -110	11.0	7.8	1.60	2.2

D.1-2 Unit 510

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
FA-74-399	80 - 90	12.0	7.6	3.01	2.6
	90 -110	11.8	7.5	3.00	2.4
	110 -140	16.2	7.5	3.40	2.6
FA-75-75	20 - 24	6.2	7.9	1.08	1.4
FA-75-84	45 - 50	13.8	7.6	0.95	0.6
FA-75-85	20 - 23	37.4	7.8	2.0	1.5
FA-75-93	14 - 17	4.8	7.5	4.0	1.7

D.1-3 Unit 280

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
FA-74-379	19 - 25	11.3	7.6	3.20	1.0
	25 - 30	10.0	7.7	1.91	1.0
	30 - 34	10.0	7.6	1.70	1.1
FA-74-383	35 - 38	7.2	7.1	1.15	0.6
FA-74-400	5 - 10	0.4	7.3	5.90	4.7
FA-75-79	8.5- 10	9.4	7.7	3.8	2.3
FA-75-82	30 - 35	7.2	7.7	1.30	0.9
	35 - 40	6.8	7.6	1.20	0.8
FA-75-90	17 - 21	2.3	7.6	0.62	1.1
FA-75-91	3 - 5	10.4	8.1	1.90	6.4
	5 - 9	3.3	7.7	5.3	5.2
	9 - 16	10.4	7.9	2.1	6.6
	16 - 21	11.0	7.9	2.3	5.6
	21 - 23	12.2	7.9	2.5	5.6
	23 - 27	12.0	8.0	2.1	6.0
	27 - 32	11.6	7.7	2.5	5.5
	32 - 34	6.0	7.6	2.6	5.3
	34 - 36	3.0	7.2	3.0	5.6
	36 - 37		6.5	5.0	5.5
	40 - 42		6.3	3.8	7.7
	42 - 50	4.1	7.7	2.0	8.6
	50 - 58	10.2	7.9	1.91	13
FA-75-93	17 - 20	12.6	7.6	3.1	1.9
	20 - 25	8.6	7.8	2.5	1.7
	25 - 32	2.6	7.6	2.0	1.7
	32 - 33	6.0	6.6	3.7	2.0
	33 - 40	1.0	7.4	2.5	2.4
	40 - 42		6.7	2.8	2.7

D.1-4 Unit 270

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
FA-74-379	34 - 40	4.0	7.7	2.99	1.0
	40 - 45	3.0	7.7	3.21	1.2
	45 - 50		7.7	1.95	1.8
FA-74-390	20 - 25		7.7	1.60	0.8
	25 - 30		7.7	1.15	0.8
	30 - 35		7.8	0.75	0.6
	35 - 40		7.8	0.84	0.9
	40 - 45	1.7	7.6	1.10	0.7
	45 - 50		7.6	1.28	0.7
FA-74-400	10 - 15	0.7	7.3	5.00	4.9
	15 - 20	0	7.7	4.50	3.5
	20 - 25	0	8.0	1.22	5.2
	25 - 30	0	8.4	0.85	6.5
	30 - 35	0	8.2	0.72	6.5
	35 - 40	0	8.2	0.81	8.1
FA-75-75	24 - 30	3.2	7.7	0.90	1.1
	30 - 35	2.9	7.7	0.90	0.9
	35 - 40	2.5	7.8	0.90	1.1
	40 - 45	4.6	7.8	0.91	1.1
	45 - 50		7.9	0.80	1.1
	50 - 55	3.2	7.8	0.76	0.9
	55 - 59	2.6	7.8	0.80	1.0
FA-75-76	41 - 42	21.2	7.5	3.1	0.6
	42 - 50	4.4	7.6	1.92	0.7
	50 - 55		7.7	1.05	0.4
	55 - 60	1.7	7.6	1.08	0.6
FA-75-77	30 - 38	8.2	7.7	2.3	0.9
	38 - 45	8.4	7.8	2.7	0.9

APPENDIX D—Continued
SATURATION EXTRACT ANALYSES

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
	45 - 50	8.6	7.8	1.62	1.0
	50 - 53	8.3	7.9	1.50	0.8
	53 - 56	8.4	7.9	1.46	1.2
	56 - 60	9.3	7.9	1.62	1.0
FA-75-78	24 - 33	3.8	7.6	0.67	0.4
	33 - 34	38.8	7.7	0.80	0.4
	34 - 40	17.4	7.4	0.91	0.5
	40 - 45	7.6	7.4	0.90	0.5
	45 - 50	5.7	7.6	0.85	0.7
	50 - 55	5.0	7.5	1.06	0.6
FA-75-79	10 - 13	8.8	7.6	4.0	2.1
	13 - 20	40.0	7.7	1.80	2.2
	20 - 25	9.0	7.7	1.49	1.3
	25 - 30	4.0	7.7	1.20	1.4
	30 - 35	4.3	7.7	1.84	1.0
	35 - 40	3.1	7.8	1.00	1.3
	40 - 45	6.6	7.8	2.2	0.9
	45 - 50	—	7.8	1.05	—
	50 - 55	9.0	7.6	0.85	0.3
	55 - 57.5	2.1	6.9	1.63	1.0
FA-75-80	47 - 55	14.2	7.6	3.4	0.6
	55 - 67	49.4	8.2	1.60	1.0
	75 - 95	3.9	8.1	1.40	1.0
	95 -100	6.8	7.7	0.77	0.4
FA-75-81	38 - 61	2.3	7.7	0.7	0.5
	61 - 66	36.8	7.9	0.77	0.6
	66 - 74		7.8	1.0	0.8
	74 - 78	41.2	7.9	1.01	0.6
	78 - 85	27.0	7.9	0.76	0.7
	85 -100	8.4	7.8	0.85	0.6
FA-75-82	40 - 44	7.7	7.6	1.60	0.9
	44 - 46	33.2	7.7	1.62	0.8
	46 - 50	19.4	7.7	1.45	1.0
	50 - 55	10.0	7.9	1.30	0.9
	55 - 60	7.9	7.6	1.29	0.9
	60 - 62	6.6	7.7	1.30	0.8
	62 - 78.5	39.2	7.9	1.60	0.6
	78.5-100	5.7	7.8	1.90	0.7
FA-75-85	23 - 30	1.5	7.6	1.30	1.3
FA-75-86	65 - 73	9.3	7.8	1.58	1.9
FA-75-88	45 - 55	3.7	7.6	1.41	1.0
	55 - 63	2.4	7.5	1.13	1.0
FA-75-91	58 - 70	10.2	8.3	1.6	26
	70 - 80	9.2	8.2	1.78	30.1
	80 - 85	6.5	8.4	1.62	23

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
FA-75-92	8 - 10	39.4	8.0	2.4	2.9
	10 - 15	10.0	7.9	2.8	1.8
	15 - 20	7.7	7.6	2.4	1.4
FA-75-93	45 - 65	16.8	7.7	2.4	7.7
	65 - 82	9.8	8.1	2.2	20

D.1-5 Unit 240

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
FA-74-393	45 - 50	8.5	7.6	1.39	0.6
	50 - 55	6.6	7.8	1.19	0.7
	55 - 60	7.3	7.5	1.44	0.6
	60 - 65	7.2	7.9	1.03	0.8
	65 - 70	7.2	7.8	1.24	0.5
	70 - 75	4.4	7.5	1.39	0.8
	75 - 80	3.0	7.4	1.29	1.0
	80 - 85	3.2	7.7	1.12	.14
	85 - 90	13.2	7.9	1.13	1.6
	90 - 95	10.7	7.2	1.79	2.5
	95 -100	11.2	7.8	1.65	3.6
	100 -105	1.9	7.3	1.98	7.1
	105 -110	9.1	8.0	1.37	8.5
	110 -115	7.6	8.1	1.60	9.7
	115 -120	8.6	8.2	1.47	7.9
	120 -125	8.3	8.3	1.54	11.4
	125 -130	6.0	8.0	1.93	13.5
	130 -135	6.0	8.2	1.70	12.1
	135 -140	8.9	8.4	1.38	12.7
FA-74-400	40 - 45	7.1	8.3	0.77	7.7
	45 - 50	8.9	8.2	0.74	8.8
	50 - 55	10.5	8.0	1.40	10.8
	55 - 60	12.5	8.2	1.49	12.2
FA-74-401	110 -120	10.5	8.0	4.3	9.0
FA-74-403	30 - 35	9.8	7.8	2.19	1.7
	35 - 40	7.6	7.8	3.65	1.6
FA-74-407	35 - 40	6.1	7.6	3.75	1.3
	35 - 38W	13.6	7.6	3.80	1.5
	38 - 40W	9.7	7.9	2.58	1.8
	40 - 43W	4.2	7.6	3.60	1.6
	40 - 45	7.2	7.6	3.20	1.4
FA-75-80	112 -130	4.9	8.0	1.30	1.3
	130 -132		7.1	1.74	1.4
FA-75-82	100 -108	3.5	7.6	1.85	0.8
FA-75-83	100 -105	12.0	7.3	4.3	3.2
	110 -133	16.1	7.3	4.6	3.0
FA-75-84	100 -105	13.4	7.8	1.45	2.2

APPENDIX D—Continued
SATURATION EXTRACT ANALYSES

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
	105 -110	13.0	7.8	1.45	2.5
	110 -115	12.2	7.8	1.6	2.5
	115 -120	18.2	7.7	1.5	2.1
FA-75-85	30 - 35	0	7.5	0.65	0.7
	35 - 40	6.0	7.7	1.29	0.7
	40 - 45	9.8	7.7	1.10	1.0
	45 - 50	4.5	7.8	1.20	1.6
FA-75-86	73 - 80	8.0	7.8	1.3	1.5
FA-75-90	21 - 25	2.8	7.6	0.65	1.0
FA-75-92	20 - 24	5.2	7.6	4.1	0.5
FA-75-94	6 - 10	10.4	8.0	0.27	0.4
	10 - 18	12.6	8.0	0.33	0.7

D.1-6 Unit 230

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
FA-74-393	140 -145	9.3	8.3	1.60	12.3
FA-74-407	45 - 48	0	7.3	2.93	1.5
FA-75-75	59 - 61	1.2	7.7	1.11	0.7
	61 - 67	3.5	7.5	1.50	0.7
FA-75-76	60 - 63		6.5	1.42	0.2
FA-75-77	60 - 65	4.6	7.6	2.2	1.0
FA-75-78	55 - 57.5		6.4	2.5	0.5
FA-75-81	100 -103	1.2	7.2	1.7	0.7
FA-75-86	80 - 84	6.6	7.3	1.78	1.1
FA-75-91	88 - 90		7.6	2.8	15.3
FA-75-92	24 - 26	1.0	6.6	4.5	0.5
FA-75-93	81 - 84		6.5	6.2	20
FA-75-94	18 - 19	1.2	6.6	0.83	0.7

D.1-7 Unit 190

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
FA-75-75	79 - 80		6.1	3.2	0.9
	80 - 82		7.0	1.45	1.0
FA-75-76	72 - 75		6.4	2.3	0.4
FA-75-78	67.5- 68		6.0	2.1	0.7
FA-75-80	142 -148	0.7	7.1	2.3	6.2
FA-75-86	96 - 97		6.6	2.8	1.2
FA-75-91	98 - 99		7.1	2.2	2.9
FA-75-94	27 - 30	0.7	4.4	2.6	0.3

D.1-8 Unit 180

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
FA-75-75	82 - 87	0.0	6.7	1.85	1.9
FA-75-90	37 - 45	4.6	7.4	1.48	0.5
	45 - 53	3.6	7.0	1.52	1.0
FA-75-92	37 - 40		5.1	2.9	0.5
	40 - 45	4.6	7.8	1.5	0.9
	45 - 50	6.3	7.8	1.35	1.5
	50 - 56	6.8	7.6	1.25	2.2
FA-75-94	30 - 35	3.8	7.5	1.30	0.8
	34 - 40		7.3	1.88	0.5
	40 - 45	11.4	7.5	1.95	0.7

D.1-9 Unit 150

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
FA-75-75	87 - 89.5	—	6.1	2.7	2.8

D.1-10 Unit 140

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
FA-74-401	145 -160	6.0	8.2	1.39	8.0
FA-74-403	100 -110	9.0	7.8	1.30	1.0
FA-75-73	15 - 18		7.5	1.00	1.2
	18 - 20	2.2	7.5	1.08	1.0
	20 - 21		6.5	1.66	0.7
FA-75-75	89.5- 90		6.2	2.5	2.6
FA-75-94	45 - 50	3.8	7.0	2.2	0.9

D.1-11 Unit 110

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
FA-75-80	150 -154		7.5	1.85	8.8

D.2 Indian Head Site

D.2-1 Unit 590

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
X-2	0 - 5	7.4	8.3	0.6	5.7
3	0 - 5	5.7	8.0	8.0	10.1

APPENDIX D—Continued
SATURATION EXTRACT ANALYSES

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
7	0 - 5	2.6	8.4	13.0	21.6
	5 - 10	4.0	8.5	3.9	23.7
12	.8- 3	3.4	8.1	8.3	13.0
14	.7- 3	3.0	8.0	8.0	12.0
15	1.4- 3	8.4	8.7	4.7	13.0
25	1.5- 3.5	13.0	8.5	0.66	4.0
9	.8- 2	5.4	8.6	2.60	16.0

D.2-2 Unit 570

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
12	3 - 5	6.4	8.3	7.20	15
	5 - 10	5.0	8.3	5.00	19
	10 - 15	3.2	8.0	8.95	18
14	3 - 5	3.7	8.5	2.92	19
	5 - 10	2.3	8.0	7.60	17
	10 - 15	2.8	8.1	8.70	19
	15 - 20	3.1	8.2	9.50	22
13	0 - 5	3.3	8.4	9.5	15.6
	5 - 10	1.4	8.3	10.0	18.5
	10 - 15	1.0	8.2	6.5	17.1
	15 - 20	4.3	8.4	3.2	27.1
15	3 - 5	—	8.9	1.19	21
9	2 - 3	3.5	8.3	10.9	16
	3 - 5	2.6	8.0	9.00	18
	5 - 10	3.0	8.1	9.00	20
	10 - 15	4.8	8.1	6.70	16

D.2-3 Unit 530

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
21	0 - 5	8.7	8.1	2.7	4.9
	5 - 10	5.9	7.8	6.0	5.3
25	3.5- 5	10.3	8.5	2.20	—

D.2-4 Unit 260

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
X-2	5 - 10	1.0	7.8	5.7	7.1
315	2 - 5	—	7.6	0.75	1.1

D.2-5 Unit 240

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
X-2	10 - 15	3.4	8.2	2.8	12.3
	15 - 20	1.2	7.4	6.0	8.2
	20 - 25	2.0	8.3	2.1	21.1
	25 - 30	4.2	8.2	1.8	21.0
315	5 - 10	—	7.8	2.1	9.3
327	0 - 5	6.2	8.2	10.0	16
	5 - 10	2.1	8.0	10.0	13

D.2-6 Unit 210

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
X-2	30 - 35	5.7	8.9	1.4	32.2
	35 - 40	9.7	9.0	1.2	25.9
	40 - 48	7.8	8.8	1.2	27.5
	50 - 55	2.2	9.0	1.2	28.4
	55 - 60	6.4	8.2	2.0	33.0
3	5 - 10	2.8	7.9	7.4	10.1
	10 - 15	3.4	7.9	7.0	11.3
	15 - 18	—	8.1	5.0	13.2
	19 - 23	—	8.1	3.6	19.8
25	5 - 10	3.0	7.5	8.00	12
	10 - 15	.01	4.5	7.50	6
315	10 - 15	—	7.5	4.5	8.2

D.2-7 Unit 190

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
25	16 - 20	—	4.4	9.10	10
1	0 - 5	10.0	8.2	9.0	11.4

D.2-8 Unit 180

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
1	5 - 10	—	7.9	12.9	12.2
	10 - 18	—	4.7	8.0	11.0
	18 - 25	2.0	6.7	6.7	11.7
	25 - 30	1.8	8.2	6.0	18.9
3	30 - 38	—	6.9	3.6	21.1

D.2-9 Unit 170

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
25	20 - 25	—	5.1	7.20	9
	25 - 30	—	4.9	9.20	13
	30 - 38	—	4.9	8.20	17
	38 - 45	2.9	8.9	2.67	28
315	14 - 20	—	5.4	3.2	12
	20 - 25	3.1	7.4	6.0	11
	25 - 30	2.0	8.2	3.7	19
	30 - 42	7.0	8.3	2.4	31
327	0 - 5	6.2	8.2	10.0	16
	5 - 10	2.1	8.0	10.0	13

APPENDIX D–Continued
SATURATION EXTRACT ANALYSES

Testhole	Depth	CaCO$_3$	pH	ECE	SAR
	15 - 20	—	7.7	7.0	10
3	38 - 45	—	8.5	2.3	29.1
	45 - 50	6.8	9.0	1.7	28.2
	52 - 60	9.0	9.1	1.4	38.4
1	30 - 39	9.2	8.8	2.3	28.0
X-2	65 - 70	—	9.1	1.1	31.0
317	0 - 5	5.2	8.0	8.6	11

D.2-10 Unit 160

Testhole	Depth	CaCO$_3$	pH	ECE	SAR
X-2	82 - 85	5.0	9.1	1.2	32.4
	85 - 90	6.1	9.0	1.2	33.7
3	60 - 67	7.5	9.1	1.4	44.5
21	10 - 15	0.6	7.6	4.0	6.0
25	45 - 50	9.4	8.7	2.30	30
317	5 - 14	5.4	7.8	6.2	10

D.2-11 Unit 150

Testhole	Depth	CaCO$_3$	pH	ECE	SAR
X-2	95 -100	—	9.3	1.0	24.5
	100 -103	8.0	9.2	1.3	34.2
12	15 - 20	3.8	8.3	7.25	20
	20 - 25	5.2	8.6	3.63	28
13	20 - 25	5.9	8.5	3.2	31.2
	25 - 30	3.9	8.7	2.9	34.5
9	15 - 20	2.1	8.2	4.80	24
	20 - 25	—	8.2	3.55	29
	25 - 30	—	8.4	2.6	29
315	44 - 45	—	7.4	2.4	48
	45 - 50	—	8.1	2.5	39
25	58 - 65	—	8.9	1.76	28
317	15 - 25	2.1	6.7	5.5	13

D.2-12 Unit 140

Testhole	Depth	CaCO$_3$	pH	ECE	SAR
1	46 - 55	—	9.0	2.0	35.9
	55 - 62	—	8.7	1.8	43.2
12	25 - 30	4.3	8.6	3.60	30
	36 - 40	—	8.9	2.01	30
13	30 - 35	4.7	8.8	2.9	37.7
	35 - 40	6.6	9.0	2.6	48.9
	40 - 45	4.7	8.9	2.7	48.8
	45 - 50	9.1	9.0	2.4	56.8
9	30 - 35	6.7	8.4	2.7	31
315	50 - 57	7.3	8.6	1.69	63
317	25 - 30	8.1	8.5	2.8	24

D.2-13 Unit 130

Testhole	Depth	CaCO$_3$	pH	ECE	SAR
3	69 - 75	—	8.9	1.5	17.6
7	10 - 15	5.8	8.5	3.2	25.2
	15 - 20	4.9	8.5	3.4	28.8
	20 - 25	8.5	8.9	2.8	36.9
	25 - 30	9.3	8.9	2.6	39.4
12	45 - 50	3.4	9.0	1.80	28
14	20 - 25	5.6	8.3	6.30	21
	25 - 30	2.6	8.6	3.78	31
	30 - 35	4.9	8.5	3.58	35
13	50 - 55	5.6	9.0	2.3	48.2
19	0 - 5	4.4	8.3	5.0	12.5
	5 - 10	6.1	8.3	1.8	19.5
	10 - 15	5.6	8.2	1.8	21.5
	15 - 20	7.1	8.4	2.7	23.8
21	20 - 25	4.1	7.7	4.9	6.6
15	5 - 10	5.5	8.6	1.20	23
	10 - 15	3.9	8.6	1.40	27
	15 - 20	7.6	8.6	2.65	33
25	65 - 78	—	8.7	2.10	35
9	35 - 40	5.2	8.7	2.4	35
22	0 - 5	1.2	8.1	8.1	12.1
	5 - 10	4.2	8.2	3.4	17.8
315	57 - 63	10.4	8.6	1.61	56
317	30 - 35	12.2	8.4	2.0	46
	35 - 40	3.9	8.4	2.6	36
327	48 - 57	10.2	8.6	1.90	39
	57 - 58	20.8	8.4	2.6	42
	58 - 60	9.9	8.3	2.3	50

APPENDIX D—Continued
SATURATION EXTRACT ANALYSES

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
	60 - 65	1.8	8.5	2.2	44
	65 - 70	—	8.6	2.0	71
D.2-14 Unit 120					
12	50 - 55	—	9.0	2.02	33
	55 - 60	—	9.1	1.69	29
	60 - 64	—	9.2	1.03	30
	64 - 67	—	8.8	1.80	31
14	37 - 45	—	9.2	3.22	39
	45 - 50	—	9.1	3.21	40
	50 - 55	—	9.1	2.80	36
	55 - 59	—	9.0	2.23	32
13	55 - 60	3.4	9.2	1.3	57.7
18	5 - 10	23.6	8.6	2.10	14
	10 - 15	51.0	8.0	4.20	10
	15 - 20	—	8.2	2.5	16
	20 - 25	—	8.2	2.9	16
	25 - 30	—	8.2	3.2	15
	30 - 35	—	8.1	3.2	17
	35 - 40	—	8.0	3.8	16
19	20 - 25	6.1	8.4	2.7	24.2
	25 - 30	2.0	8.1	3.3	26.0
21	25 - 30	2.9	7.7	5.5	5.1
	30 - 35	3.7	7.8	4.7	7.6
15	20 - 25	5.6	8.7	2.55	33
22	10 - 15	6.7	8.3	2.0	18.3
	15 - 20	3.4	8.1	1.9	14.6
	20 - 25	5.3	7.9	1.8	11.1
315	63 - 77	4.9	8.7	1.58	54
	77 - 85	7.8	8.7	1.50	43
	85 - 87	4.0	8.7	1.46	51
317	40 - 45	8.0	8.4	1.85	57
	45 - 50	6.4	8.5	1.80	49
	55 - 60	—	8.6	1.83	59
D.3-15 Unit 110					
3	75 - 80	—	8.9	1.6	41.4
7	30 - 35	3.1	8.2	4.0	40.0
19	30 - 33	0.1	6.7	4.3	22.5
21	35 - 40	0.6	6.0	6.6	6.4

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
22	25 - 28	0.2	7.1	2.2	10.7
315	87 - 89	—	8.1	1.75	49
327	70 - 72	—	8.7	1.57	52
D.3 Beulah-Hazen Site					
D.3-1 Unit 570					
74-76	5 - 10	—	8.0	5.10	0.3
74-83	0 - 5	7.8	7.6	0.47	0.8
	5 - 10	4.9	8.4	0.33	1
	10 - 15	6.7	8.2	0.33	2
	15 - 20	—	8.2	0.27	2
	20 - 25	7.8	8.1	0.40	2
D.3-2 Unit 530					
74-76	10 - 15	13.3	7.7	5.29	3
	15 - 20	9.0	7.6	4.95	3
	20 - 25	8.2	7.5	4.07	2
	25 - 30	8.5	7.5	3.98	2
	30 - 35	7.7	7.6	3.70	2
	35 - 40	7.9	7.6	3.70	2
74-82	0 - 5	13.4	8.1	0.50	2
	5 - 10	13.2	8.0	0.73	2
	10 - 15	12.5	7.9	2.36	1
74-84	0 - 5	9.6	7.7	2.54	3
	5 - 10	7.9	7.8	6.50	5
	10 - 15	6.6	7.7	3.62	5
	15 - 20	6.6	7.8	1.64	5
	20 - 25	5.9	7.8	1.18	4
	25 - 30	6.2	7.7	1.50	4
	30 - 35	6.1	7.8	1.11	4
74-85	0 - 5	2.8	7.4	0.68	1
	5 - 10	9.3	7.7	4.70	2
	10 - 15	8.1	7.6	4.20	2
	15 - 20	7.2	7.5	4.00	2
	20 - 40	6.1	7.5	3.16	2
74-88	0 - 5	9.0	8.2	0.50	2
	5 - 10	6.7	7.7	3.68	2
	10 - 15	5.9	7.6	3.65	1
	15 - 20	5.3	7.7	1.91	1
	20 - 25	6.0	7.6	3.10	0.6
	25 - 30	3.5	7.8	1.21	0.4
74-89	0 - 5	11.3	8.1	0.50	2
	5 - 10	5.8	7.7	4.30	0.2
	10 - 15	6.1	7.6	3.65	0.2

APPENDIX D—Continued
SATURATION EXTRACT ANALYSES

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
D.3-3 Unit 510					
74-84	35 - 40	4.8	7.8	1.10	5
	40 - 45	3.0	8.0	0.81	5
	45 - 50	4.9	7.9	0.75	7
74-88	30 - 35	4.1	7.7	1.26	0.4
	35 - 40	2.2	7.9	0.58	0.5
	40 - 45	5.0	7.8	0.50	0.3
	45 - 50	3.6	8.0	0.71	0.5
	50 - 55	3.4	7.9	0.75	0.6
	55 - 60	3.5	7.8	0.73	0.6
	60 - 65	3.4	7.9	0.92	0.6
D.3-4 Unit 240					
74-80	5 - 10	2.2	8.0	2.15	3
	10 - 15	0	8.1	1.21	4
	15 - 20	0	7.9	0.83	3
	20 - 25	0	7.9	0.74	2
	25 - 30	0	7.6	1.39	1
	30 - 35	0	7.5	0.72	1
	35 - 40	0	7.3	0.80	1
	40 - 45	0	7.7	0.69	0.8
	45 - 50	0	7.6	0.62	0.7
	50 - 55	0	6.2	2.30	0.4
	55 - 60	0	7.8	0.80	0.8
	60 - 65	0	7.2	1.11	1
74-81	5 - 10	0.9	8.1	5.05	3
	10 - 15	0	8.0	4.95	4
	15 - 20	—	7.8	3.75	3
	20 - 25	—	4.8	4.60	2
	25 - 30	—	4.0	5.70	2
	30 - 35	—	3.8	7.10	2
	35 - 40	—	3.8	8.50	2
	40 - 45	—	4.9	6.60	1
	45 - 50	—	6.6	3.05	0.8
	50 - 55	—	4.2	3.10	2
	55 - 60	—	5.0	3.12	2
	60 - 65	—	6.8	3.78	3
74-82	15 - 20	—	7.7	1.43	2
	20 - 40	—	7.8	0.90	2
	40 - 60	—	7.6	0.99	2
	60 - 68	5.5	7.8	1.55	3
	70 - 80	—	7.3	4.45	2
	80 - 85	—	7.2	0.80	1
	85 - 92	—	7.6	1.11	1
D.3-5 Unit 190					
74-80	65 - 70	3.7	7.9	1.28	4
74-82	130 -140	7.0	8.7	1.71	23
D.3-6 Unit 170					
74-80	80 -100	8.5	8.6	1.56	33
	100 -110	6.5	8.8	1.44	30
74-81	65 - 70	—	8.2	2.77	5
74-89	15 - 20	—	6.7	4.70	1.5
	20 - 25	4.3	7.5	4.49	0.9
	25 - 30	3.7	7.5	4.40	0.9
	30 - 35	2.4	7.6	3.53	0.9
	35 - 40	2.7	7.5	3.10	0.9
	40 - 45	4.3	7.5	3.50	0.8
	45 - 50	—	7.5	2.33	0.9
	50 - 55	—	7.8	1.85	0.8
	55 - 60	—	7.5	1.80	0.7
	60 - 65	—	6.6	1.87	0.8
D.3-7 Unit 140					
74-81	90 - 95	—	8.8	1.38	20
	95 -100	7.6	9.3	1.73	25
	100 -105	6.8	8.9	1.57	35
	105 -110	10.4	9.1	1.41	33
	110 -115	12.9	9.1	1.62	37
D.3-8 Unit 130					
74-81	115 -120	10.9	9.1	1.72	36
74-89	80 -100	5.7	8.3	1.79	12
D.3-9 Unit 120					
74-81	120 -125	11.7	9.2	1.57	32
	125 -130	8.8	9.4	1.49	34
	130 -135	4.6	9.4	1.52	34
	135 -140	8.2	9.4	1.64	33
D.3-10 Unit 110					
74-80	117 -140	8.7	9.1	1.48	32
74-81	140 -150	8.0	8.9	1.50	32
	150 -160	5.6	8.2	2.20	41
74-84	50 - 55	4.5	8.0	0.67	6
	55 - 58	5.4	7.8	0.91	5
74-89	100 -125	5.0	8.8	2.30	27
74-82	140 -160	11.6	9.2	1.73	35

APPENDIX D—Continued
SATURATION EXTRACT ANALYSES

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
	160 -180	6.9	9.2	1.72	34
	180 -190	3.8	8.5	1.79	32

D.4 Dunn Center Site

Overburden analyses from the Dunn Center site have been arranged primarily according to depth of the sample, secondarily according to testhole.

Depth (ft)	Testhole	$CaCO_3$	pH	ECE	SAR
D.4-1 C-Interval					
2.4- 3.5	17	0	7.6	4.4	1.9
3.5- 5.5	17	0	7.5	3.2	1.8
5.5- 13.0	17	0	7.2	5.0	3.4
8.0- 12.0	18	0	4.1	2.2	2.1
12.4- 12.8	17	0	5.1	3.1	10.0
13.0- 14.5	17	0	5.0	6.9	8.7
14.1- 14.5	17	0	4.7	5.0	9.2
20.4- 20.6	18	0	8.2	1.7	3.4
20.6- 20.9	18	0	8.1	1.5	4.8
30.3- 30.6	17	3.1	8.2	3.4	12.0
35.0- 40.0	18	0	8.8	1.5	19.0
D.4-2 Unit 320					
58.1- 58.4	17	0	8.3	2.2	10.0
60.1- 60.5	17	0	8.1	1.7	9.5
D.4-3 Unit 310					
6.0- 12.0	19	3.0	7.8	8.0	7.1
55.0- 60.0	18	0.0	8.3	1.6	5.3
D.4-4 Unit 260					
20.5- 21.0	29	—	7.6	6.5	9.4
21.0- 23.0	29	—	7.9	5.3	10.9
28.5- 29.0	29	—	8.3	2.8	15.0
29.0- 31.0	29	—	8.2	3.2	16.4
D.4-5 Unit 250					
4.9- 7.5	6	0	7.5	0.3	1.2
7.5- 9.0	6	0	7.7	0.8	1.9
9.2- 13.0	6	0	7.9	2.3	2.4
13.0- 14.0	6	1.2	8.0	5.0	3.5
14.0- 16.0	6	0	7.8	3.4	4.8
19.0- 20.5	4417JA	—	8.7	2.6	13.7
20.5- 21.0	4417JA	—	8.8	2.7	21.0
82.0- 92(c)	18	4.2	8.7	0.9	19.0
82.0- 92(s)	18	0	8.9	1.3	21.0
D.4-6 Unit 240					
21.0- 23.8	4417JA	—	7.9	4.4	16.5
21.6- 22.2	4417JA	—	8.4	2.3	19
25 - 26.3	4417JA	—	7.8	5.0	21.7
26.3- 26.8	4417JA	—	8.6	2.7	19
81 - 81.4	17	6.4	8.3	1.1	13
D.4-7 Unit 230					
1.5- 2.5	30	9.9	8.1	7.0	12
2.5- 4.3	30	5.4	8.0	10.0	18
4.3- 6.0	30	7.7	8.0	11.1	19
6.0- 10	30	8.4	8.0	7.3	18
10 - 14	30	9.1	8.5	3.1	28
14.2- 14.5	30	8.6	8.5	2.9	27
14 - 18	30	8.0	8.4	2.8	27
20.6- 20.9	19	0	7.2	5.0	8.8
31 - 32.5	4417JA	—	8.8	3.3	24.7
32.5- 33	4417JA	—	8.8	2.6	24
35 - 37	4417JA	—	8.7	2.6	33.2
37.5- 38	4417JA	—	8.6	2.6	30
39.5- 40	29	—	8.6	2.3	30
41 - 43	29	—	8.9	2.0	29.4
42 - 45.5	4417JA	—	7.8	3.3	29.6
43.5- 44	4417JA	—	8.6	2.0	33
45 - 45.5	29	6.9	8.5	2.2	37
53 - 55	29	—	8.5	2.9	30.4
63 - 63.5	29	—	8.8	2.2	34
105 -110	18	0	8.9	0.9	22
125 -130	18	6.2	8.6	1.5	25
D.4-8 Unit 220					
22.6- 22.9	19	0	7.0	5.0	8.8
23.4- 24.0	14	—	7.9	1.1	3.9
24.7- 25.0	19	0	7.8	5.5	7.8
26 - 28	14	—	7.9	1.0	3.6
48 - 50	14	—	7.9	1.3	2.4
56.9- 57.4	14	—	7.0	0.9	1.6
65 - 67	29	—	8.8	2.2	35.1
D.4-9 Unit 210					
3 - 5	16	7.2	8.6	0.6	6.2
5 - 6.8	16	2.3	7.9	5.0	5.0
41.4- 43.2	19	0	5.8	5.0	13
51.5- 52	4417JA	12.7	8.2	3.6	30
52 - 54	4417JA	—	8.5	3.1	25.6
56 - 58	4417JA	—	8.2	3.5	26.7
56.5- 67.2	4417JA	—	8.1	1.8	16.8
58.0- 58.4	4417JA	12.9	8.6	2.0	29
58 - 60	14	—	7.6	1.7	1.6

APPENDIX D—Continued
SATURATION EXTRACT ANALYSES

Depth (ft)	Testhole	$CaCO_3$	pH	ECE	SAR
62.5- 63	14	—	7.0	3.4	1.0
141.9-142.2	17	6.7	8.5	2.0	34
143.3-143.5	17	0	9.1	1.1	34
167 -168	18	7.0	7.9	0.3	0.3

D.4-10 Unit 130

Depth (ft)	Testhole	$CaCO_3$	pH	ECE	SAR
10.5- 14	16	0	6.4	5.2	7.0
14.7- 15.9	16	0	4.5	3.1	8.1
18.9- 19.2	16	0	8.4	3.3	10.0
58.5- 58.8	6	0	8.2	0.7	1.3
60.6- 60.8	6	0	8.2	0.7	1.7
62.3- 62.5	6	0	8.2	0.7	2.1
72 - 74	14	—	8.4	1.1	4.5
73.4- 73.9	4417JA	19.7	8.2	3.4	28
73.8- 74.1	6	16.4	8.2	1.5	4.4
74 - 76	4417JA	—	8.3	3.2	26.1
75.1- 75.6	14	—	8.5	1.1	7.3
76.1- 76.3	6	15.5	8.2	1.5	5.2

D.4-11 Unit 123

Depth (ft)	Testhole	$CaCO_3$	pH	ECE	SAR
30.6- 30.9	16	6.0	9.0	1.8	23
33.9- 34.2	16	6.6	9.0	1.8	27
78 - 80	14	—	7.8	3.6	6.0
80.5- 81	14	—	8.4	1.7	10

D.4-12 Unit 120

Depth (ft)	Testhole	$CaCO_3$	pH	ECE	SAR
1.5- 4	2	0	7.7	0.2	0.2
3 - 5	13	4.1	7.8	0.3	0.7
4 - 6.3	2	3.4	8.1	0.5	4.3
5 - 8.5	13	1.6	7.9	0.2	0.4
6.3- 11.5	2	0	8.1	0.6	4.1
6.7- 8.3	5	1.1	7.9	0.5	4.6
8.3- 15	5	0	7.4	3.9	2.9
10 - 12	13	—	7.7	0.3	0.7
19.8- 20.3	68	23.8	8.0	0.6	1.3
21 - 23	68	—	7.8	0.67	0.5
19.6- 20.1	4411EA	—	8.7	1.0	4.1
21 - 23	4411EA	—	7.7	1.1	2.8
25 - 25.5	68	23.7	7.9	0.5	0.8
27 - 29	68	—	7.4	1.52	0.7
32 - 32.4	13	—	7.6	0.3	0.9
36 - 36.5	4411EA	—	7.8	1.2	2.9
37 - 39	4411EA	—	8.5	1.1	3.2
46.3- 48.6	19	0	7.1	6.5	12
56 - 60	19	0	6.5	11.0	10
65 - 75	19	0	4.7	8.0	9.5
100 -105	6	0	8.0	2.3	9.5
153 -157	6	0	8.4	1.3	2.7

D.4-13 Unit 110

Depth (ft)	Testhole	$CaCO_3$	pH	ECE	SAR
39.8- 40	2	0	7.2	0.2	0.9
48.8- 49.1	30	23.6	8.6	2.6	45
51.8- 52.2	16	6.3	8.8	1.4	37
56.0- 56.3	16	6.2	8.7	1.2	34
81 - 90	19	8.9	8.0	8.0	10
83.5- 84.0	4417JA	21.0	8.7	3.5	42
84 - 86	4417JA	—	8.6	2.8	34.3
84 - 86	29	—	8.5	3.4	32.6
86 - 86.5	29	—	8.8	1.6	54
95 - 98	19	0	8.5	2.4	14
104 -106	29	—	8.5	2.0	33.6
106 -106.5	29	9.7	8.7	1.7	59
106 -118	29	—	8.5	1.8	25.9
110.2-110.7	14	9.2	8.4	1.7	42
112.8-114.8	14	—	8.6	2.1	32.0
115.5-116.0	29	7.4	8.8	1.6	48
200.6-200.9	17	6.4	8.7	1.1	32
203.3-203.6	17	6.4	8.6	1.6	41

D.5 Center Site

The overburden analyses from the Center site include pH, ECE, and SAR values for all testholes. $CaCO_3$ values were determined for only three testholes (300, 348, and 364).

D.5-1 Unit 580

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
370	0- 5		7.9	6.0	8.0
374	0- 5		7.7	0.83	1.9
377	0- 5		7.9	0.30	0.3
348	0- 5	4.0	8.0	0.40	1.1

D.5-2 Unit 530

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
346	5- 10		7.9	5.6	5.4
333	0- 5		8.0	1.6	2.6
	5- 10		8.2	2.4	4.0
338	0- 5		7.2	6.2	6.4
	5- 10		8.0	5.0	9.1
	10- 15		8.2	2.4	13.2
	15- 20		8.0	0.97	14.3
335	0- 5		6.1	0.25	0.5
	5- 10		7.8	0.30	0.3
337	0- 5		7.8	0.96	2.0
	5- 10		7.8	3.2	2.9
	10- 15		7.6	3.6	2.7

APPENDIX D–Continued
SATURATION EXTRACT ANALYSES

Testhole	Depth	CaCO3	pH	ECE	SAR
310	0- 5		8.1	0.59	2.5
	5- 10		7.8	4.1	2.5
	10- 15		7.6	4.0	2.3
312	0- 5		8.0	0.65	2.6
	5- 10		7.9	6.7	3.5
	10- 15		7.9	3.6	3.8
	15- 20		7.8	2.7	4.0
	20- 25		7.8	1.0	2.3
363	0- 5		8.0	0.27	0.4
	5- 10		7.8	0.60	2.0
	10- 15		7.8	0.60	1.5
386	0- 5		7.5	0.62	0.7
	5- 10		7.6	0.42	0.3
	10- 15		7.7	0.40	0.6
393	0- 5		7.7	1.1	1.1
	5- 10		8.1	0.74	2.9
	10- 15		7.9	0.58	1.6
	15- 20		8.0	0.51	1.7
	20- 25		7.7	0.70	1.6
	25- 30		7.7	0.60	1.3
	30- 35		7.7	0.66	1.7
	35- 40		7.5	0.9	1.8
362	0- 5		7.9	4.1	1.5
	5- 10		7.8	3.6	5.9
	10- 15		7.8	1.8	3.1
	15- 20		7.8	0.63	1.4
	20- 25		7.6	0.55	0.5
369	0- 5		7.7	5.6	1.8
	5- 10		7.9	5.7	2.0
	10- 15		7.7	5.8	0.6
	15- 20		7.6	2.6	1.6
	20- 25		7.5	3.2	1.1
	25- 30		7.6	2.6	1.2
	30- 35		7.6	3.9	1.5
	35- 40		7.4	3.4	1.8
	40- 45		7.8	2.4	1.9
	45- 50		7.7	1.9	2.4
	50- 55		7.6	2.4	2.5
	55- 60		7.7	2.0	2.8
	60- 65		7.7	2.0	3.7
	65- 70		7.8	3.0	3.7
	70- 75		7.6	2.0	7.6
	75- 80		8.0	1.4	10.6
372	0- 5		7.7	5.3	4.9
	5- 10		7.9	8.5	11.0
	10- 15		8.1	2.6	12.4
	15- 20		8.0	2.2	9.5

Testhole	Depth	CaCO3	pH	ECE	SAR
	20- 25		6.6	2.4	2.6
D.5-3 Unit 180					
302	5- 10		7.8	3.0	4.1
	10- 15		7.6	3.3	2.4
397	0- 5		7.7	0.85	4.0
	5- 10		7.8	0.68	4.3
	10- 15		7.6	0.60	3.7
	15- 20		7.9	0.52	2.8
	20- 25		7.6	0.32	0.6
	25- 30		7.6	0.50	1.7
	30- 35		7.5	0.50	1.6
366	0- 5		8.0	8.5	10.3
	5- 10		8.1	9.7	12.8
365	0- 5		7.6	2.4	5.2
	5- 10		8.1	3.3	8.1
348	5- 10	6.4	7.8	5.0	1.8
D.5-5 Unit 160					
333	60- 65		7.2	2.1	0.7
312	50- 55		7.6	1.5	2.9
	55- 60		7.9	1.1	7.4
374	5- 10		7.7	5.2	4.4
382	5- 10		7.9	8.0	2.9
	10- 15		7.8	6.1	2.4
366	15- 20		7.9	2.7	4.4
	20- 25		8.0	1.2	4.0
D.5-6 Unit 150					
346	10- 15		7.7	3.4	4.1
	15- 20		4.3	3.2	1.6
302	15- 20		7.8	1.7	2.1
	20- 25		7.9	1.6	0.8
	25- 30		7.8	1.7	0.9
	30- 35		7.9	2.0	0.6
	35- 40		7.7	1.9	0.70
	40- 45		7.6	3.2	0.64
	45- 50		6.9	3.6	0.67
333	65- 70		7.8	1.6	0.7
	70- 75		8.0	1.6	0.8
	75- 80		7.8	1.7	1.0

APPENDIX D—Continued
SATURATION EXTRACT ANALYSES

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
	80-85		7.8	1.7	0.7
	85-90		7.8	2.8	0.6
	90-95		7.8	2.3	0.6
	95-100		7.9	2.6	0.8
335	10-15		8.4	0.35	1.2
	15-20		7.8	0.32	0.4
	20-25		7.7	0.25	0.4
	25-30		7.8	0.28	0.3
	30-35		7.4	0.62	0.9
337	15-20		7.8	2.1	2.6
	20-25		7.7	4.2	1.6
310	15-20		7.9	0.80	1.7
	20-25		7.9	0.60	0.9
	25-30		6.7	3.0	0.6
	30-35		6.1	2.6	0.6
	35-40		6.8	2.3	0.4
	40-45		7.7	1.5	0.7
312	60-65		8.0	1.9	10.8
	65-70		8.1	1.7	13.1
	70-75		8.1	1.0	9.2
374	10-15		7.6	4.5	3.0
	20-25		7.7	1.2	1.1
	25-30		7.7	1.1	0.8
	30-35		7.5	1.4	0.7
	35-40		7.7	1.3	0.8
	40-45		7.7	1.2	0.6
	45-50		7.7	1.2	0.6
	50-55		7.0	2.0	0.6
	55-60		7.9	0.86	0.9
	60-65		7.9	0.84	2.1
388	0-5		8.2	0.55	1.9
	5-10		8.1	0.30	0.6
	10-15		7.8	0.32	0.4
	15-20		7.8	0.23	0.4
	20-25		7.7	0.50	0.8
376	0-5		7.0	0.42	0.5
	5-10		8.1	0.70	1.5
	10-15		5.5	4.3	1.6
382	15-20		7.4	2.7	1.5
	20-25		7.4	3.9	0.9
	25-30		7.5	3.6	1.0
	30-35		7.4	3.1	1.3
	35-40		7.2	2.6	1.8
380	0-5		7.9	<0.15	0.2
	5-10		7.9	0.15	0.4

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
	10-15		7.9	0.25	0.4
	15-20		7.8	0.22	0.2
	20-25		7.9	0.24	0.4
	25-30		7.9	0.28	1.2
	30-35		7.9	0.79	3.5
	35-40		8.1	0.73	6.3
	40-45		8.2	0.75	7.5
	45-50		7.7	1.8	15.7
381	0-5		7.8	1.2	6.9
389	5-10		8.0	6.7	8.1
	10-15		7.9	5.0	7.4
	15-20		7.9	4.2	7.0
	20-25		7.7	5.3	7.3
365	10-15		7.3	6.0	5.9
	15-20		8.1	1.9	12.9
	20-25		7.4	6.6	11.3
	25-30		7.7	5.3	15.2
	30-35		8.0	3.8	19.6
300	0-5	29.8	8.7	0.48	0.5
	10-15	30.0	8.1	0.30	0.4
	15-20	38.2	8.2	0.31	0.5
348	10-15	9.2	7.7	3.45	1.5
	15-20	7.0	7.7	2.65	1.1
	20-25	5.7	7.3	3.40	0.9
364	0-5	9.6	8.0	0.48	2.1
	5-10	6.6	7.8	2.40	3.9
	10-15	18.2	7.9	2.43	3.8
	15-20	7.9	7.7	2.80	2.9
	20-25	lignite contamination	6.1	1.75	2.6

D.5-7 Unit 140

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
302	50-55		6.1	4.2	0.84
	55-60		6.5	3.4	1.2
333	100-105		7.5	2.2	1.4
	105-110		7.2	2.1	1.1
328	5-10		8.1	7.3	14.9
	10-15		8.2	2.2	16.7
	15-20		8.2	1.8	19.2
	20-25		8.2	2.3	15.4
335	35-40		7.8	0.49	0.3
	40-45		7.8	0.47	0.4
337	25-30		7.8	4.5	1.8

APPENDIX D—Continued
SATURATION EXTRACT ANALYSES

Testhole	Depth	CaCO3	pH	ECE	SAR
	30- 35		7.1	4.1	2.3
310	45- 50		7.8	1.2	0.8
	50- 55		7.2	1.1	1.5
370	5- 10		7.9	6.0	9.8
	10- 15		7.7	6.8	10.7
	15- 20		7.9	5.4	12.2
	20- 25		8.0	3.6	23.6
374	65- 70		7.9	0.78	1.4
	70- 75		8.0	0.84	2.5
388	25- 30		7.9	0.37	0.7
	30- 35		7.7	1.0	0.8
	35- 40		8.2	1.1	1.6
	40- 45		7.7	1.0	1.7
383	0- 5		7.6	7.5	7.6
377	5- 10		8.0	5.2	2.2
	10- 15		7.8	5.3	2.5
	15- 20		7.6	2.8	1.2
	20- 25		7.5	4.0	0.7
380	50- 55		8.3	1.3	17.4
	55- 60		8.3	1.3	20.8
	60- 65		8.6	1.6	25.1
	65- 70		8.4	1.6	27.1
	70- 75		8.6	1.3	17.7
381	5- 10		8.0	5.0	8.8
	10- 15		8.1	1.7	13.3
	15- 20		8.3	2.2	23.4
	20- 25		8.4	1.1	15.9
	25- 30		8.3	1.1	20.0
375	0- 5		7.8	0.70	1.0
	5- 10		7.9	6.0	2.4
	10- 15		7.8	4.0	2.8
	15- 20		7.8	1.2	1.0
	20- 25		7.7	1.0	1.0
	25- 30		7.8	0.85	0.8
	30- 35		7.8	0.70	1.0
	35- 40		8.0	0.76	1.5
386	15- 20		8.1	0.79	4.1
	20- 25		8.2	1.0	10.6
	25- 30		8.0	1.5	16.5
	30- 35		8.2	1.9	22.5
	35- 40		8.5	1.6	36.0
366	25- 30		7.9	1.8	4.7
	30- 35		8.1	1.9	18.0
	35- 40		8.2	1.4	10.1
	40- 45		8.1	1.8	16.7
	45- 50		8.1	2.4	17.6
	50- 55		8.3	1.6	8.4
369	80- 85		8.4	1.8	14.8
	85- 90		8.4	1.4	17.1
	90- 95		8.6	1.8	20.9
	95-100		8.8	1.6	45.4
300	20- 25	44.4	8.2	0.33	0.5
	25- 30	33.2	8.4	0.69	0.7
	30- 35	33.8	8.3	0.73	0.6
	35- 40	31.6	7.9	0.85	0.5
	40- 45	8.4	7.9	0.80	0.5
	45- 50	10.6	7.8	1.00	0.4
	50- 55	15.2	7.9	0.80	0.5
	55- 60	11.5	7.8	0.94	0.8

D.5-8 Unit 130

Testhole	Depth	CaCO3	pH	ECE	SAR
302	60- 65		7.8	2.4	1.5
	65- 70		7.8	1.7	2.5
328	25- 30		8.0	1.3	7.0
335	45- 50		7.0	1.4	1.0
312	75- 80		6.8	2.5	4.7
370	25- 30		7.4	3.6	17.2
388	45- 50		8.1	1.4	2.7
380	75- 80		8.2	1.8	21.9
381	30- 35		8.0	1.5	14.3
375	40- 45		7.9	0.92	2.0
386	40- 45		8.5	2.0	29.2
366	55- 60		7.0	2.0	5.1
369	100-105		8.1	1.6	16.9
300	60- 65	13.2	7.9	0.82	0.8

D.5-9 Unit 110

Testhole	Depth	CaCO3	pH	ECE	SAR
343	0- 5		7.7	0.53	2.4
	5- 10		8.0	0.36	4.4
	10- 15		8.3	0.80	11.6
	15- 20		8.1	0.60	6.6

APPENDIX D—Continued
SATURATION EXTRACT ANALYSES

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
	20- 25		8.1	0.80	10.6
	25- 30		8.1	1.3	9.5
	30- 35		8.1	2.0	12.5
	35- 40		8.2	2.2	14.0
346	25- 30		5.8	3.0	2.5
	30- 35		7.2	1.5	2.8
	35- 40		7.6	2.2	4.6
	40- 45		7.8	1.7	4.3
	45- 50		7.8	1.7	4.9
	50- 55		7.7	3.5	5.0
302	80- 85		8.1	1.7	8.3
	85- 90		8.1	1.5	9.0
	90- 95		8.3	1.7	11.2
	95-100		8.1	1.2	10.4
	100-105		8.1	1.3	12.0
	105-110		8.2	1.1	16.7
	110-115		8.3	1.6	15.7
	115-120		8.2	1.0	15.7
	120-125		7.4	1.9	16.2
328	40- 45		7.6	2.4	11.9
	45- 50		7.5	2.8	13.8
	65- 70		8.2	1.9	22.2
338	20- 25		7.7	3.7	7.0
	25- 30		8.0	2.6	8.6
	30- 35		7.1	3.8	7.6
335	55- 60		7.7	1.3	9.0
	60- 65		8.2	1.2	24.4
	65- 70		8.2	1.1	20.9
	70- 75		8.4	1.9	25.8
	75- 80		8.4	1.2	27.6
	80- 85		8.2	0.90	22.4
	85- 90		7.3	1.8	24.4
	90- 95		7.5	1.8	45.1
337	40- 45		6.5	3.3	6.5
	45- 50		7.8	2.4	10.1
	50- 55		8.2	2.2	15.2
	55- 60		8.4	1.7	19.4
	60- 65		8.3	2.3	30.1
	65- 70		8.4	1.6	28.4
	70- 75		8.6	1.8	30.2
	75- 80		8.5	1.8	50.3
	80- 85		8.5	1.7	49.4
	85- 90		8.5	2.0	45.1
310	65- 70		7.7	1.2	6.2
	70- 75		8.0	1.8	7.6
	75- 80		8.2	1.2	11.1
	80- 85		8.0	2.0	16.3
	85- 90		8.2	1.5	31.1
	90- 95		8.3	1.6	25.1
	95-100		8.3	1.6	23.0
	100-105		8.2	2.0	33.8
	105-110		8.4	1.7	39.3
	110-115		8.5	1.2	32.3
312	85- 90		6.5	2.8	3.0
	90- 95		7.5	2.1	8.4
	95-100		7.7	2.2	10.6
	100-105		8.0	1.4	18.4
370	35- 40		8.6	1.6	35.8
	40- 45		8.8	2.0	25.1
	45- 50		8.8	1.3	36.2
	50- 55		8.8	1.1	39.7
	55- 60		8.8	1.3	30.9
	60- 65		8.9	1.5	49.7
	65- 70		8.9	1.0	23.3
	70- 75		9.0	1.9	27.2
	75- 80		8.5	1.6	35.1
	80- 85		8.5	1.8	37.6
	85- 90		8.5	1.7	36.2
374	90- 95		7.1	2.3	9.0
	95-100		7.9	2.0	14.6
	100-105		8.3	1.5	16.8
	105-110		8.2	1.3	21.3
	110-115		8.3	1.5	15.4
388	60- 65		7.8	1.4	7.1
	65- 72		7.9	1.9	7.0
376	20- 25		8.1	1.5	2.1
	25- 30		7.9	2.0	2.3
	30- 35		7.7	2.1	2.5
	35- 40		7.9	1.5	3.5
	40- 45		7.9	1.1	5.8
	45- 50		8.1	1.1	7.4
	50- 55		8.2	1.0	8.6
	55- 60		8.1	2.0	17.2
	60- 65		8.2	1.6	15.9
348	30- 35	—	4.5	3.15	2.1
	35- 40	—	7.1	2.90	2.5
	40- 45	—	7.1	2.58	3.7
	45- 50	—	7.6	1.85	5.4
	50- 55	6.8	7.6	1.85	5.8
	55- 60	4.4	7.8	1.89	6.2
364	35- 40	1.9	7.9	2.75	9.5
	40- 45	9.2	8.3	1.70	17
	45- 50	8.6	8.3	1.46	24
	50- 55	8.5	8.3	1.83	34

APPENDIX D—Continued
SATURATION EXTRACT ANALYSES

Testhole	Depth	$CaCO_3$	pH	ECE	SAR
	55- 60	7.3	7.9	2.30	35
	60- 65	10.0	8.5	1.78	49
	65- 70	—	7.2	3.2	40
389	30- 35		6.5	6.7	14.4
	35- 40		8.7	1.5	22.5
	40- 45		8.6	1.3	16.3
	45- 50		8.4	1.3	28.7
	50- 55		8.5	1.5	18.0
	55- 60		8.5	1.8	38.0
	60- 65		8.6	2.1	32.7
	65- 70		8.6	1.6	27.3
	70- 75		8.5	1.8	39.8
	75- 77		8.6	1.6	24.3
372	30- 35		6.8	1.8	2.3
365	40- 43		7.4	2.8	33.4
	45- 50		7.4	4.4	45.6
	50- 55		8.4	3.0	20.1
	55- 60		8.5	1.0	15.6
	60- 65		8.4	1.6	41.4
	65- 70		8.3	1.7	23.6
	70- 75		8.3	1.4	18.9
300	75- 80	1.1	7.3	1.95	2.1
	80- 85	6.8	7.8	2.05	2.7
	85- 90	6.8	7.8	1.55	3.9
	90- 95	10.3	7.9	1.45	5.4
	95-100	10.0	8.0	1.30	6.1
	100-105	11.2	8.0	1.30	5.9
	105-110	12.5	8.0	1.25	5.1
	110-113	9.3	8.1	1.28	5.0
363	15- 20		7.8	1.6	7.4
	20- 25		4.4	4.2	3.5
	25- 30		3.7	5.4	3.7
382	45- 50		6.6	3.7	4.6
	50- 55		8.0	2.2	7.8
	55- 60		8.3	2.4	11.7
	60- 65		8.2	1.7	14.4
	65- 70		8.2	1.7	15.3
	70- 75		8.1	1.4	14.8
	75- 80		8.2	1.4	17.8
	80- 85		8.6	1.1	20.9
377	30- 35		6.8	2.1	2.0
	35- 40		8.2	1.4	2.9
	40- 45		7.7	3.0	3.0
	45- 50		8.1	1.6	4.2
	50- 55		8.1	1.5	7.0
	55- 60		8.1	1.3	8.6
	60- 65		8.3	1.3	11.5
	65- 70		8.1	1.2	10.2
375	55- 60		7.6	2.0	12.6
	60- 65		8.6	1.2	30.8
	65- 70		8.6	1.4	25.0
	70- 75		8.6	2.4	32.5
	75- 80		8.6	1.1	47.3
	80- 85		8.5	1.8	50.8
	85- 90		8.8	1.2	24.8
	90- 95		8.7	1.9	39.2

PLATE A.2.2-1

CROSS-SECTION OF HIGHWALL AT INDIAN HEAD MINE

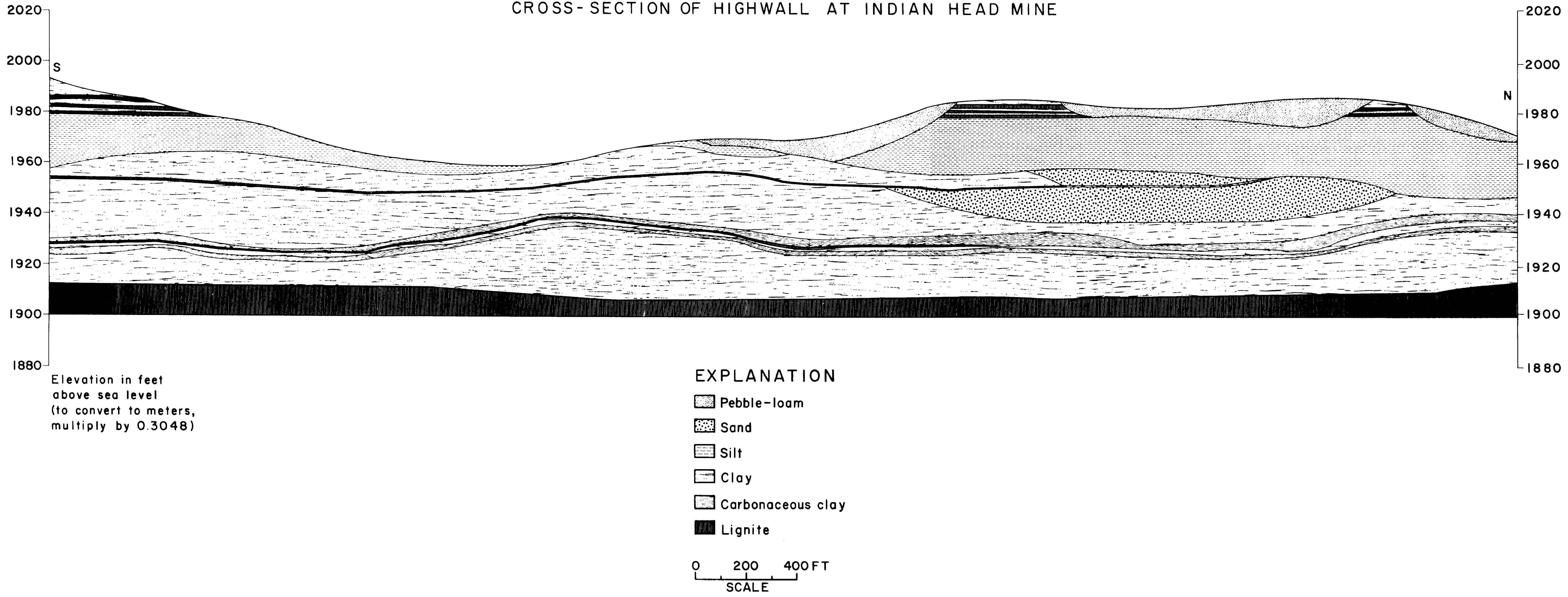


PLATE C.1-1 DIAGRAMMATIC CROSS SECTION OF THE FALKIRK SITE, Mc LEAN COUNTY, NORTH DAKOTA

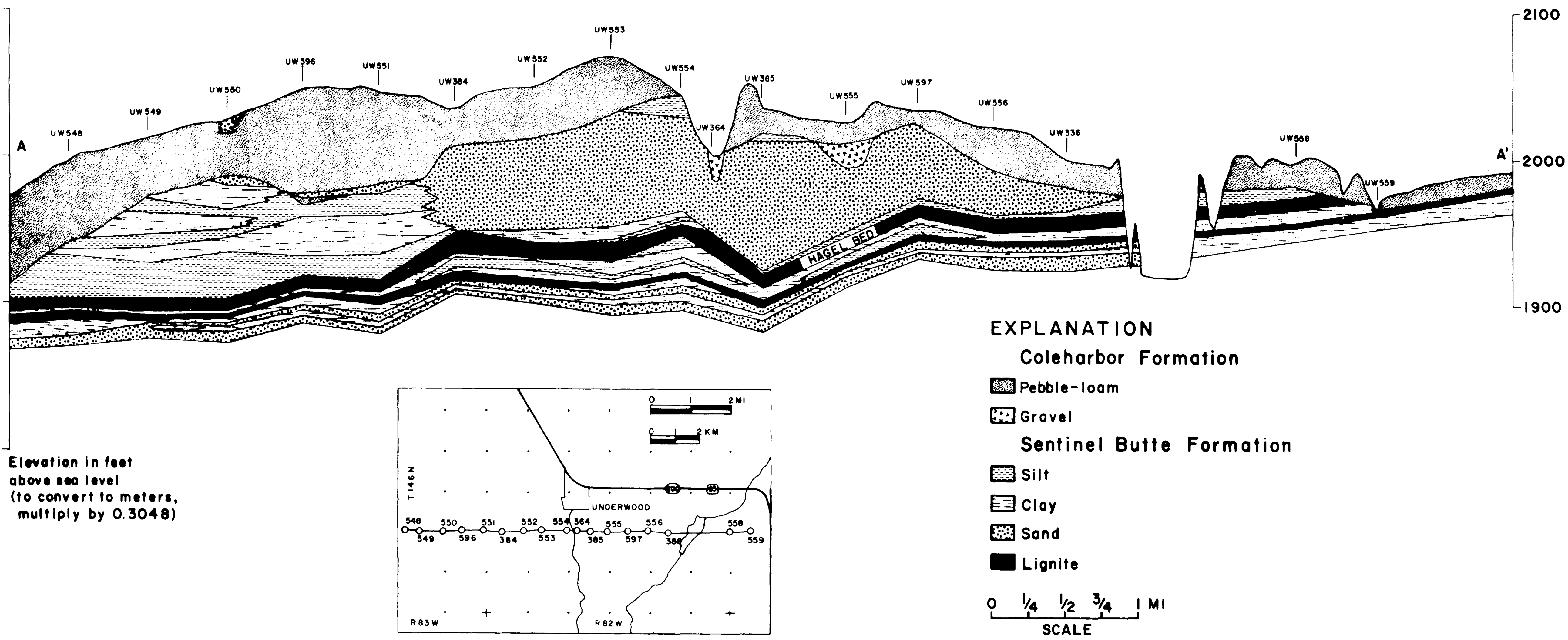
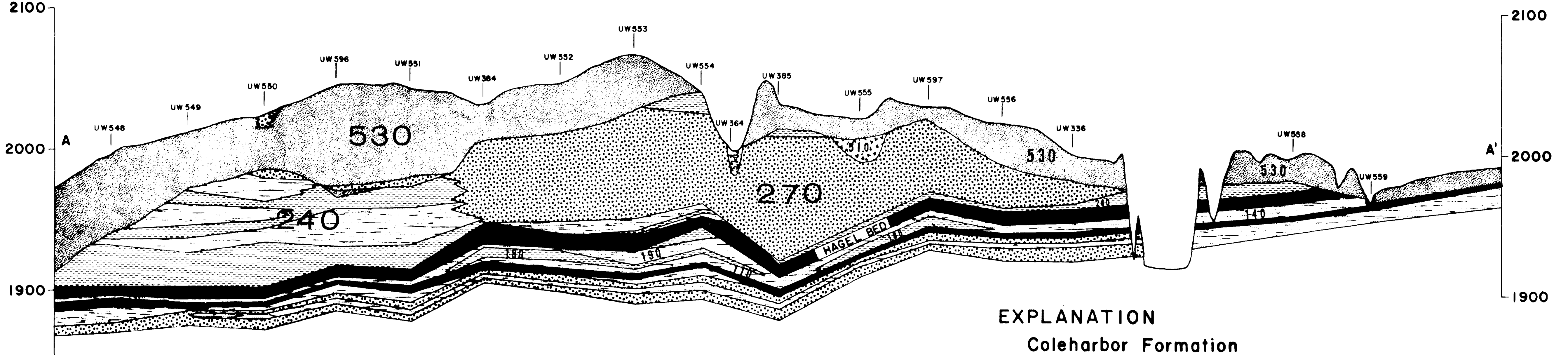
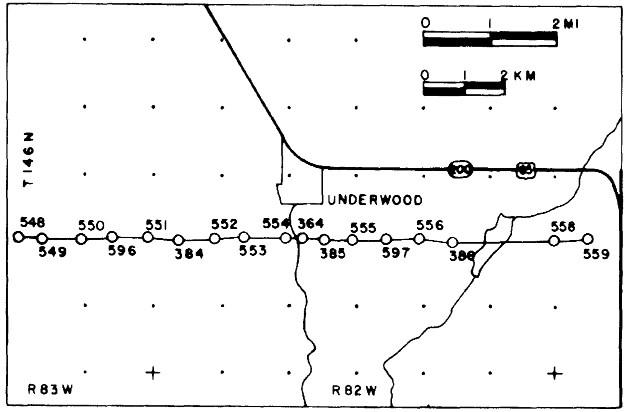


PLATE C.1-2 CODED DIAGRAMMATIC CROSS SECTION OF THE FALKIRK SITE, McLEAN COUNTY, NORTH DAKOTA



Elevation in feet
above sea level
(to convert to meters,
multiply by 0.3048)



EXPLANATION

Coleharbor Formation

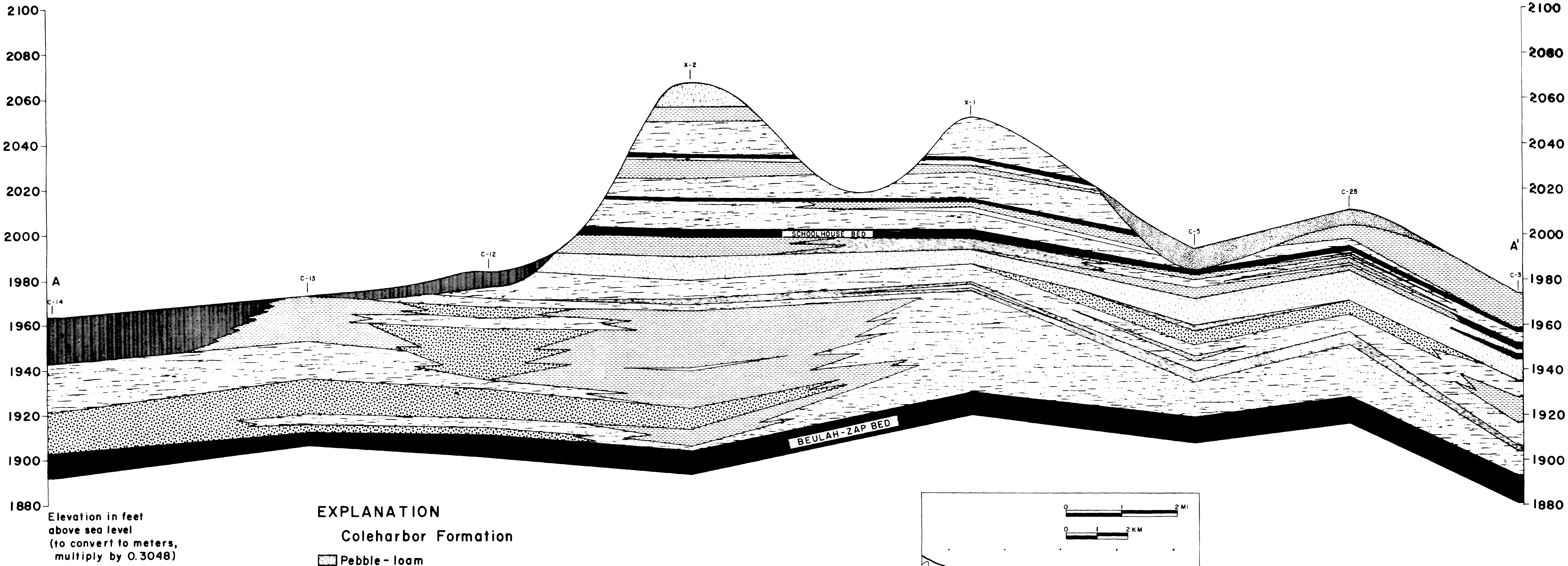
- ▨ Pebble-loam
- ⁙ Gravel

Sentinel Butte Formation

- ▤ Silt
- ☰ Clay
- ⁙ Sand
- ■ Lignite

0 1/4 1/2 3/4 1 MI
SCALE

PLATE C.2-1 DIAGRAMMATIC CROSS SECTION OF THE INDIAN HEAD MINE SITE, MERCER COUNTY, NORTH DAKOTA



EXPLANATION

Coleharbor Formation

▨ Pebble - loam

■ Silt and clay

Sentinel Butte Formation

▨ Sand

▨ Sandy silt - silty sand

▨ Silt

▨ Clay

▨ Carbonaceous clay

■ Lignite

0 250 500 FT
SCALE

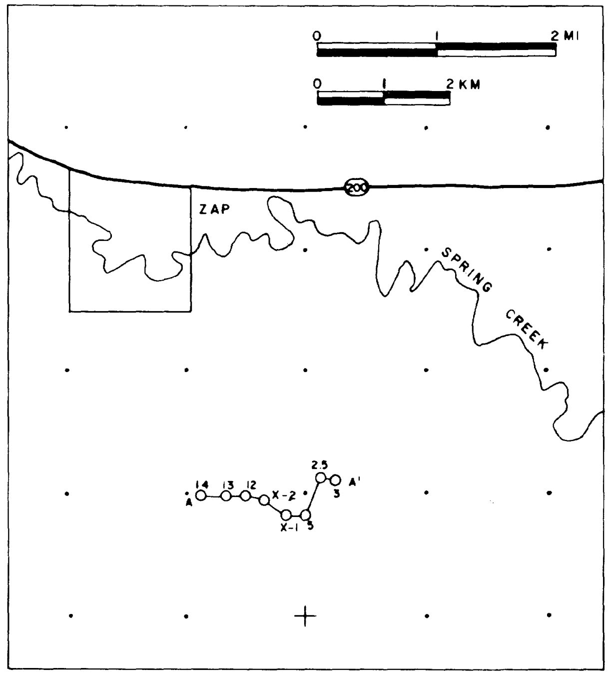
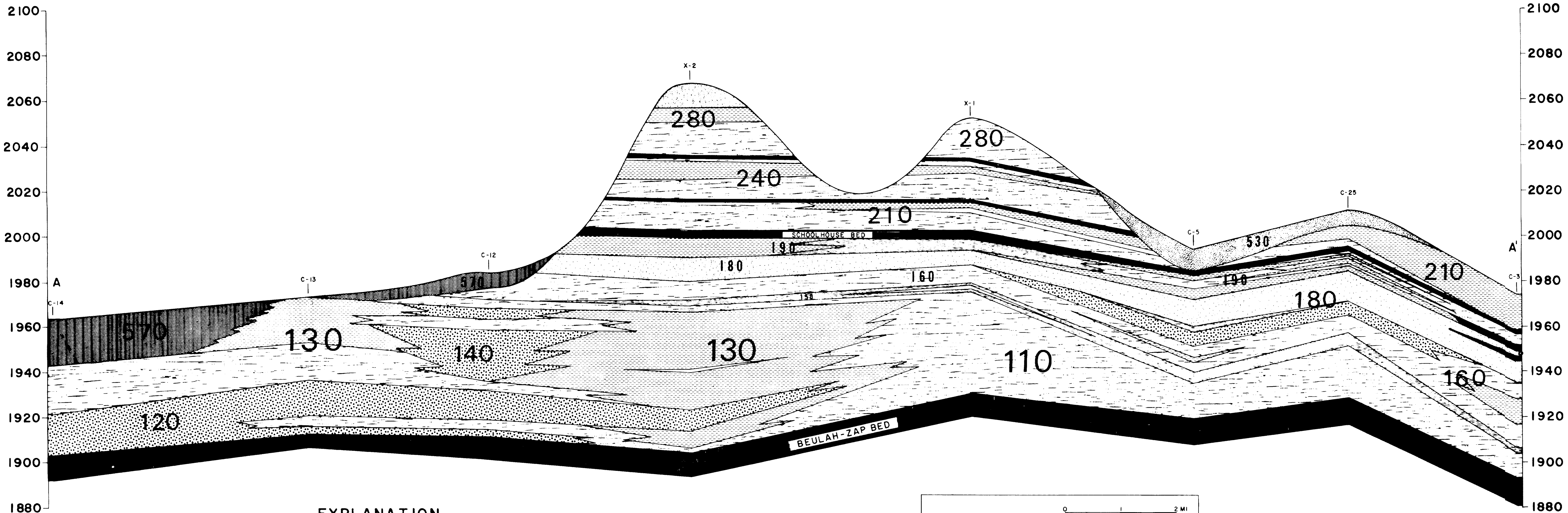


PLATE C.2-2 CODED DIAGRAMMATIC CROSS SECTION OF THE INDIAN HEAD MINE SITE, MERCER COUNTY, NORTH DAKOTA



Elevation in feet
above sea level
(to convert to meters,
multiply by 0.3048)

EXPLANATION

Coleharbor Formation

- ▨ Pebble - loam
- ■ Silt and clay

Sentinel Butte Formation

- ▨ Sand
- ☐ Sandy silt - silty sand
- ▨ Silt
- ☐ Clay
- ▨ Carbonaceous clay
- ■ Lignite

0 250 500 FT
SCALE

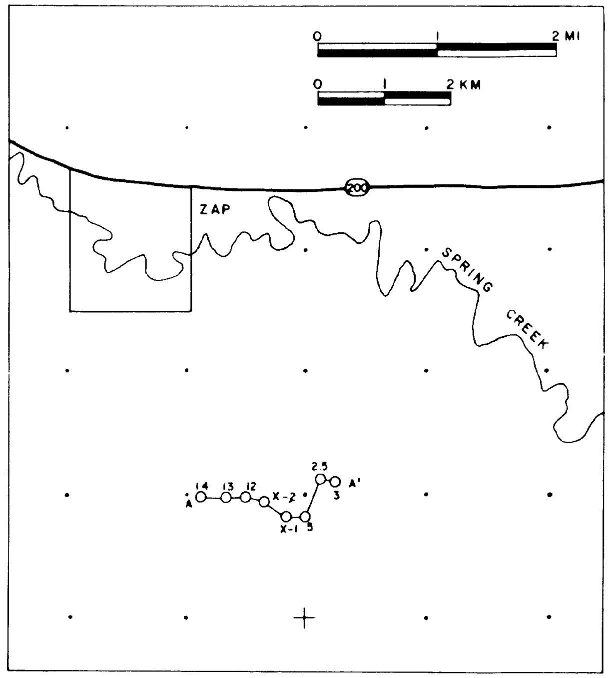


PLATE C. 3-1 DIAGRAMMATIC CROSS SECTION OF THE BEULAH-HAZEN SITE, MERCER COUNTY, NORTH DAKOTA

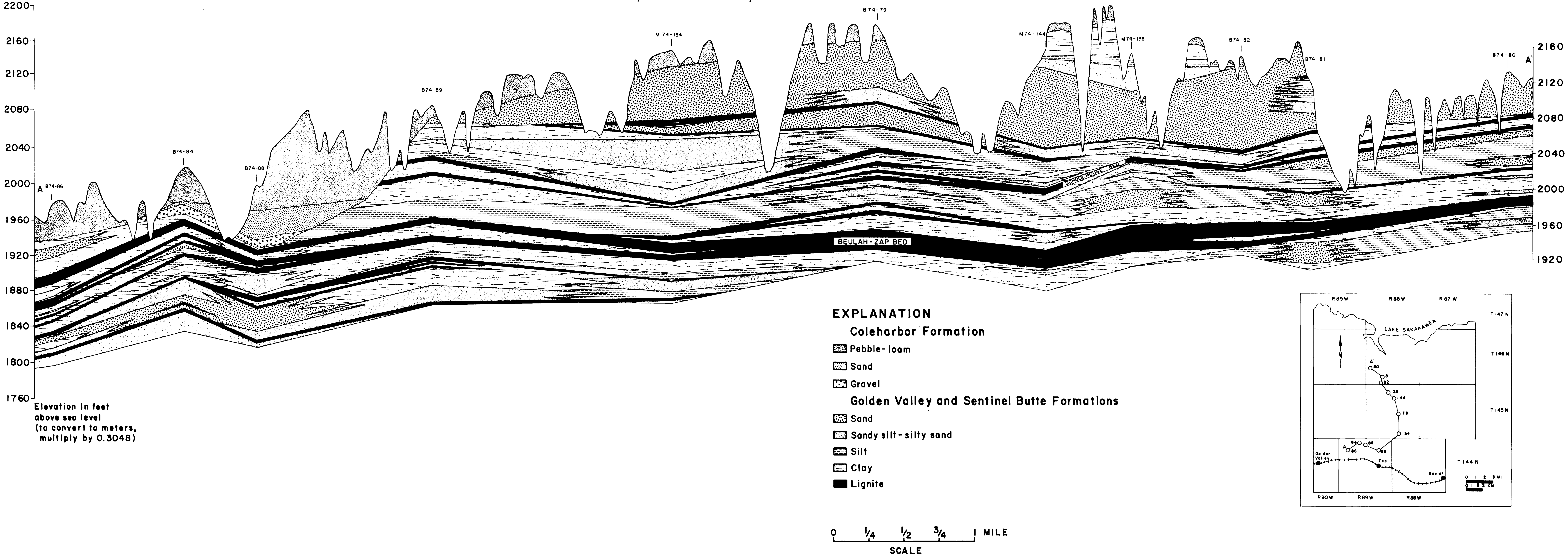


PLATE C.3-2 CODED DIAGRAMMATIC CROSS SECTION OF THE BEULAH-HAZEN SITE, MERCER COUNTY, NORTH DAKOTA

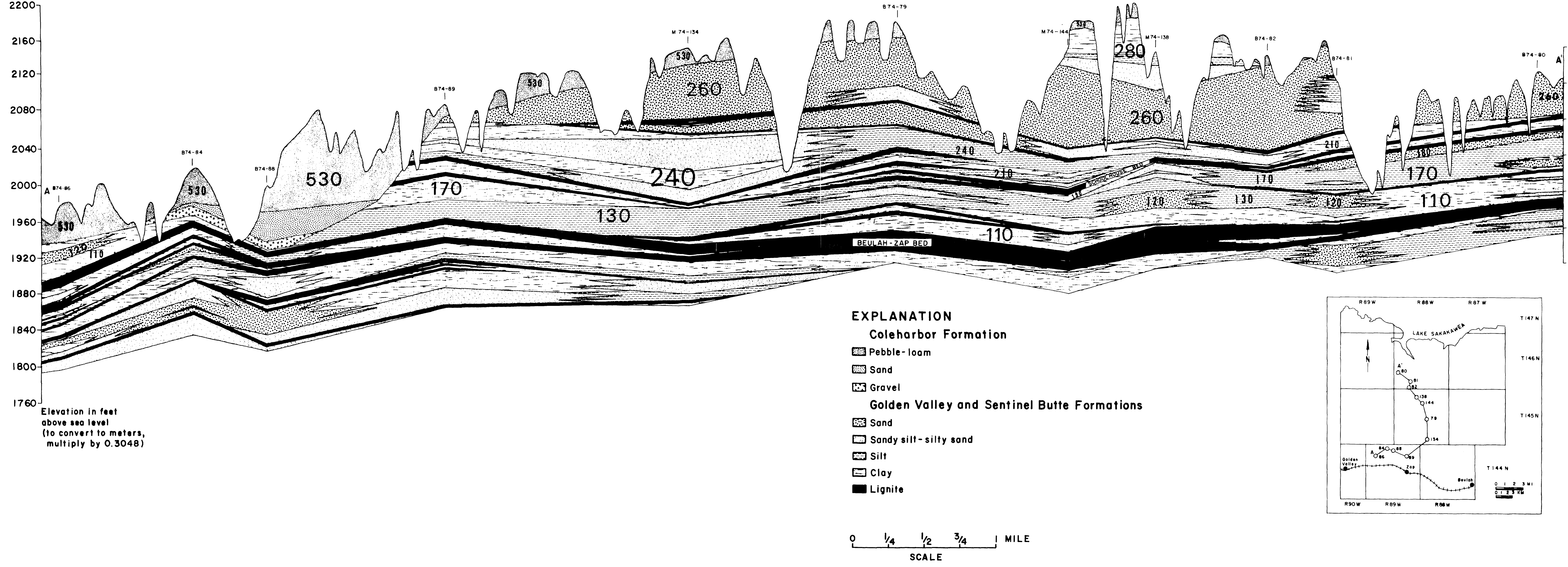


PLATE C.4-1 EAST - WEST DIAGRAMMATIC CROSS SECTION OF THE PROPOSED MINE AREA NO. 1, DUNN CENTER SITE, DUNN COUNTY, NORTH DAKOTA

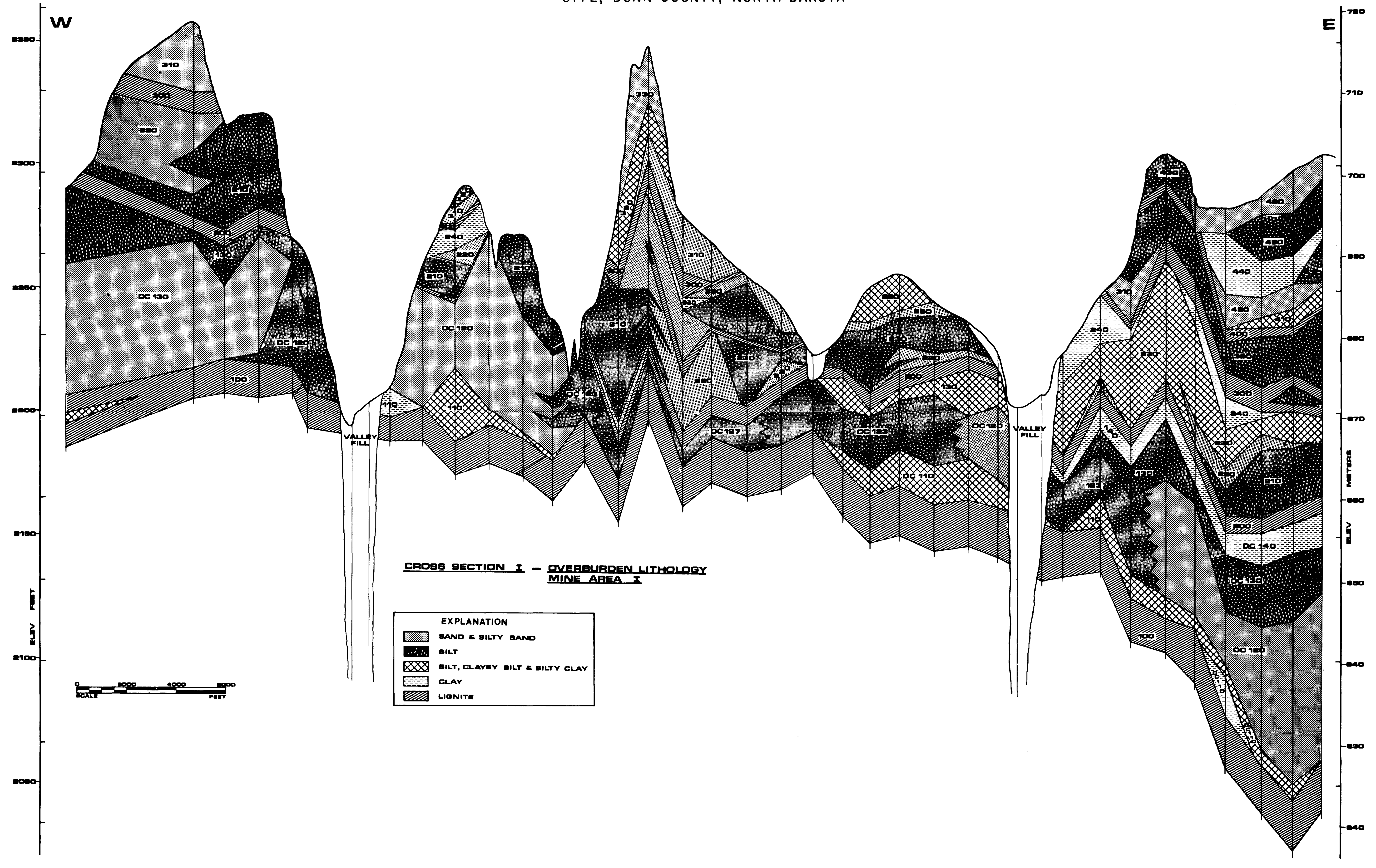


PLATE C.4.1-2 DIAGRAMMATIC CROSS SECTION OF THE PROPOSED AMAX DUNN CENTER NO. 1 MINE, DUNN COUNTY, NORTH DAKOTA

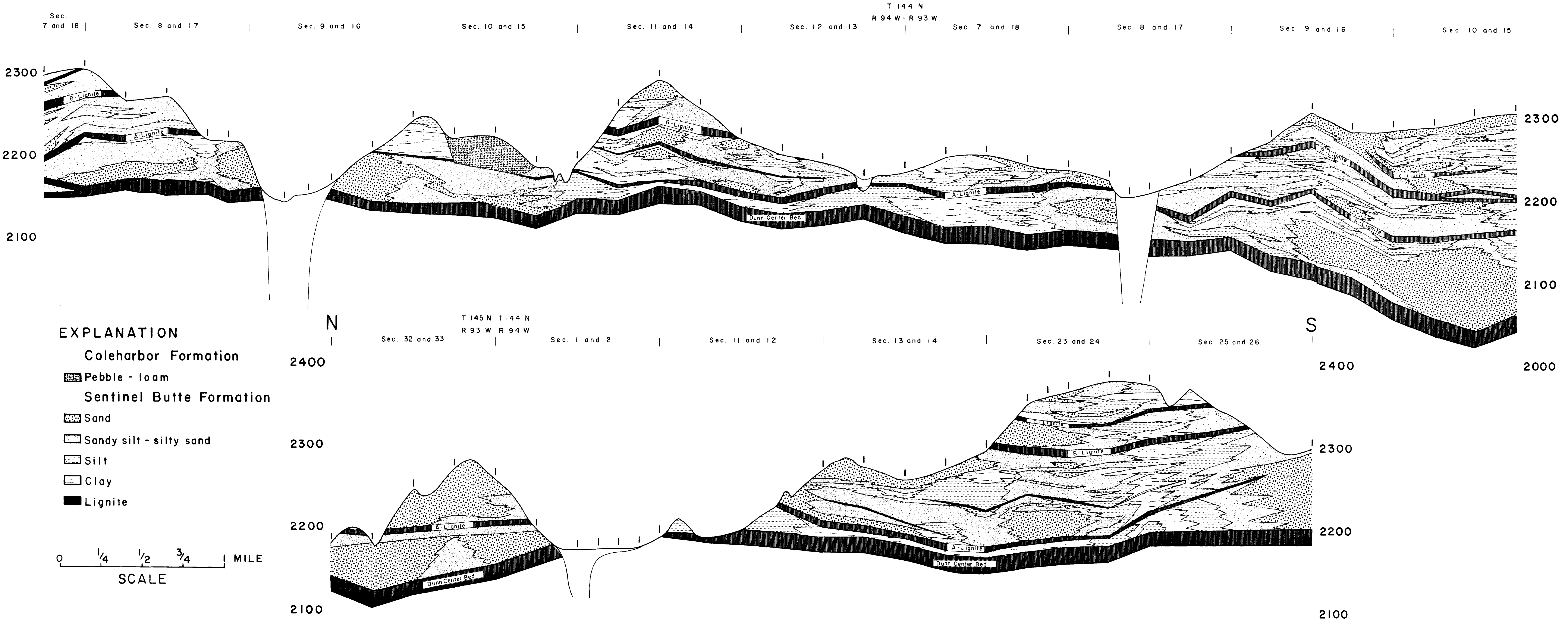


PLATE C.4-2 NORTH-SOUTH DIAGRAMMATIC CROSS SECTION OF THE PROPOSED MINE AREA NO. 1, DUNN CENTER SITE, DUNN COUNTY, NORTH DAKOTA

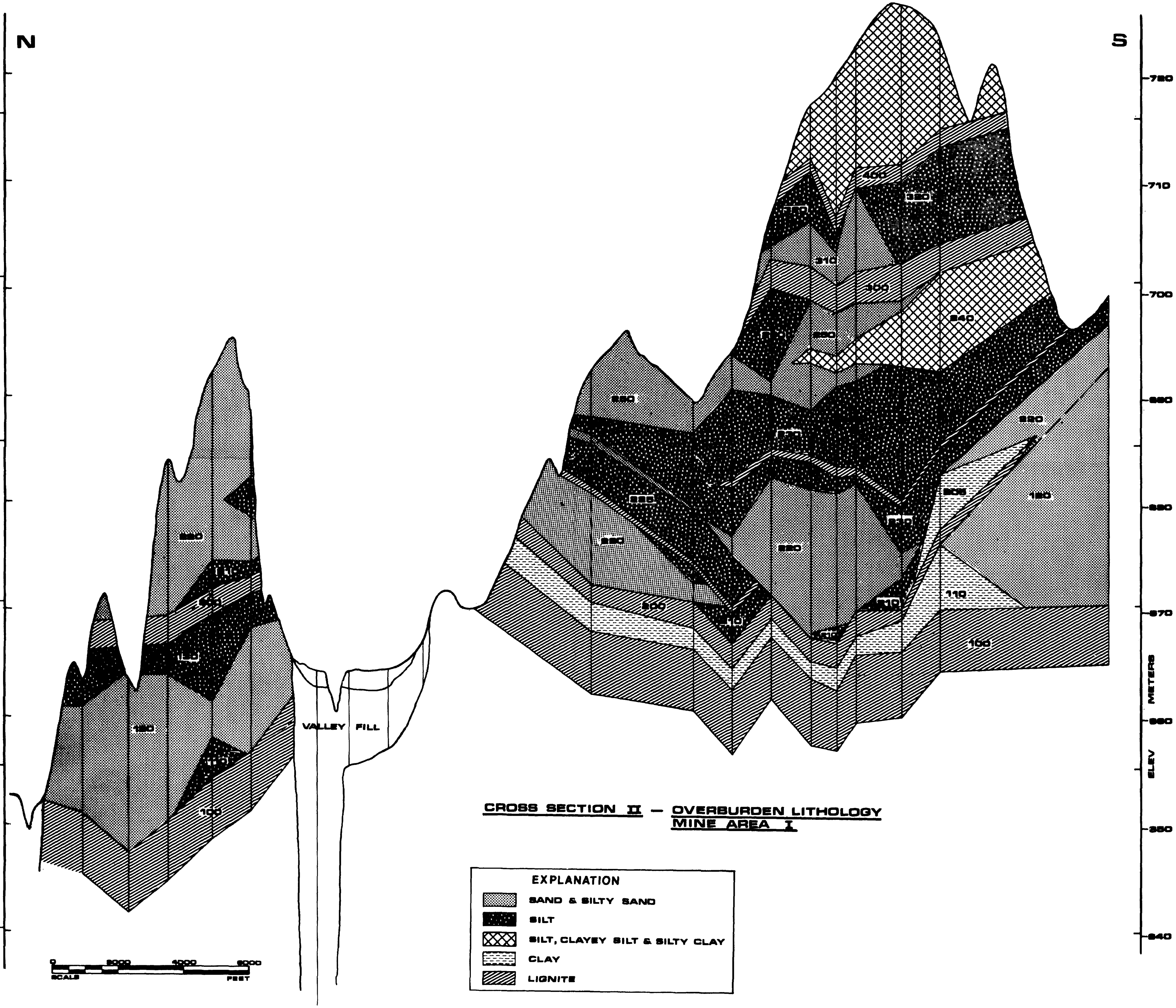


PLATE C.5-1 DIAGRAMMATIC CROSS SECTION OF THE CENTER SITE OLIVER COUNTY, NORTH DAKOTA

Elevation in feet above sea level (to convert to meters, multiply by 0.3048)

EXPLANATION

Coleharbor Formation

- ▨ Pebble - loam
- ■ Silt and clay

Sentinel Butte Formation

- ▨ Sand
- ▨ Sandy silt - silty sand
- ▨ Silt
- ☐ Clay
- ■ Lignite

PLATE C.5-2 CODED DIAGRAMMATIC CROSS SECTION OF THE CENTER SITE OLIVER COUNTY, NORTH DAKOTA